J. Agric. Food Chem. 1994, 42, 1361–1368

Swiss Chard and Alfalfa Responses to Soils Amended with Municipal Solid Waste Incinerator Ash: Growth and Elemental Composition[†]

Carl J. Rosen,* Peter M. Bierman, and Daniel Olson

Department of Soil Science, University of Minnesota, St. Paul, Minnesota 55108

The effects of three municipal solid waste (MSW) incinerator ashes on soil chemical properties, plant growth, and elemental composition of Swiss chard (*Beta vulgaris* L.) and alfalfa (*Medicago sativa* L.) were investigated in greenhouse pot experiments. Ash rates of 13.1, 16.2, and 26.7 g kg^{-1} of soil, based on their available K content, were compared with K fertilizer, P fertilizer, P + K fertilizer, and nonamended controls. Plant dry matter production in ash-amended soil was similar to or greater than that in fertilized soil. Responses varied with crop and ash type, but increases occurred in MSW ash treatments for soil pH, soluble salts, extractable soil P, K, Ca, Na, Cu, Zn, Mo, Cd, and Pb, and plant tissue (leaf plus stem) concentrations of P, K, Ca, Mg, Na, B, Cu, Zn, Mo, and Cd. No phytotoxic effects were observed, but some alfalfa treatments exceeded livestock dietary tolerances for Mo (>5 mg kg^{-1}) and Cd (>0.5 mg kg^{-1}).

INTRODUCTION

Incineration has been and continues to be a common method for reducing the volume of municipal solid waste (MSW). Although incineration effectively reduces MSW volume, and may also provide usable energy, the environmental implications of MSW incineration and ash disposal have made managing the resulting ash a major issue (Lisk, 1988). The use of landfills for ash disposal is expensive and is being discouraged by more stringent regulations and frequent public opposition. Finding an environmentally acceptable alternative to landfilling the ash is important, because incineration of MSW is a waste management option that continues to be practiced.

Municipal solid waste incinerator ash has been shown to contain elements considered essential for plant growth (Bache and Lisk, 1990). However, the ash also contains heavy metals of environmental concern (Giordano et al., 1983; Wadge and Hutton, 1986; Bache and Lisk, 1990). Ash typically has a high pH and may be beneficial as a liming agent. When properly managed, the use of MSW ash as a soil nutrient and liming amendment could help ease the burden of disposal, while at the same time recycle or transform the waste into a beneficial agricultural product.

There are few studies examining plant availability of elements derived from MSW incinerator ash. Giordano et al. (1983) reported that corn and Swiss chard plants grown in MSW ash-amended soils accumulated high levels of Cd, Pb, and Zn; however, the phytotoxicity of the ash was associated with its high salt content rather than a specific metal. When soil was amended with leached ash, a positive growth response by Swiss chard was recorded compared to that with nontreated soil. Wadge and Hutton (1986) reported that barley and cabbage plants contained elevated levels of Cd, Pb, and Se when grown in ash-amended soils, but they also considered poor growth at the highest ash rate to be caused by elevated soluble salts and high pH. Bache and Lisk (1990) found that the Cd, Pb, and Zn content of perennial ryegrass and Swiss chard was significantly correlated with the concentrations of these metals in the ashes from 18 incinerators used as soil amendments.

In the soil amendment studies discussed above, which were all greenhouse pot experiments, the amount of ash added to the soil was between 5 and 40% by weight. This loading rate generally exceeds the nutrient requirements for crop production and can also lead to salt problems. No studies could be found that dealt with the addition of agriculturally accepted rates based on the nutrient content or liming ability of the ash. Studies have also not dealt with the plant availability of major nutrients in MSW ash. Although most of the N is lost during combustion, MSW ashes contain potentially useful amounts of P and K (Lisk, 1988; Bache and Lisk, 1990).

In this research, greenhouse pot experiments were conducted to provide initial information for evaluating the feasibility of using MSW ash as an agricultural soil amendment. The objectives were to (1) chemically characterize selected MSW incinerator ashes and base soil amendment rates on their plant nutrient content, (2) examine the availability of essential plant nutrients in MSW incinerator ash and its effectiveness as a liming amendment, and (3) determine potential soil accumulation and plant uptake of trace elements that may pose environmental or animal health risks.

MATERIALS AND METHODS

Ash Selection and Characterization. The three MSW incinerator ashes studied were primarily selected on the basis of their relatively high K content. Secondary considerations were to select a representative range of incinerator facilities/ash types that also varied in other agriculturally or environmentally important characteristics. These included liming potential, soluble salts, P content, and trace element concentrations. The three ash types selected were (1, ash A) a fly ash from an incinerator that co-burns MSW and sewage sludge, (2, ash B) a bottom ash from a mass-burn facility, and (3, ash C) a combined ash from a mass-burn facility. Mass-burning refers to burning of the ash as received, with only limited sorting to remove very large, noncombustible items.

Selected properties of the three MSW ashes are presented in Table 1. The MSW waste stream for ash A was from an urban

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* Author to whom correspondence should be addressed.

[†] Paper No. 21026 of the Journal Series, Minnesota Agricultural Experiment Station. Funding for this project was approved by the Minnesota Legislature [M.L. 89, Chapter 335, Art. 1, Sec. 29, Subd. 4(i).] as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Future Resources Fund.

0021-8561/94/1442-1361$04.50/0

Table 1. Selected Properties of Three Municipal Solid Waste Incinerator Ashes

	ash source and type		
property	ash A (fly)	ash B (bottom)	ash C (combined)
particle size (% by weight <2 mm)	100.0	75.0	62.1
pH (1:1, water)	10.7 ± 0.6[a]	12.5 ± 0.1	9.9 ± 0.1
calcium carbonate equivalence (%)	12.6 ± 1.4	25.9 ± 0.6	15.2 ± 2.4
soluble salts (dS m^{-1})	3.1 ± 0.1	53.2 ± 1.4	35.2 ± 0.3
chloride (mg kg^{-1})	253 ± 5	10117 ± 33	5501 ± 253
fertilizer value			
total nitrogen (g kg^{-1})	<1	<1	<1
available phosphorus (g kg^{-1})	10.2 ± 1.5	4.8 ± 0.9	0.7 ± 0.0
available potassium (g kg^{-1})	8.7 ± 0.4	10.8 ± 1.7	5.2 ± 0.2
acid-digestible elements			
aluminum (g kg^{-1})	86.6 ± 1.8	63.5 ± 3.4	51.9 ± 2.0
calcium (g kg^{-1})	53.2 ± 1.7	107.5 ± 3.8	62.9 ± 1.6
iron (g kg^{-1})	15.7 ± 3.8	40.9 ± 4.6	15.5 ± 1.2
magnesium (g kg^{-1})	8.3 ± 0.2	9.8 ± 0.4	7.9 ± 0.1
phosphorus (g kg^{-1})	16.3 ± 0.1	6.8 ± 0.5	2.9 ± 0.2
potassium (g kg^{-1})	11.3 ± 0.2	18.2 ± 0.8	8.5 ± 0.3
sodium (g kg^{-1})	15.0 ± 0.1	17.3 ± 0.4	11.3 ± 0.3
sulfur (g kg^{-1})	4.3 ± 0.2	7.9 ± 0.4	8.6 ± 0.2
barium (mg kg^{-1})	974 ± 14	950 ± 78	694 ± 66
boron (mg kg^{-1})	100 ± 4	214 ± 18	153 ± 1
cadmium (mg kg^{-1})	25 ± 1	26 ± 3	39 ± 2
cobalt (mg kg^{-1})	<1.2	10 ± 3	<1.2
chromium (mg kg^{-1})	140 ± 16	363 ± 85	115 ± 18
copper (mg kg^{-1})	1582 ± 34	2001 ± 363	2489 ± 1517
lead (mg kg^{-1})	1134 ± 55	1447 ± 752	1950 ± 77
manganese (mg kg^{-1})	822 ± 13	1550 ± 95	690 ± 69
molybdenum (mg kg^{-1})	7 ± 1	35 ± 3	12 ± 3
nickel (mg kg^{-1})	71 ± 3	512 ± 159	123 ± 55
strontium (mg kg^{-1})	143 ± 2	279 ± 7	157 ± 4
zinc (mg kg^{-1})	2395 ± 86	6820 ± 835	2920 ± 77

[a] Means of three samples ± standard deviation.

area with a population of about 100 000, ash B was from a predominantly rural area, and ash C was from a town of about 15 000 and its surrounding rural area. The chemical composition of the three ashes was within the ranges reported in a review of MSW incineration by Lisk (1988), except that Co and Cr concentrations were lower in all three, Mn was lower in ash C, Sr was higher in ash B, and P was higher in ash A, where MSW was co-incinerated with sewage sludge.

Ash was obtained from each incinerator facility in September 1989 and stored in acid-washed plastic containers. Collection consisted of daily random grab samples that were composited over a 2-week interval. Following collection, ash was air-dried, ground, passed through a 2-mm plastic screen, and mixed thoroughly. The fraction that did not pass through the 2-mm sieve primarily consisted of glass and metal debris. Only the <2-mm-size fraction was used for chemical analyses and as a soil amendment in the greenhouse experiments.

Three random subsamples were removed from each ash type for chemical analyses and dried to constant weight at 105 °C. Ash pH was determined on a 1:1 (w/v) ash/water slurry. Calcium carbonate equivalence (CCE), a measure of liming potential, was determined by acid dissolution and back-titration with base (Johnson, 1990a). Soluble salts were determined by measuring the electrical conductivity (EC) of a saturated paste extract (Dahnke and Whitney, 1988) after an equilibration time of 2 h. Chloride was extracted with 0.1 M calcium sulfate and measured colorimetrically using the mercuric thiocyanate method (Fixen et al., 1988). The major nutrient value of the ashes was determined by standard methods for fertilizer analysis (Johnson, 1990b). Total N was determined after reduction and digestion procedures, available P content following extraction with ammonium citrate, and available K content following ammonium oxalate extraction.

Ash digestion for analyses of other elements was achieved by weighing 1.0 g of ash into a 120-cm^3 Teflon microwave digestion vessel with 5 mL of concentrated nitric acid and 0.5 mL of redistilled concentrated (70%) perchloric acid. Samples were digested in a Model MDS-81D (CEM Corp., Matthews, NC) microwave oven that was powered for a total of 130 min over a 24-h digestion period. Following digestion, 61% of ash A, 57% of ash B, and 65% of ash C remained insoluble. Inductively coupled plasma-atomic emission spectroscopy (ICP) was used to determine the elemental composition of the extract (Munter and Grande, 1981).

Soil and Plant Characteristics. The A horizons of two soil types were selected for use based on their low available K concentrations: (1) a Gotham loamy fine sand (sandy, mixed, mesic Psammentic Hapludalf) and (2) a Verndale coarse sandy loam (coarse-loamy, mixed, Udic Argiboroll). Initial chemical properties of the Gotham soil were as follows: pH 6.0 [1:1 (w/v) soil/water; Eckert, 1988], 17 g kg^{-1} organic matter (modified Walkley-Black method; Schulte, 1988), 79 mg kg^{-1} ammonium acetate extractable K (Brown and Warncke, 1988), and 33 mg kg^{-1} Bray P-1 extractable P (Bray and Kurtz, 1945). The Verndale soil had an initial pH of 5.9, 19 g kg^{-1} organic matter, 53 mg kg^{-1} ammonium acetate extractable K, and 15 mg kg^{-1} Bray P-1 extractable P.

The effects of MSW incinerator ash on plant growth were studied on two crops. Swiss chard (*Beta vulgaris* L. Cicla group cv. Fordhook Giant) was chosen because it is a frequently used indicator crop that represents the affinity of green leafy vegetables to accumulate metals. Alfalfa (*Medicago sativa* L. cv. Epic) was chosen because of its economic importance as a forage crop and its higher pH requirement of 6.5.

Experimental Treatments and Cultural Practices. Treatments included the two selected soil types, the three selected ash types, commercial K and P fertilizer, and controls without ash or fertilizer for each soil type. Ash and fertilizer rates were identical in both the Swiss chard and alfalfa experiments. Treatments are summarized in Table 2.

Amendment rates differed for each ash, because they were designed to supply equivalent amounts of plant-available K and the three ashes differed in available K concentration (Table 1). The applied K rate was based on soil test values for available K in the two soils used and standard fertilizer recommendations for field-grown crops (Rehm et al., 1988). Table beet (*B. vulgaris*

Table 2. Summary of Municipal Solid Waste Incinerator Ash and Fertilizer Treatments for the Swiss Chard and Alfalfa Greenhouse Experiments

soil type	ash/fertilizer treatment	ash rate (g kg^{-1} of soil)	available K rate (mg kg^{-1} of soil)	available P rate (mg kg^{-1} of soil)
Gotham	control	0	0	0
Gotham	ash A	16.19	141	165
Gotham	ash B	13.08	141	63
Gotham	ash C	26.98	141	18
Gotham	K	0	141	0
Gotham	P	0	0	25
Gotham	P + K	0	141	25
Verndale	control	0	0	0
Verndale	ash A	16.19	141	165
Verndale	ash B	13.08	141	63
Verndale	ash C	26.98	141	18
Verndale	K	0	141	0
Verndale	P	0	0	50
Verndale	P + K	0	141	50

L.) recommendations were used for Swiss chard, because both crops are in the same plant species.

The recommended K rate for both alfalfa and Swiss chard, in both soils, was 140 kg of K ha^{-1}. The ash rates applied to each pot were calculated to supply this amount on a surface area basis (15.2-cm-diameter pots were used). The total ash, available K, and available P rates in Table 2 are expressed on a soil weight basis rather than a surface area basis, because amendments were thoroughly mixed with the soil and soil-weight-based rates more accurately describe the actual experimental conditions for plants grown in pots. Total ash applications, on a surface area rather than a soil weight basis, were approximately 8.1, 6.5, and 13.2 Mg ha^{-1} for ashes A, B, and C, respectively.

Potassium fertilizer treatments supplied K at rates equivalent to the available K in ash treatments, using KCl (524 g of K kg^{-1} of fertilizer) as the K source. Phosphorus fertilizer treatments were based on soil test values for available P and standard fertilizer recommendations (Rehm et al., 1988). Ordinary superphosphate (87.4 g of P kg^{-1} of fertilizer) was the P source, and applications to both Swiss chard and alfalfa on a surface area basis corresponded to P rates of 24.5 kg ha^{-1} for the Gotham soil and 49 kg ha^{-1} for the Verndale soil. Phosphorus fertilizer rates were less than the amount of available P supplied by ashes A and B but greater than that supplied by ash C (Table 2). The combined fertilizer treatments (P + K) received applications of superphosphate and KCl that were identical to the rates used for each soil type in the individual (P or K) fertilizer treatments.

Soil was sieved through a 5-mm screen and mixed thoroughly, and treatments were prepared by mixing ash or fertilizer with 1.8 kg of soil on a dry weight basis. Plants were grown in 1-L plastic pots, and precautions were taken to avoid losses of soluble ash constituents. Pots were placed on plastic saucers to collect drainage water, which was allowed to move back into the pot by capillary action. Any salts forming on the plate were rinsed back into the pot on a weekly basis. Leaching losses could be substantial in some field conditions, but these procedures permitted the evaluation of salt effects and plant uptake of metals under "worst case" conditions.

Swiss chard was planted October 4, 1990, thinned to three plants per pot, and grown for 41 days. Alfalfa seeds were inoculated with mixed strains of *Rhizobium meliloti*, planted October 4, 1990, thinned to six plants per pot, and grown for 111 days. Swiss chard was irrigated with an ammonium nitrate solution that supplied 272 mg of N kg^{-1} of soil (269 kg of N ha^{-1}) over the 41-day growing period. Alfalfa was irrigated with plain water. For both crops, pots were spaced 28 cm apart, plants were grown under natural light, and day/night temperatures were approximately 29/18 °C.

Plant Growth, Tissue Analyses, and Soil Analyses. Alfalfa plants were cut back twice. Every 37 days, shoots measuring 20 cm or greater were cut back to 15 cm. Alfalfa tissue from the two cuttings was combined with that from the final harvest for yield determinations and elemental analyses. Temporal variability in alfalfa tissue composition may have occurred, but data on the average concentration of all tissue produced over the entire growing period was judged to be sufficiently informative and more cost effective. The final harvest of both Swiss chard and alfalfa consisted of cutting entire plants 1 cm above the soil surface. Yields were measured on a total above-ground biomass basis and expressed in terms of dry matter yield per plant.

All harvested plant material was rinsed three times in deionized water, oven-dried at 65 °C, weighed, and then ground with a Wiley mill to pass through a 1-mm screen. Multielement ICP analysis (Munter et al., 1984) was performed on ashed samples dissolved in 2 M HCl for Al, Ba, B, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Sr, and Zn.

Following plant harvest, soil samples were collected from each pot and air-dried. Soil pH (Eckert, 1988) and EC (Dahnke and Whitney, 1988) were determined on 1:1 (w/v), soil/water mixtures. Subsamples were extracted with ammonium acetate (Brown and Warncke, 1988), hydrochloric acid–ammonium fluoride (Bray and Kurtz, 1945), sodium bicarbonate (Olsen et al., 1954), diethylenetriaminepentaacetic acid (DTPA) (Lindsay and Norvell, 1978), and nitric acid. Ammonium acetate extracts were analyzed for Ca and Mg by atomic absorption spectroscopy and for K and Na by atomic emission spectroscopy (Brown and Warncke, 1988). Bray P-1 and Olsen P were measured colorimetrically (Murphy and Riley, 1962). DTPA extracts were analyzed for Cd, Cr, Cu, Mn, Ni, Pb, and Zn by ICP (Munter and Grande, 1981). Nitric acid extractable Mo and B were determined by shaking 3 g of soil with 30 mL of 1 M nitric acid for 1 h, centrifuging at 1.5 m s^{-2} for 15 min, and analyzing the supernatant by ICP.

Experimental Design and Statistical Analysis. A randomized complete block design with three replications was used for both experiments. The significance of treatment differences was assessed by analysis of variance and multiple comparison procedures (Steel and Torrie, 1980). The Waller–Duncan Bayesian k-ratio t-test, with $k = 100$, was used for mean separation. In this test, the $k = 100$ condition is roughly comparable to choosing a 0.05 significance level (Steel and Torrie, 1980). Statistical analyses were performed with SAS version 6.04 (SAS Institute, 1985).

RESULTS AND DISCUSSION

There were significant differences in soil chemical properties, plant growth, and tissue composition due to both soil type and ash or fertilizer amendment. The overall effects of ash or fertilizer were generally consistent for both soils, however, so the discussion of all results is focused on amendment effects averaged over soil type. Differences between the two soils in the magnitude of amendment effects are discussed where there were significant interactions between ash or fertilizer amendment and soil type, but data are presented only for main effects.

Soil Chemical Properties. Soil pH, soluble salts, and extractable elements were determined after Swiss chard and alfalfa plants were harvested (Tables 3 and 4). In both experiments, all three ashes were effective liming agents at the rates applied, and the liming potential of each ash was consistent with its CCE (Table 1). Ash A amended soils were lower in pH than ash B and ash C amended soils, but changes in soil pH per unit of CCE applied (total units of CCE = ash loading rate × ash CCE) were similar for all three ashes. Bache and Lisk (1990) reported that 18 of the 20 MSW ashes or ash combinations they studied also increased soil pH. Soil pH was lower for Swiss chard than alfalfa because of the acidifying effect of the ammonium nitrate fertilizer. In the alfalfa experiment, ash liming effects were greater for Gotham soil than Verndale soil (data not presented).

Soluble salts increased with ashes B and C, but ash A had little effect on soil EC. These results are consistent with the much higher soluble salt levels in ashes B and C than in ash A (Table 1). Ash B had a higher salt content than ash C, but ash C had a greater effect on EC because its loading rate was twice as high (Table 2). Higher soluble salts in the Swiss chard soil than in the alfalfa soil were

Table 3. Main Effects and Interactions of Soil Type and Amendment with Municipal Solid Waste Incinerator Ash or Fertilizer on Selected Soil Chemical Properties at the Conclusion of the Swiss Chard Experiment

			extractable elements (mg kg^{-1} of soil)															
		EC[a]	ammonium acetate				Bray	Olsen	DTPA								HNO_3	
treatment	pH	(dS m^{-1})	K	Ca	Mg	Na	P	P	Fe	Mn	Zn	Cu	Pb	Ni	Cd	Cr	Mo	B
soil type																		
Gotham	5.3	1.8	45	834	101	7.5	56	26	44	25	8.7	1.8	3.8	0.75	0.15	<0.03	0.30	1.14
Verndale	5.4	1.5	52	1337	163	8.7	37	19	41	26	8.0	1.9	4.7	0.97	0.18	<0.03	0.39	1.27
significance[b]	NS	**	NS	**	**	NS	**	**	*	NS	NS	NS	NS	**	**		**	**
amendment																		
control	4.9	1.6	39	851	136	6.7	29	14	49	31	1.0	0.4	1.0	0.65	0.06	<0.03	0.23	0.45
ash A	5.4	1.6	53	1046	125	14.1	92	37	33	13	5.2	5.3	2.9	0.77	0.11	<0.03	0.54	1.58
ash B	6.3	1.9	48	1555	143	10.3	42	21	31	12	31.6	1.9	7.4	1.32	0.19	<0.03	0.44	2.07
ash C	6.3	2.2	55	1617	160	11.5	42	18	28	10	18.2	4.1	15.8	0.93	0.59	<0.03	0.47	3.00
K	4.8	1.4	48	827	116	4.8	27	13	55	42	0.8	0.4	1.0	0.81	0.07	<0.03	0.23	0.39
P	4.8	1.5	42	852	123	5.1	47	29	52	39	1.0	0.4	1.0	0.65	0.06	<0.03	0.23	0.46
P + K	4.9	1.3	53	850	118	3.9	46	28	49	31	0.9	0.4	0.9	0.88	0.07	<0.03	0.24	0.49
significance	**	**	NS	**	**	**	**	**	**	**	**	**	**	**	**		**	**
BLSD[c]	0.2	0.4		66	26	5.0	5	2	3	7	2.5	0.3	2.8	0.16	0.02		0.04	0.15
interactions																		
soil type × amendment	NS	NS	NS	NS	NS	NS	NS	**	NS	*	NS	NS	NS	NS	**		NS	NS

[a] Electrical conductivity. [b] NS, not significant; *, significant at 5%; **, significant at 1%. [c] Waller–Duncan Bayesian *k*-ratio *t*-test for minimum significant difference, $k = 100$.

Table 4. Main Effects and Interactions of Soil Type and Amendment with Municipal Solid Waste Incinerator Ash or Fertilizer on Selected Soil Chemical Properties at the Conclusion of the Alfalfa Experiment

			extractable elements (mg kg^{-1} of soil)															
		EC[a]	ammonium acetate				Bray	Olsen	DTPA								HNO_3	
treatment	pH	(dS m^{-1})	K	Ca	Mg	Na	P	P	Fe	Mn	Zn	Cu	Pb	Ni	Cd	Cr	Mo	B
soil type																		
Gotham	6.4	0.8	59	816	155	68	46	17	35	10	6.8	1.6	3.0	0.64	0.12	<0.03	0.33	1.24
Verndale	6.4	0.6	53	1217	204	59	32	12	36	16	8.9	1.7	3.0	0.71	0.16	<0.03	0.47	1.25
significance[b]	NS	**	NS	**	**	*	**	**	NS	**	NS	*	NS	*	**		**	NS
amendment																		
control	6.0	0.4	47	818	172	36	22	9	43	16	1.0	0.5	0.8	0.73	0.05	<0.03	0.31	0.50
ash A	6.7	0.5	35	956	179	53	84	19	28	9	5.1	4.7	2.0	0.52	0.09	<0.03	0.60	1.46
ash B	7.4	1.1	55	1356	196	116	36	15	23	7	31.2	1.7	2.7	0.76	0.15	<0.03	0.45	2.15
ash C	7.5	1.4	54	1413	193	126	36	14	22	7	14.9	3.4	13.1	0.34	0.54	<0.03	0.52	3.33
K	5.8	0.7	95	852	176	42	23	9	43	17	0.9	0.4	0.7	0.66	0.05	<0.03	0.30	0.42
P	5.9	0.4	40	856	171	35	36	18	43	16	1.0	0.5	0.8	0.84	0.05	<0.03	0.31	0.43
P + K	5.6	0.7	69	864	171	39	38	18	45	20	1.0	0.5	0.8	0.81	0.05	<0.03	0.32	0.43
significance	**	**	**	**	NS	**	**	**	**	**	**	**	**	**	**		**	**
BLSD[c]	0.1	0.1	21	94		15	6	2	2	3	7.4	0.3	0.6	0.11	0.01		0.04	0.44
interactions																		
soil type × amendment	*	**	NS	NS	NS	NS	NS	**	NS	NS	NS	*	NS	NS	**		NS	NS

[a] Electrical conductivity. [b] NS, not significant; *, significant at 5%; **, significant at 1%. [c] Waller–Duncan Bayesian *k*-ratio *t*-test for minimum significant difference, $k = 100$.

probably due to the N fertilizer additions. In the alfalfa experiment, EC increases with ashes B and C were greater in Gotham soil than in Verndale soil (data not presented).

B. vulgaris species similar to Swiss chard are considered moderately tolerant to tolerant of salt stress, whereas alfalfa is moderately sensitive (Rhoades and Miyamoto, 1990). The values for EC presented here are based on 1:1 soil/water slurries. A value less than 1.1 dS m^{-1} is nonsaline, and values between 1.1 and 2.4 are slightly saline (Dahnke and Whitney, 1988), so the increases in soluble salts with ashes B and C were probably not large enough to affect the growth of either crop. Salt-sensitive crops could be adversely affected by the observed increases, but these results indicate that growth inhibition from MSW ash due to soluble salts (Giordano et al., 1983; Wadge and Hutton, 1986) can be mitigated when ash amendment rates are based on their plant nutrient content.

Although these experiments were based on additions of plant-available K, there were few differences in residual available K in postharvest soil samples. Ammonium acetate extractable K, a standard test for available K in the soil, increased with K fertilizer in the alfalfa experiment but was not significantly affected by any ash amendment in either experiment. To some extent the lack of an ash response was due to depletion of soil K by plant uptake, but uptake did not account for all of the added K in either experiment. Ammonium oxalate extraction, the standard test for available K in fertilizers, appeared to overestimate available K in the ashes.

All three ashes, in both experiments, increased ammonium acetate extractable Ca and Na. The much higher extractable Na levels in alfalfa soil were due to greater Na uptake by Swiss chard and depletion of soil Na.

Bray P-1 and Olsen extractable P increased with all three ashes, for both crops, compared to the controls or K-only fertilizer treatments. Increases were greatest with ash A, reflecting the higher rates of citrate-soluble P added in ash A amendments (Table 2). Increases with ashes B and C were similar, even though ash B supplied 3.5 times more citrate-soluble P than ash C. The significant interaction between soil type and amendment for Olsen P was due to fertilizer P increasing extractable P in Verndale soil to a much greater extent than in Gotham soil (data not presented).

Changes in extractable soil P per unit of citrate-soluble P added to the soil were different for the three ashes, with ash C > ash A > ash B for both extractants. This suggests that citrate solubility was not an adequate index of availability for the various chemical forms of P in the three ashes. The relative effectiveness of ash amendment in

Table 5. Main Effects and Interactions of Soil Type and Amendment with Municipal Solid Waste Incinerator Ash or Fertilizer on Swiss Chard Growth and Elemental Composition

treatment	dry wt (g plant^{-1})	elements																		
		g kg^{-1}					mg kg^{-1}													
		K	P	Ca	Mg	Na	Al	Ba	B	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Sr	Zn
soil type																				
Gotham	2.03	31	2.9	23	14	13	60	91	54	3.9	1.7	0.69	10.2	86	861	0.73	2.7	4.8	64	216
Verndale	1.70	26	2.6	26	15	14	56	113	57	3.0	1.5	0.61	9.7	86	823	0.68	2.0	4.5	61	176
significance[a]	**	*	NS	**	*	NS	NS	*	NS	**	*	NS	NS	NS	NS	NS	**	NS	NS	NS
amendment																				
control	0.95	30	2.3	23	15	12	57	163	48	3.4	1.5	0.48	6.6	84	1151	0.40	2.5	4.2	71	79
ash A	2.04	19	3.1	24	16	12	62	92	76	2.2	1.4	0.67	22.9	92	456	1.21	2.2	4.9	57	345
ash B	2.92	25	2.8	27	15	18	44	101	80	2.1	1.5	0.75	11.0	81	331	1.11	2.5	4.9	62	402
ash C	2.46	24	2.2	25	14	24	54	79	72	6.4	1.4	0.70	13.3	75	323	0.90	1.8	5.0	52	342
K	1.62	44	1.8	25	16	9	72	161	42	4.5	2.2	0.57	6.3	74	2056	0.47	3.3	5.0	77	82
P	1.21	23	3.7	23	12	9	70	61	37	2.4	1.4	0.75	4.7	106	591	0.40	2.1	4.2	61	61
P + K	1.76	36	3.4	23	13	8	46	58	34	3.2	1.7	0.61	4.8	90	984	0.45	2.3	4.3	59	59
significance	**	**	**	NS	NS	**	NS	**	**	**	**	NS	**	**	**	**	**	NS	**	**
BLSD[b]	0.43	8	0.5			3		39	8	1.1	0.4		1.9	13	368	0.11	0.6		11	69
interactions																				
soil type × amendment	NS	NS	NS	NS	NS	*	NS	*	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] NS, not significant; *, significant at 5%; **, significant at 1%. [b] Waller–Duncan Bayesian *k*-ratio *t*-test for minimum significant difference, $k = 100$.

increasing available soil P, compared to P fertilizer, was different for the two P extractants. Averaged across both crops and both soils, ash C increased Bray P-1 extractable P by 0.75 mg for each milligram of citrate-soluble P added to the soil, compared to increases of 0.4 mg/mg of added P for both P fertilizer treatments. Ash C increased Olsen extractable P by only 0.25 mg/mg of added P, however, compared to 0.3 mg/mg of added P for P fertilizer. Comparisons between ashes A and B and P fertilizer were similar, with Bray P-1 consistently indicating a greater relative effectiveness for ash in increasing available soil P than Olsen's extractant. Soil extractants for available P are calibrated to responses to P fertilizer, so these results indicate that reliable interpretations of the P fertility status of ash-amended soils will depend on evaluation of the relative accuracy of these extractants.

DTPA-extractable Fe and Mn were consistently lower in all ash treatments for both crops, probably due to the higher soil pH. DTPA-extractable Zn, Cu, Pb, and Cd and nitric acid extractable Mo and B were higher in all three ash treatments, for both crops, than in the control and fertilizer treatments. Ashes B and C significantly increased DTPA-extractable Ni compared to the control, but only in the Swiss chard experiment. Extractable trace metals were generally highest for ashes B and C, reflecting their higher trace metal loading rates (Tables 1 and 2). Extractable Cu and Mo were highest for ash A, however, even though it did not have the highest Cu and Mo loading rates.

The interaction between soil type and DTPA-extractable Mn in the Swiss chard experiment was due to the P fertilizer treatment having higher extractable Mn in Gotham soil than in Verndale soil, whereas all other treatments had higher extractable Mn in Verndale soil. In the alfalfa experiment, ash A increased DTPA-extractable Cu to a greater extent in Verndale soil than Gotham soil. In both experiments, ash C increased DTPA-extractable Cd to a greater extent in Verndale soil than Gotham soil (data not presented).

Growth and Tissue Elemental Composition: Swiss Chard. Swiss chard growth was 2–3 times greater in all ash-amended soils than in the controls (Table 5). The largest response was to ash B. Ash A increased growth more than commercial fertilizer, but increases were only significant compared to P fertilizer alone. Growth in ash B and ash C amended soils was significantly greater than that in all fertilized soils, indicating a response to more than their P and K content. Growth responses to ash were associated with differences in tissue composition (Table 5) and total nutrient uptake (concentration × dw). In most cases, trends in elemental concentration and total uptake were similar.

Tissue K concentrations in plants grown in ash-amended soil were lower than in the control or K-fertilized treatments. Total plant K uptake, however, did increase with ash amendment, indicating that all three ashes supplied plant-available K. Total K uptake from ashes B and C was comparable to that from K fertilizer. Total K uptake from ash A was higher than from the control or P fertilizer treatments but less than from K fertilizer and the other ashes. The ammonium oxalate extractable K test apparently overestimated plant availability of the K in ash A. Differences between the three ashes in K concentrations and K uptake paralleled their effects on plant growth.

Tissue Na concentrations and total Na uptake were higher in plants grown in ash-amended soils. Ash C had the greatest effect, but Swiss chard grows normally at Na concentrations twice as high as those measured in ash C plants (Lunt, 1973). Giordano et al. (1983) also found substantial increases in tissue Na, for both Swiss chard and corn, in ash-amended soil. Ash amendment increased tissue Na to a greater extent in Gotham soil than in Verndale soil (data not presented), possibly due to greater Ca and Mg competition for uptake in Verndale soil (Table 3).

In Na-accumulating plant species, such as Swiss chard, Na can partially substitute for K and can also directly stimulate plant growth (Marschner, 1986). Sodium substitution probably compensated for the lower K concentrations in ash-treated plants, and preferential Na uptake may have contributed to low tissue K concentrations by depressing K uptake. Although Na probably had a positive effect on Swiss chard growth, the Na content of MSW ash would not be an agricultural benefit in most crop or soil situations.

Tissue P concentrations and total P uptake were higher in plants grown in soil amended with ashes A and B than in treatments that did not receive P fertilizer. Using the table beet sufficiency range of 2.5–5.0 g of P kg^{-1} for recently matured leaf tissue as a guide (Jones et al., 1991), amendment with ashes A and B increased tissue P from low to sufficient levels. These results demonstrate that MSW ash can supply plant-available P and suggest that growth responses to ash were partially due to improved

P nutrition. Tissue P in ash C treatments was significantly lower than in the other two ashes, which was consistent with the higher rates of citrate-soluble P supplied by ashes A and B (Table 2). Ash C increased total P uptake, indicating that it did supply plant-available P.

The highest tissue P concentrations were in P-fertilized soils, even though citrate-soluble P rates were higher with ashes A and B than with P fertilizer (Table 2). Plants grown in ash B amended soil had the highest total P uptake, however, and total P uptakes from ash A and P + K fertilizer were similar to one another. Because growth responses, and thus total uptake, were affected by factors other than P nutrition, it is difficult to clearly evaluate the relative availability of P from ash versus fertilizer sources.

All three ashes increased tissue concentrations and total uptake of B, Cu, Mo, and Zn. Because soil Mo is more available with increasing pH (Marschner, 1986), the Mo content of the ashes cannot be separated from their liming effect as an explanation for the increases in plant Mo. Boron, Cu, Mo, and Zn are all essential plant nutrients that can also be phytotoxic or a threat to animal health at excessive concentrations. Although Swiss chard is not an animal feed crop, the metal concentrations in Swiss chard can be usefully compared to livestock tolerances as an indicator of potential health effects.

Tissue B in all three ash treatments was at the 75 mg kg^{-1} level that can cause phytotoxicity in some plant species (Chaney, 1990). Ashes A and B increased tissue B to a greater extent in Verndale soil than in Gotham soil (data not presented). Ash A increased tissue Cu close to the 25 mg kg^{-1} level that can be phytotoxic to some plants or cause adverse effects in sheep during continuous long-term feeding (Chaney, 1990). Tissue Zn concentrations did not reach the phytotoxic range, but in all ash treatments they were above the 300 mg kg^{-1} level that can be excessive for chronic ingestion by sheep (Chaney, 1990). Tissue Zn concentrations in all three ash treatments were higher than those reported for Swiss chard by Giordano et al. (1983) and higher than that found with all but one of the ashes studied by Bache and Lisk (1990), even though ash amendment rates in those studies were much higher than the rates used here.

Concentrations of Cd in Swiss chard tissue, as well as total Cd uptake, were highest in plants grown in soils amended with ash C. Plants grown in ashes A and B had the lowest tissue Cd concentrations and intermediate levels of total Cd uptake, even though ashes A and B did increase DTPA-extractable Cd (Table 3).

High Cd uptake with ash C corresponded to the higher Cd loading rates in ash C treatments (Tables 1 and 2) and illustrates a serious potential problem in using this ash as a soil amendment. Ash C increased tissue Cd above the 5 mg kg^{-1} concentration that can be phytotoxic to some plant species and to 12 times the 0.5 mg kg^{-1} concentration that can cause health problems for cattle, sheep, swine, and chickens (Chaney, 1990). Cadmium concentrations in Swiss chard tissue were well above 0.5 mg kg^{-1} in all treatments, including soils not amended with ash, which demonstrates the ability of this crop to accumulate trace metals. Tissue Cd concentrations in ash C treatments were much lower than those observed by Giordano et al. (1983), except for their early harvests in treatments where leached ash was applied only to the soil surface. Bache and Lisk (1990) also reported much higher tissue Cd concentrations in Swiss chard with four of the ashes they studied.

Tissue concentrations of Al, Ba, Ca, Co, Cr, Fe, Mg, Mn, Ni, Pb, and Sr were either not significantly affected by ash amendment or were significantly lower than in controls. Ashes B and C did not increase tissue Ni or Pb, even though they did significantly increase DTPA-extractable Ni and Pb compared to the controls (Table 3). The absence of an increase in tissue Pb concentrations differed from the increases reported in several treatments by Giordano et al. (1983) and from the increases observed by Bache and Lisk (1990) with some of the ashes that they tested. Except for Mn, ash amendment generally did increase total uptake of all of the above elements.

The K fertilizer treatment had elevated tissue concentrations and total uptake of Ba, Cd, Co, Mn, and Ni, but the reasons for these increases are not clear. Similar increases did not occur in the P + K fertilizer treatment, so contamination of the K fertilizer with these elements was apparently not the source. The significant interaction between amendment and soil type for tissue Ba was due to Ba concentrations in K fertilizer treatments being twice as high in Verndale soil as in Gotham soil (data not presented).

Growth and Tissue Elemental Composition: Alfalfa. Alfalfa growth was significantly greater in ash A and ash B amended soils than in the controls and the soils fertilized with K only or P only, but growth increases were not significant compared to those observed with P + K fertilizer (Table 6). Alfalfa growth in ash C amended soil was numerically higher than the controls, but the growth increase was not statistically significant.

All alfalfa roots were qualitatively inspected for nodulation by *Rhizobia* bacteria. Nodules were present on roots of plants grown in all treatments. Nodulation in ash-amended soils was not visually different from that in control or fertilized soils. Soil pH in all treatments not amended with ash was below the level of 6.5 required for optimum alfalfa growth (Table 4). Growth responses to ash were also associated with differences in tissue composition (Table 6) and total nutrient uptake (concentration × dw). In most cases, trends in elemental concentration and total uptake were similar.

Ashes B and C significantly increased tissue K compared to the control, ash A, and P fertilizer. Increases were equivalent to those from K and P + K fertilizer and were in the range where a growth response would be expected to occur. Tissue K in plants grown in the ash B, ash C, and K-containing fertilizer treatments was in the alfalfa sufficiency range of 20–35 g kg^{-1}, whereas other treatments were deficient (Jones et al., 1991). All three ashes increased total plant K uptake, but ash A was the least effective. The lower plant availability of the K in ash A, compared to that in ashes B and C, is in agreement with results from the Swiss chard experiment.

Plants grown in all three ash amendments had higher tissue P concentrations and total P uptake than plants grown without P fertilizer. Increases in P concentration were also in the range where a growth response would be expected to occur, because plants in the P-only fertilizer treatment were the only ones in which tissue P reached the minimum sufficiency level of 26 g kg^{-1} (Jones et al., 1991). Ash C plants had similar P concentrations but lower total P uptake than ash A or ash B plants. The significant interaction between soil type and amendment for tissue P was due to fertilizer P increasing tissue P in Verndale soil to a much greater extent than in Gotham soil (data not presented). This was consistent with the interaction between soil type and amendment for Olsen extractable P in alfalfa soil.

Ash A increased tissue Mg and total Mg uptake. All three ashes increased tissue concentrations and total uptake of Na, Ca, B, and Mo. As in the Swiss chard experiment, the Mo content of the ashes could not be clearly differentiated from their effect on soil pH to explain

Table 6. Main Effects and Interactions of Soil Type and Amendment with Municipal Solid Waste Incinerator Ash or Fertilizer on Alfalfa Growth and Elemental Composition

treatment	dry wt (g plant^{-1})	elements																	
		g kg^{-1}					mg kg^{-1}												
		K	P	Ca	Mg	Na	Al	Ba	B	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb[a]	Sr	Zn
soil type																				
Gotham	1.33	21	2.2	19	36	0.39	76	28	57	0.41	0.74	0.81	8.1	79	65	2.3	1.1	<1.9	52	40
Verndale	0.85	19	2.1	21	42	0.48	60	32	60	0.48	0.80	0.81	6.6	60	85	2.2	1.0	<2.0	46	37
significance[b]	**	**	NS	**	**	NS	NS	*	NS	NS	NS	NS	*	**	**	NS	NS		**	NS
amendment																				
control	0.83	19	1.8	19	40	0.28	79	47	50	0.30	0.78	0.78	7.2	69	92	0.3	1.1	<1.8	52	30
ash A	1.31	17	2.2	22	49	0.60	76	32	77	0.34	0.80	0.87	9.7	69	51	3.4	1.0	<2.0	53	44
ash B	1.45	22	2.1	22	32	0.50	57	16	77	0.39	0.78	0.81	7.8	79	51	6.0	1.0	<2.1	49	53
ash C	1.08	22	2.1	21	34	0.66	59	12	74	0.67	0.73	0.81	9.5	81	55	5.1	0.9	<2.1	42	46
K	0.76	22	1.8	17	36	0.23	65	52	46	0.43	0.66	0.68	6.6	60	92	0.3	1.0	<1.7	49	31
P	1.03	16	2.6	19	45	0.51	66	27	43	0.39	0.78	0.82	4.8	65	78	0.3	1.1	<1.9	49	31
P + K	1.18	22	2.3	19	41	0.28	73	25	40	0.56	0.87	0.88	5.9	66	106	0.3	1.3	<2.0	48	35
significance	**	**	**	**	**	**	NS	**	**	**	NS	NS	**	NS	**	**	*		*	**
BLSD[c]	0.28	2	0.3	3	5	0.16		5	8	0.14			2.2		11	1.0	0.3		6	9
interactions																				
soil type × amendment	NS	NS	**	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	*	NS	NS		NS	NS

[a] Many samples were below the Pb detection limit of 1.7 mg/kg; approximate means were computed using the detection limit as an assumed value for those samples, so the true means for all treatments are less than the calculated values. [b] NS, not significant; *, significant at 5%; **, significant at 1%. [c] Waller–Duncan Bayesian *k*-ratio *t*-test for minimum significant difference, $k = 100$.

the increases in Mo. Alfalfa shoots did not accumulate Na to the very high levels observed in Swiss chard (Table 5). Alfalfa is more sensitive to Na, but the highest tissue concentrations were <20% of levels that significantly inhibit growth (Lunt, 1973). Tissue B in all ash treatments was slightly less than the 80 mg kg^{-1} concentration considered high and beyond the sufficiency level in alfalfa (Jones et al., 1991). Increases in tissue Mo concentration had both positive and potentially negative implications. Molybdenum is a component of the enzyme nitrogenase (Marschner, 1986), so it is critically important to N-fixing crops such as alfalfa. Concentrations above 5–10 mg kg^{-1}, however, may cause molybdenosis in ruminant animals (Marschner, 1986).

The sufficiency range for Mo in alfalfa is 1.0–5.0 mg kg^{-1} (Jones et al., 1991). Ash amendment, therefore, raised tissue Mo from deficiency levels to within or slightly above the sufficiency range. These 10–20 fold increases in tissue Mo were not phytotoxic and probably stimulated alfalfa growth, but ashes B and C also increased tissue Mo to levels that could cause molybdenosis. These results demonstrate the problematic nature of using Mo-containing waste products as soil amendments. Amendment rates must be adjusted to prevent excessive Mo uptake, particularly on Mo-accumulating leguminous crops, in addition to the more prevalent concerns that focus on adjusting amendment rates to limit the uptake of other trace metals such as Cd and Pb.

Alfalfa did not accumulate most trace metals to the levels observed in Swiss chard, but ash amendment did increase tissue concentrations and plant uptake of several trace metals besides B and Mo compared to the controls. Ashes A and C increased tissue Cu and total Cu uptake, and all three ashes increased tissue Zn and total Zn uptake. Levels of Cu and Zn in alfalfa were not in a range that would cause phytotoxicity or be harmful to animals ingesting the tissue.

As in Swiss chard, tissue Cd and total Cd uptake increased when plants were grown in ash C amended soils. Ashes A and B did not increase Cd accumulation in the plant, despite increases in DTPA-extractable soil Cd (Table 4). Alfalfa grown in ash C had tissue Cd above the 0.5 mg kg^{-1} concentration that is the maximum level in the diet chronically tolerated by domestic livestock (Chaney, 1990). The P + K fertilizer treatment also had tissue Cd concentrations >0.5 mg kg^{-1}. This may have been due to the Cd content of the superphosphate fertilizer (3.4 mg kg^{-1}), but P fertilizer alone did not increase tissue Cd or total Cd uptake, nor did superphosphate affect plant Cd in the Swiss chard experiment (Table 5).

Chloride can have an effect on Cd solubility and bioavailability. Giordano et al. (1983) suggested that Cd mobility in MSW ashes was enhanced by their high chloride content and the formation of soluble Cd complexes with chloride. More recently, Roy et al. (1993) found that chloride complexation in MSW ash leachate reduced Cd adsorption by soil clays and increased Cd mobility. Bingham et al. (1983) found that in addition to increasing Cd solubility, chloride treatment increased plant uptake of Cd.

The chloride content of the three ashes studied was variable (Table 1), but the differences between them did not appear to have an effect on Cd uptake. Cadmium loading rates from ashes A and B were similar, and so were tissue Cd concentrations and uptake in both alfalfa and Swiss chard, even though the chloride loading rate from ash B was 30 times that from ash A (Tables 1 and 2). Ashes B and C had similar chloride loading rates, and the higher tissue Cd and total Cd uptake in ash C treatments were related to Cd loading rates that were 3 times higher for ash C than for ash B. Chloride application from KCl fertilizer was comparable to the chloride loading rates from ashes B and C. The chloride from KCl may have increased the solubility and availability of native soil Cd and contributed to high Cd conncentrations and uptake in Swiss chard in the K fertilizer treatment (Table 5) and in alfalfa in the P + K fertilizer treatment, but if these effects occurred, they were not consistent across all treatments receiving KCl.

Tissue concentrations of Al, Ba, Co, Cr, Fe, Mn, Ni, and Sr were either not significantly affected by ash amendment or were significantly lower than those in controls. Total uptake of these elements was also generally unaffected. Tissue Pb was below the detection limit of 1.7 mg kg^{-1} in the majority of samples, so comparisons between treatments could not be made.

Conclusions. The results of this study show that MSW incinerator ash can influence plant growth in a positive manner, as well as cause potential problems. Growth of alfalfa and Swiss chard in ash-amended soils was similar to or greater than that in soils amended with P and K fertilizer, indicating that MSW ash can supply essential nutrients for plant growth. On the basis of plant tissue analyses, the positive growth responses to ash amendment probably involved improved P, K, and micronutrient nutrition. In addition, Swiss chard probably responded to Na and alfalfa to increases in soil pH. All three ashes studied were effective liming agents.

At the ash rates applied, no phytotoxic effects on plant growth were observed. The high Mo concentrations in alfalfa tissue may be of concern if consumed by ruminant animals in large quantities. In one of the three ashes tested, alfalfa uptake of Cd was high enough to be of concern if the plant tissue was ingested by cattle, sheep, swine, and chickens. The soluble salt content of two of the ashes could cause problems with sensitive plant species or at higher amendment rates.

Because MSW ash characteristics are dependent on the materials burned and the incineration process used, the feasibility of land-applying MSW incinerator ash will require evaluation on an individual ash/incinerator basis. Feasibility will also depend on the specific crop and soil environment, and thorough evaluation will require studies under field conditions. The potential for land application would be enhanced if glass, metal debris, and materials high in trace elements were recycled prior to incineration.

ABBREVIATIONS USED

MSW, municipal solid waste; CCE, calcium carbonate equivalence; EC, electrical conductivity; ICP, inductively coupled plasma–atomic emission spectroscopy; DTPA, diethylenetriaminepentaacetic acid.

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Received for review October 15, 1993. Revised manuscript received March 1, 1994. Accepted March 25, 1994.[⊗]

[⊗] Abstract published in *Advance ACS Abstracts*, May 1, 1994.