

Mixtures of Coal Ash and Compost as Substrates for Highbush Blueberry

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ABSTRACT. Bottom ash from a coal-fired power plant and two composts were tested as components of soil-free media and as soil amendments for growing highbush blueberry (*Vaccinium corymbosum* L.). Combinations of ash and compost were compared to Berryland sand, and Manor clay loam, and compost amended Manor clay loam. The pH of all treatment media was adjusted to 4.5 with sulfur at the beginning of the experiment. In 1997, plants of 'Bluecrop' and 'Sierra' were planted in 15-dm³ pots containing the pH-adjusted treatment media. The first substantial crop was harvested in 1999. At the end of the 1999 season, one half of the plants were destructively harvested for growth analysis. The remaining plants were cropped again in 2000. Yield and fruit size data were collected in both seasons, and leaf and fruit samples were collected in 1999 for elemental analysis. The presence of coal ash or composted biosolids in the media had no detrimental effect on leaf or fruit elemental content. Total growth and yield of both cultivars was reduced in clay loam soil compared to Berryland sand, whereas growth and yield of plants in coal ash–compost was similar to or exceeded that of plants in Berryland sand.

The cultivars of highbush blueberry have been derived primarily from selections of *Vaccinium corymbosum* L., which are naturally adapted to acidic, swampy conditions (Eck et al., 1990). Under cultivation, these plants prefer low-pH, moist, well-drained, sandy soils containing high levels of organic matter. These soil requirements effectively limit the number of suitable sites for commercial production to a few specific geographic regions (Eck and Childers, 1966; Pritts, 1992).

In the more populated regions of the United States, direct marketing of fruit, either on farm or at local farm markets, is becoming more prevalent, as indexed by the growth in farm markets between 1994 and 2000 (Holley, 2000). In many regions however, the relatively specific site and soil requirements of highbush blueberry has limited their ability to be produced on diversified, direct-market oriented fruit farms. These farms, by nature, are located near population centers, and may or may not have sites suitable for highbush blueberry production.

A number of research efforts have focused on these limitations. Extensive effort has been expended in breeding for upland soil adaptability (Finn et al., 1993a, 1993b; Korcak, 1988a, 1989; Korcak et al., 1982; Scheerens et al., 1999), which has yet to produce upland soil-adapted varieties. Other efforts investigated amending upland soils to improve soil properties (Dale et al., 1989; Goulart et al., 1998), optimizing management inputs to maximize tolerance to upland soil (Chandler et al., 1984; Erb et al., 1993; Korcak, 1983), and growing blueberries in a potting medium, similar to that used in the container nursery industry (Smolarz, 1985). However, the cost of potting mixes or their components as soil amendments may be prohibitively expensive for fruit production, even on a small scale.

In regions with coal-fired electrical generation, coal combustion by-products may provide a relatively low cost substrate for plant growth. Several of these combustion by-products, such as fly ash, bottom ash, and fluidized bed combustion by-product, have desirable horticultural characteristics, are available at low cost, and are

currently being under-used (Korcak, 1993). Bottom ash has a particle size ranging from 0.1 to 10 mm, and may contain usable levels of micronutrients. However, these materials may also have a basic pH and contain phytotoxic levels of some elements, or have appreciable levels of elements considered environmental contaminants. Elemental content of these products depends on coal source, and whether or not the coal was cleaned before combustion (Korcak, 1993). Bottom ash was used in our studies as a substitute for sand. A wide range of materials are now being composted by commercial facilities. We selected two commercial composts to represent different classes of materials. One was a sewage sludge or biosolids compost, and the other was primarily a leaf compost from a yard waste recycling program.

We conducted a multiyear study to evaluate bottom ash and compost as components of soil-free media for highbush blueberry production. Comparison treatments included a typical blueberry soil, and an upland clay loam soil either alone or compost amended.

Materials and Methods

MEDIA TREATMENTS. Bottom ash was obtained from the PEPCO Chalk Point power plant in Prince Georges County, Md. A biosolids compost was obtained from a commercial composting facility at the Baltimore, Md., waste water treatment facility. A commercial leaf compost (Leafgro) was obtained from a yard-waste recycling program in Montgomery County, Md., and acid peatmoss was obtained from a commercial source. These components were then combined in the proportions listed in Table 1, to give six experimental media treatments. Controls included Berryland sand (Typic Haplaquad, Coastal Plain soil) obtained from the Philip E. Marucci Center for Blueberry and Cranberry Research and Extension, Chatsworth, N.J., and Manor clay loam soil (Typic Dystrocrept, Piedmont soil) collected from the Henry A. Wallace Beltsville Agricultural Research Center, Md. Properties of these soils have been previously reported (Korcak, 1986). Treatments of Manor clay loam with compost amendment at 25% and 50% of soil volume were also included. The initial pH of Berryland sand was 4.0 and the pH of the remaining media treatments were lowered with the addition of powdered sulfur. Samples of the ash–compost mixes and the soil–compost mixes were titrated with nitric acid, and sulfur requirements were calculated for a target pH of 4.5 (Brown and Chaney,

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personal communication). Sulfur was added to the treatment mixes 2 weeks before planting, and media were again mixed just prior to planting.

At the time of composting the treatment mixes, samples of components were collected, dried and later sent to the agricultural analytical services laboratory at Pennsylvania State University for analysis (Table 2). Media components were analyzed according to protocols for determining the suitability of biosolids for agricultural

application (U.S. Environmental Protection Agency, 1986, 1993). Total P, K, Ca, Mg, Na, Fe, Al, Mn, As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, and Zn were determined according to U.S. Environmental Protection Agency (EPA) methods 3050/3051, 6010, 7060, and 7740 (U.S. EPA, 1986). Total N was determined by Kjeldahl digestion (Isaac and Johnson, 1976).

PLANT CULTURE. In Spring 1997, 1-year-old tissue culture plants of 'Bluecrop' and 'Sierra' blueberries were obtained from a com-

Table 1. Composition of media treatments expressed as percent. Components include Manor clay loam soil, bottom ash from coal-fired power plant (ash), municipal biosolid waste compost, Leafpro, leaf compost from a yard-waste recycling program (leaf), and Michigan acid peatmoss (peat). Treatment 1 was an unamended Berryland sand.

Treatment	Component (%)				
	Clay loam	Ash	Biosolid	Leaf	Peat
2	100	---	---	---	---
3	75	---	12.5	12.5	---
4	50	---	25	25	---
5	---	75	12.5	12.5	---
6	---	50	25	25	---
7	---	75	6.25	6.25	12.5
8	---	50	12.5	12.5	25
9	---	75	25	---	---
10	---	75	---	25	---
Comparisons	Treatment contrasts				
Ash to compost ratio	5 and 7 vs. 6 and 8				
Effect of acid peat	5 and 6 vs. 7 and 8				
Compost blending	5 vs. 9 and 10				
Soil to compost ratio	2, 3, 4				
Berryland compared to ash-compost treatments	1 vs. 5-10				

Table 2. Elemental analysis of media components. Environmental Protection Agency (EPA) alternative pollutant limits (APL) for agricultural use of biosolids are shown for comparison.

Element	Component					EPA APL
	Berryland sand	Clay loam	Ash	Biosolid	Leaf	
	(g·kg ⁻¹)					
N	0.6	1.0	0.3	27.0	15.5	
P	0.1	0.3	0.3	18.8	2.5	
K	0.2	2.7	0.6	2.0	7.6	
Ca	0	1.3	2.5	20.3	28.1	
Mg	0.1	2.3	0.5	3.7	6.1	
Na	0.1	0.2	0.4	0.7	0.3	
Fe	1.1	18.6	10.3	76.0	10.5	
Al	1.9	27.8	7.1	13.2	11.3	
	(mg·kg ⁻¹)					
Mn	5	297	24	740	1001	
As	<0.6	6.9	10.2	19.4	4.7	41
Cd	<2.1	<2.1	<2.1	2.8	<2.2	39
Cr	6	32	14	172	34	
Cu	3.8	22	8	346	42	1500
Pb	8.1	27	<4	146	38	300
Hg	0.02	0.38	<0.006	1.23	0.19	17
Mo	1	1.9	1.8	12.1	1.5	75
Ni	4.3	14	13	44	20	420
Se	<1.1	<1.1	<1.1	3.4	<1.1	100
Zn	4	74	16	1425	190	2800

Table 3. pH of treatment media on 24 July 1997, 8 June 1999, and 10 Aug. 1999 (single observation pooled across replication), and on Dec. 1999, and Dec. 2000 (means of five replications).

Media	July	June 1999		Aug. 1999		Dec. 1999		Dec. 2000	
	1997	Bluecrop	Sierra	Bluecrop	Sierra	Bluecrop	Sierra	Bluecrop	Sierra
1	3.8	6.9	6.6	7.0	7.2	5.1	4.6	5.7	5.6
2	6.3	6.3	5.2	5.7	5.3	5.2	5.3	5.1	4.7
3	6.0	6.5	6.1	5.5	5.5	5.2	5.5	5.3	5.5
4	5.7	6.5	6.5	6.0	5.7	5.5	5.4	5.6	5.6
5	5.5	6.6	6.7	7.2	7.4	6.0	5.8	6.4	6.0
6	6.2	6.4	6.8	7.1	7.3	5.7	5.9	6.3	6.0
7	5.2	6.6	6.7	7.5	7.6	5.9	5.8	6.3	5.8
8	6.2	6.6	6.9	6.8	6.7	5.8	5.7	5.9	6.3
9	5.4	6.6	6.7	7.4	7.3	5.9	5.6	6.3	6.2
10	5.2	6.7	6.6	7.6	7.5	5.9	5.9	6.5	6.3

Analysis of variance		Dec. 1999		Dec. 2000	
Cultivar		NS		*	
Media		***		***	
Cultivar × media		**		NS	
Contrast					
Ash to compost ratio (5,7 vs. 6,8)				*	NS NS
Clay					
Linear (2,3,4)		**	NS		***
Quadratic (2,3,4)		*	NS		NS
Berryland vs. ash to compost (1 vs. 5–10)		***	***		***

NS,*,**,*** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 4. Macronutrient element composition of leaves collected 28–30 July 1998. Samples were analyzed at a commercial laboratory.

Mean	Element (mg·g ⁻¹)						
	N		P		K	Ca	Mg
	Bluecrop	Sierra	Bluecrop	Sierra			
Media							
1	16.2	14.0	1.00	0.74	3.80	4.94	2.04
2	16.2	18.1	0.60	0.56	4.42	7.31	3.06
3	16.0	15.4	1.00	0.96	4.89	3.77	1.39
4	15.7	15.4	1.06	0.92	5.45	4.08	1.32
5	14.9	15.4	1.14	1.20	5.23	3.49	1.23
6	15.7	15.2	1.24	1.08	5.32	3.86	1.26
7	15.2	14.6	1.08	1.12	4.91	4.34	1.56
8	16.4	14.8	1.14	0.96	4.63	5.02	1.50
9	15.3	14.9	1.14	1.02	5.14	3.48	1.19
10	14.3	15.3	0.94	1.08	4.73	4.44	1.46
Cultivar							
Bluecrop	15.6		1.03		5.08	3.77	1.48
Sierra		15.3		0.96	4.62	5.17	1.73
Analysis of variance							
Cultivar	NS		0.004		0.0001	0.0001	0.0002
Media	0.0030		0.0001		0.0001	0.0001	0.0001
Cultivar × media	0.0162		0.008		NS	NS	NS
Contrasts							
Ash to compost ratio (5,7 vs. 6,8)	NS	NS	NS	**	NS	NS	NS
Peat vs. no peat (5,6 vs. 7,8)	NS	NS	NS	*	**	**	**
Compost blend (5 vs. 9,10)	NS	NS	NS	*	NS	NS	NS
Clay							
Linear (2,3,4)	NS	***	***	***	***	***	***
Quadratic (2,3,4)	NS	NS	NS	**	NS	**	*
Berryland vs. ash–compost (1 vs. 5–10)	NS	*	NS	***	***	*	***

NS,*,**,*** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

mercial nursery and planted singly in 15-dm³ plastic pots containing pH-adjusted treatment media. The planting was arranged as a randomized complete block design with five blocks, and two plants per treatment, cultivar and block. Irrigation water was provided uniformly by a trickle irrigation system. Due to the differences in water holding capacity, the clay loam treatment may have been periodically over-watered. Plants were fertilized in July 1997 with 21-7-7 fertilizer at a rate of 0.30 g N/plant. Ammonium sulfate fertilizer was applied 19 May 1998 and 9 July 1998 at a rate of 0.77 g N per plant, and on 20 May 1999, 9 July 1999, and 17 May 2000 at 2.57 g N/plant. After the first growing season, irrigation water was drawn from a different source due to the high pH (>8.0) of the initial water source. Media samples were collected periodically during the experiment for pH measurements (Table 3).

ELEMENTAL ANALYSIS. On 28–30 July 1998, 20 midshoot leaves were collected from each plant for elemental analysis. Leaves were washed in water containing 0.1% surfactant, rinsed in tap water and then distilled water before drying at 70 °C for 48 h. Dried leaves were ground to pass through a 30-mesh sieve and sent to the analytical services laboratory at Pennsylvania State University. Tissue concentrations of P, K, Ca, Mg, Mn, Fe, Cu, B, Al, Zn, Na, Cd, Ni, Pb, Mo, and As were determined by inductively coupled plasma atomic emission spectrometry (Dahlquist and Knoll, 1978), and N content was determined by combustion (Campbell, 1991). During the 1999 harvest, samples of ripe fruit were collected, frozen in liquid nitrogen, lyophilized, and ground to pass a 40-mesh sieve, and analyzed for elemental content as described for leaves.

FRUIT HARVEST. Although there was some fruit set in 1998, the first significant harvest occurred in 1999. Ripe fruit was harvested at weekly intervals from 23 June 1999 to 19 July 1999, and at twice-weekly intervals from 9 June 2000 to 4 Aug. 2000. Total fruit weight at each harvest was determined for each plant, and subsamples of 10 randomly selected fruit were weighed to estimate mean fruit size. Yield data were analyzed as a cultivar × media factorial, with data from the two seasons treated as repeated measures.

DESTRUCTIVE GROWTH ANALYSIS. Following the 1999 growing season, one of the two plants in each block and treatment was removed from the planting for growth analysis. Height of the two tallest stems was measured and averaged, and two perpendicular measurements of canopy spread were taken. Canopy volume was calculated from height and spread assuming a cylindrical shape (Erb et al., 1993). Each root ball was removed from the pot and the upper 10 cm of the root ball was separated from the remaining profile, before washing media from the roots. Stems and the upper and lower washed root masses were oven dried at 65 °C and weighed.

STATISTICAL ANALYSIS. Statistical analysis was carried out using the GLM procedure of the SAS program. The experiment was analyzed as a randomized complete block design with 2 cultivar × 10 media factorial treatment structure. Where factorial analysis showed cultivar × treatment interactions significant at *P* < 0.10, data were analyzed separately for each cultivar.

Contrast statements were used for specific treatment comparisons (Table 1). For example, results from treatments 5 through 8 were used to compare ash to compost ratio and the effects of acid

Table 5. Micronutrient element composition of leaves collected 28–30 July 1998. Samples were analyzed at a commercial laboratory.

Means	Element $\mu\text{g}\cdot\text{g}^{-1}$												
	B	Cu	Fe	Mn		Mo		Zn	Al		Na		As
				Bluecrop	Sierra	Bluecrop	Sierra		Bluecrop	Sierra	Bluecrop	Sierra	
Media													
1	25.6	6.8	43.9	37.6	57.6	0.21	0.10	11.2	81.8	67.2	32.4	11.2	2.15
2	93.0	6.4	37.7	78.0	191.0	0.06	0.04	12.9	35.0	29.0	248.2	20.0	1.42
3	44.2	5.3	35.7	79.8	113.8	0.12	0.07	10.6	20.8	22.2	47.8	13.8	1.41
4	42.4	4.3	36.4	58.2	84.8	0.22	0.11	11.5	13.8	15.8	50.4	16.4	1.30
5	22.0	4.8	31.4	23.6	65.6	1.11	0.62	13.7	6.6	14.0	24.4	11.8	1.14
6	29.7	3.8	30.5	42.8	73.2	0.91	0.53	11.7	7.4	12.8	36.2	13.8	1.52
7	27.7	4.5	29.9	31.4	41.6	0.75	0.65	12.8	12.2	11.0	40.2	10.6	1.68
8	42.5	3.3	44.8	33.0	36.8	0.53	0.35	10.0	10.4	12.4	42.4	10.4	1.29
9	19.4	4.7	31.3	34.8	63.2	0.73	0.51	13.1	13.6	16.2	41.4	10.0	1.30
10	33.7	3.9	28.6	40.8	96.4	0.39	0.43	12.8	11.8	12.4	48.4	10.4	1.58
Cultivar													
Bluecrop	37.1	4.80	36.4	46.0		0.50		9.9	21.4		61.2		1.59
Sierra	38.9	4.76	33.6		82.4		0.34	14.2		21.3		12.8	1.37
Analysis of variance													
Cultivar	NS	NS	NS	0.0001		0.0001		0.0001	NS		0.0001		0.076
Media	0.0001	0.0001	NS	0.0001		0.0001		0.0002	0.0001		0.0001		0.030
Cultivar × media	NS	NS	NS	0.0001		0.095		NS	0.0054		0.0001		NS
Contrasts													
Ash to compost (5,7 vs. 6,8)	**	***		NS	NS	*	**	***	NS	NS	NS	NS	NS
Peat/no peat (5,6 vs. 7,8)	**	NS		NS	*	***	NS	*	NS	NS	NS	NS	NS
Compost blend (5 vs. 9,10)	NS	NS		*	NS	***	NS	NS	*	NS	NS	NS	NS
Clay													
Linear (2,3,4)	***	***		*	***	NS	NS	*	***	**	***	NS	NS
Quadratic (2,3,4)	***	NS		*	NS	NS	NS	NS	NS	NS	NS	NS	NS
Berryland vs. ash-compost (1 vs. 5–10)	NS	***		NS	NS	***	***	NS	***	***	NS	NS	***

NS,*,**,***Nonsignificant or significant at *P* ≤ 0.05, 0.01, or 0.001, respectively.

peatmoss addition. Treatment 5 was compared to 9 and 10 to determine the effects of using a blend of the composts compared to the individual composts used separately. Contrast statements were used to test for linear and quadratic trends of amending clay loam soil with compost.

Results and Discussion

Media components and soils were analyzed for elemental content, and levels of As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, and Zn were compared to Alternative Pollutant Limits (APL) set by the U.S. EPA for land application of biosolids (U.S. EPA, 1993). None of the media components or soils exceeded the APL for any of these elements. Levels of Cd, Hg, and Se were <5% of ceiling limits in all components (Table 2). Levels of Cu, Pb, Mo, Ni, and Zn were <10% of APL for all components except biosolid compost, where levels were 23.0%, 48.5%, 16.1%, 10.4%, and 50.9% of ceiling limits, respectively. Levels of As were 16.8% and 24.9% of APL for Manor clay loam and coal ash, respectively. Leafpro compost had As levels that were 11.5% of ceiling limits, compared to 47.3% for biosolid compost. Although early studies indicated that heavy metal content of biosolids might be problematic, this is no longer the case with modern high-quality biosolids composts (Sommers, 1977; U.S. EPA, 1990). The results from the analysis of compost from our source were consistent with that of a typical high-quality compost.

The chemical composition of coal ash varies with the source and

type of coal, and the type of combustion process used (Korcak, 1993). Although coal ash may be a source of a number of the essential macro- and micronutrients (Ca, Fe, Mg, K, B, Cu, Mn, Mo, Zn), some of these may occur at levels that are phytotoxic. Other less favorable components of coal ash may include appreciable levels of Al, As, Cd, Na, Ni, Cr, Pb and others (Korcak, 1993). None of these were found in appreciable concentrations in the bottom ash used for these studies.

LEAF ELEMENTAL CONTENT. Leaf samples collected during the second growing season (1998) were analyzed for elemental content to determine whether uptake or accumulation of nutrients or metals were adversely affected by treatment media (Tables 4 and 5). There were significant treatment differences both among media and between cultivars. It should be noted however, that there were also significant treatment differences in overall plant growth. Consequently, differences in leaf elemental content may be due in part to a dilution effect. Unless otherwise indicated, leaf macro and micro nutrient concentrations were compared to thresholds for deficient, sufficient and excessive concentrations as found in Hanson et al. (1992) and Hanson and Hancock (1996).

Although there were significant treatment differences in leaf N content, these differences were only found in 'Sierra', where leaf N was significantly lower for Berryland sand, and significantly higher for unamended Manor clay loam (Table 4). In most cases, leaf N content indicated slight deficiencies relative to the recommended range of 17 to 21 mg·g⁻¹. Concentrations of leaf P also differed

Table 6. Macronutrient content of fruit. Fruit samples were collected during the 1999 harvest. Fruit was frozen in liquid nitrogen, lyophilized and ground to pass a 40-mesh filter. Samples were sent to a commercial laboratory for elemental analysis as described for leaf samples.

Means	Element (mg·g ⁻¹)						
	N	P		K	Ca	Mg	
		Bluecrop	Sierra			Bluecrop	Sierra
Media							
1	5.59	0.538	0.506	5.16	0.680	0.448	0.406
2	6.55	1.014	0.394	5.61	0.916	0.705	0.364
3	6.80	0.822	0.794	5.69	0.800	0.492	0.384
4	6.58	0.818	0.828	5.61	0.750	0.456	0.380
5	5.23	0.746	0.680	5.35	1.000	0.594	0.450
6	5.83	0.870	0.802	5.00	0.930	0.584	0.444
7	6.38	0.722	0.680	5.49	1.050	0.636	0.498
8	6.25	0.788	0.708	4.79	0.910	0.544	0.446
9	5.83	0.694	0.674	5.32	0.950	0.568	0.482
10	6.35	0.508	0.502	5.34	0.990	0.590	0.470
Cultivar							
Bluecrop	6.55	0.753		5.87	0.953	0.562	
Sierra	5.73		0.657	4.80	0.842		0.432
Analysis of variance							
Cultivar	0.0005		0.0001	0.0001	0.0012		0.0001
Media	0.0263		0.0001	0.0008	0.0001		0.0001
Cultivar × media	NS		0.0001	NS	NS		0.0583
Contrasts							
Ash to compost ratio (5,7 vs. 6,8)	NS	**	*	***	*	NS	NS
Peat vs. no peat (5,6 vs. 7,8)	*	NS	NS	NS	NS	NS	NS
Compost blend (5 vs. 9,10)	*	**	*	NS	NS	NS	NS
Clay							
Linear (2,3,4)	NS	*	***	NS	NS	**	NS
Quadratic (2,3,4)	NS	NS	*	NS	NS	NS	NS
Berryland vs. ash-compost (1 vs. 5-10)	NS	***	***	NS	***	***	*

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

among media treatments, where ash–compost treatments generally had higher leaf P levels than did the soil controls. The lowest levels were found in the unamended clay loam, while P levels for the remaining media treatments were above the 0.8 mg·g⁻¹ threshold for sufficiency. Leaf K, Ca, Mg, and B levels showed significant differences due to clay loam content, and peatmoss amendment (Tables 4 and 5). However, levels for all treatments were well within ranges considered sufficient. Leaf Cu content was significantly higher in both soil controls than in the remaining treatments where levels were below the 5 µg·g⁻¹ deficiency threshold.

There were no significant cultivar or media treatment differences in leaf Fe content, and levels in all treatments indicated potential Fe deficiency. Although Fe deficiency symptoms are common in highbush blueberry (Hanson and Hancock, 1996), leaf analysis data must be interpreted carefully as published sufficiency ranges may not be diagnostic for blueberry (Korcak, 1988b). Leaf Mn levels in the ash–compost treatments were similar to that of Berryland sand, but significantly lower than that of clay loam treatments. Blueberry and other calcifuges are Mn accumulators (Korcak, 1988b, 1988c), but concentrations reported here are well below the 450 µg·g⁻¹ threshold considered excessive. Although there were statistically significant trends in leaf Zn concentration related to the ash and peatmoss content of the treatment media, the magnitude of differences was small and all treatments fell within the sufficiency range (Table 5). Al toxicity is commonly associated with soil pH below 5.0 (Adams, 1981), but leaf Al concentrations reported here are well

below those previously reported for the shoots of plants grown on Berryland sand (300 µg·g⁻¹) and acidified Manor clay loam (1200 to 1700 µg·g⁻¹) (Korcak, 1986; Korcak et al., 1982).

Leaf content of Cd, Pb, and Co were at or below detection limits of 0.02, 0.13, and 0.02 µg·g⁻¹, respectively (data not shown). Mean Cr, Ni and Se levels were 0.34, 0.44, and 0.86 µg·g⁻¹, respectively, and did not differ significantly among treatments. Although there were significant differences in As content, the highest levels were found in the Berryland control with 2.15 µg·g⁻¹, compared to values ranging from 1.14 to 1.68 µg·g⁻¹ for ash–compost treatments. This treatment difference in As content may be related to the binding capacity of organic matter which could have reduced plant-available As in compost treatments (R. Chaney, personal communication).

ELEMENTAL ANALYSIS OF FRUIT. Fruit samples collected in 1999 were analyzed for elemental content to determine whether blueberry plants grown on ash–compost treatments were accumulating enough of any one element in the fruit to pose a health risk. Levels of Cd, Co, and Ni were below detection limits. For the remaining elements, there were statistically significant treatment differences (Tables 6 and 7), but the levels of these elements, and the magnitude of treatment differences were unexceptional, and will not be discussed in detail.

CROPPING. Ripe fruit were harvested in 1999 and 2000, and total fruit yield calculated for each plant. Yield data were analyzed as a cultivar × media factorial, with data from the two seasons treated as

Table 7. Micronutrient and trace element composition of blueberry fruit. Fruit sample collection and analysis are described in Table 6. Cd, Co and Ni levels were below detection limits.

Means	Element (µg·g ⁻¹)										
	B	Cu	Fe	Mn		Mo		Zn	Al	Na	
				Bluecrop	Sierra	Bluecrop	Sierra			Bluecrop	Sierra
Media											
1	4.10	4.10	11.50	5.0	6.8	0.45	0.19	6.60	5.60	26.4	6.4
2	4.71	3.76	7.84	16.1	24.4	0.84	0.02	9.73	1.79	47.5	20.6
3	5.10	4.40	10.30	24.2	15.8	0.26	0.13	8.70	2.40	44.6	17.0
4	4.80	3.60	9.50	12.4	10.0	0.34	0.25	8.90	1.70	44.2	11.4
5	4.50	2.30	5.80	5.4	7.4	0.93	0.44	9.10	1.10	35.8	12.8
6	4.50	2.30	6.00	10.0	9.0	0.84	0.43	9.10	1.60	31.2	10.8
7	4.60	2.50	5.30	5.6	5.2	0.84	0.55	8.10	2.10	29.2	15.8
8	4.30	2.10	5.90	4.8	4.6	0.95	0.50	8.80	1.60	30.8	18.0
9	4.30	2.70	8.40	6.2	7.0	0.69	0.55	9.10	1.70	37.6	11.8
10	4.70	1.90	5.70	7.4	9.2	0.65	0.35	7.90	1.80	26.2	35.2
Cultivar											
Bluecrop	5.12	2.67	8.35	9.68		0.68		9.56	2.32	35.1	
Sierra	4.00	3.26	6.90		10.04		0.34	7.64	1.96		16.0
Analysis of variance											
Cultivar	0.001	0.001	0.007	NS		0.001		0.001	NS	0.001	
Media	0.041	0.001	0.001	0.001		0.001		0.023	0.001	NS	
Cultivar × media	NS	NS	NS	0.089		0.001		NS	NS	0.080	
Contrasts											
Ash to compost ratio (5,7 vs. 6,8)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Peat vs. no peat (5,6 vs. 7,8)	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
Compost blend (5 vs. 9,10)	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS
Clay											
Linear (2,3,4)	NS	NS	NS	NS	***	*	***	NS	NS	NS	NS
Quadratic (2,3,4)	NS	**	NS	***	NS	*	NS	NS	NS	NS	NS
Berryland vs. ash–compost (1 vs. 5–10)	NS	***	***	NS	NS	***	***	***	***	NS	NS

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

repeated measures. The main effects of cultivar and media treatment were significant at $P < 0.0001$. The main effect of year was significant at $P < 0.001$, and media \times year and cultivar \times year terms were significant at $P < 0.01$ and $P < 0.05$, respectively. These year and media \times year effects can be attributed to several factors. First, fruiting was delayed in several of the slower growing treatments such as 'Bluecrop' in clay loam soil. In these cases, yields increased dramatically from the first to the second fruiting year (Fig. 1A). Second, in media treatments that resulted in rapid plant growth, plants quickly reached the capacity of the 15-dm³ pots. Consequently, yields were relatively high during the first fruiting year, but the same or lower the following season (Fig. 1B–C). Because of these year \times treatment interactions, cumulative yields over the two seasons are presented as a stacked bar graph in Fig. 1, and contrasts of media treatments are presented for cumulative yields.

There were dramatic differences in fruit yield among media treatments, with the lowest yields found in the unamended clay loam

control. Amending clay loam with compost improved yields, but even a 1:1 mix of soil to compost (treatment 4) produced less fruit than the Berryland control (Fig. 1A). The highest yields were found in the coal ash–compost treatments, with ash to compost ratio of 1:1 having significantly higher yields than that of the 3:1 treatment ($P = 0.020$, Fig. 1B). Treatments without peatmoss had significantly higher yields than with peatmoss ($P = 0.014$), and treatments containing either biosolid compost or blended compost had higher yields than did the treatment containing only leaf compost (Fig. 1C).

The largest mean fruit weight of 1.30 g berries was found in 'Bluecrop' grown in Berryland sand. The smallest mean fruit weight of 0.77 g berries was found in 'Bluecrop' grown in unamended clay loam. Fruit weight among ash–compost and soil–compost treatments for 'Bluecrop' was 1.08 g and did not differ significantly among treatments. Mean fruit weight for 'Sierra' was 1.17 g and there were no significant differences among media treatments (data not shown).

GROWTH ANALYSIS. There were significant cultivar and media treatment differences in plant growth and dry weight partitioning (Table 8). A number of these treatment differences were similar to those found for fruit yield, since fruit yield was significantly correlated with plant growth ($P < 0.001$). However, several of these treatment differences are instructive. First, there was a significant cultivar \times media interaction for both total plant biomass and root penetration (Table 8). The nature of this interaction can be best illustrated by comparing Berryland sand and Manor clay loam controls for each cultivar. 'Bluecrop' appears to be more sensitive to soil type with greater treatment differences between Berryland sand and Manor clay loam for plant growth, root penetration, and fruit yield. These cultivar differences were expected since 'Bluecrop' was selected to represent an industry standard, and 'Sierra' is a newer cultivar perceived to be more tolerant of different soil types. One notable cultivar difference in growth parameters is that of root penetration, particularly among the most productive media treatments. For 'Bluecrop' on Berryland sand and the 1:1 ash–compost treatments, 18% to 22% of the total root biomass extended below the top 10 cm of media. Root penetration for 'Sierra' in the same media treatments ranged from 7% to 13%. However, 'Sierra' had a higher root to shoot ratio indicating that a higher percentage of total plant biomass was partitioned to the roots, but the root system was not as deep.

Among media treatments, clay loam treatments showed very little root penetration, and higher root to shoot ratio. The plants were obtained from a commercial nursery and were growing in 0.5-dm³ pots containing a standard greenhouse potting mix. Planted into unamended clay loam soil, the plants produced a dense fibrous root system that did not extend very far beyond this pocket of potting media. Amending the clay loam with compost did reduce root to shoot ratio by increasing shoot growth, but did not increase vertical root penetration.

Taken together, these data indicate that a combination of coal ash and compost provide an excellent substrate for growing highbush blueberry. For 'Bluecrop' and 'Sierra' plants maintained in 15-dm³ pots, fruit yield and plant growth over the first three seasons met or exceeded that of plants grown on a typical blueberry soil. For the best ash–compost treatments, 'Bluecrop' produced average annual yields >600 g/plant in the third and fourth year. It is admittedly difficult to extrapolate results from these pot–culture experiments to field production, but the following is provided as a general point of reference. Assuming 2500 plants per hectare, a field planting of blueberries would be expected to yield ≈ 250 and 500 g per plant in the third and fourth year of production, respectively (Pritts and

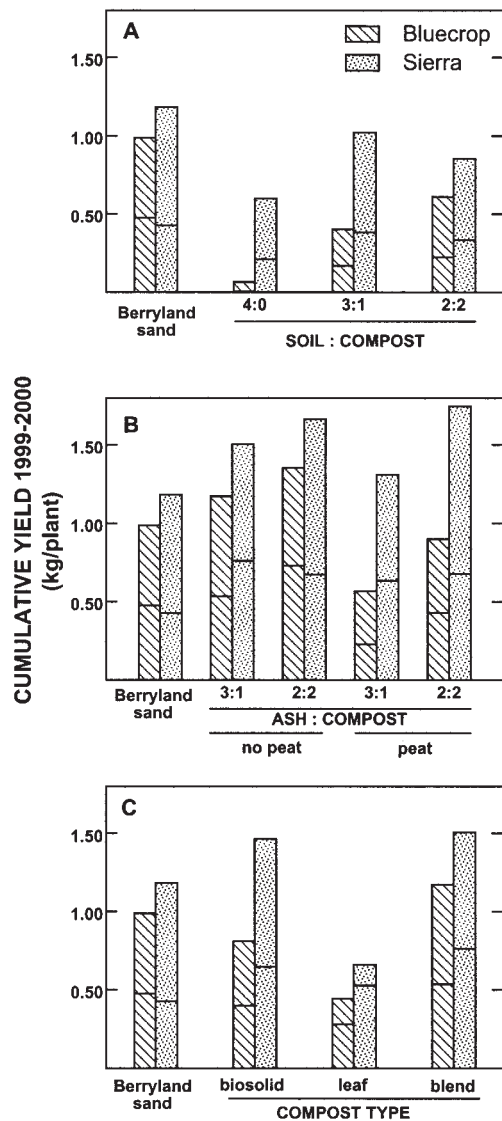


Fig. 1. Cumulative fruit yields (kg/plant) in 1999 and 2000. The lower and upper portions of each bar represent yields for the 1999 and 2000 harvests, respectively. Individual comparisons show the effects of (A) amending Manor clay loam with blended compost, (B) ash to compost ratio and presence of peatmoss, and (C) a comparison of unblended yard waste compost, biosolid compost, and a combination of these. The control treatment of Berryland sand is shown in each graph for comparison.

Castaldi, 1992). At full maturity, a field planting of 'Bluecrop' will produce 3.6 to 5.4 kg/plant annually (M. Ehlenfeldt, personal communication). The maximum potential for cropping in ash-compost mixes has yet to be determined, but plants in this study were clearly reaching the limits of the pot volume provided.

The purpose of this research was to investigate the horticultural aspects of using these materials as substrates, and not to evaluate the economic feasibility of this approach. Clearly, these materials are not practical for large-scale commercial fruit production. However, for a small-scale diversified operation interested in producing high-value fruit for direct market, but without suitable soil for highbush blueberry production, this may represent an economically viable approach. Coal combustion by-products are often freely available, with transportation representing the major cost of using these materials. Proximity to a source of clean, high quality coal ash will determine the viability of this approach.

As with composts from different sources, it should be noted that there are a wide range of coal combustion by-products, with varied chemical and physical properties. Also, the chemical composition of any one combustion by-product, such as bottom ash, can vary with the source and type of coal, and the type of combustion process used (Korcak, 1993). When considering the use of a coal combustion by-product or a compost as a substrate, a component of a blended media, or as a soil amendment, good horticultural practices

would dictate detailed elemental analysis with particular attention to those elements that may induce phytotoxicity, or exceed regulatory standards based on risk assessment research (U.S. EPA, 1993).

These experiments were limited in scale, using relatively small volumes of treatment media, comparing only two blueberry cultivars and two compost sources. In addition, horticultural practices were directed at optimizing the growth and plant health of the entire experiment, and not specifically tailored to each media treatment or cultivar, whereas optimizing water and nutrient management for each media would further improve growth and yield (Chandler et al., 1984; Erb et al., 1993; Korcak, 1983). Additional research is needed to compare different compost sources, to optimize ash and compost content, and to determine minimum root-zone volume required for long term growth and productivity. Additional cultivars will also need to be compared for adaptability to this system, and guidelines will need to be developed for horticultural practices such as managing crop load, irrigation, and plant nutrition.

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Table 8. Nondestructive and destructive measurements of plant growth. Canopy volume was calculated from two measurements of plant height and two perpendicular measurements of canopy spread (Erb et al., 1993) assuming a cylindrical shape. Total biomass and root to shoot (R:S) ratios were determined from stem and root dry weights. Root penetration is the percent of total root biomass extending more than 10 cm below the soil surface.

	Canopy vol dm ³	Total biomass (g)		R:S ratio	Root penetration (%)	
		Bluecrop	Sierra		Bluecrop	Sierra
Means						
Media						
1	163	402	289	1.179	21.30	9.72
2	68	70	228	1.912	0.62	5.77
3	99	116	206	1.424	0.55	0.45
4	112	149	191	1.099	0.00	1.03
5	163	183	270	0.945	7.41	6.90
6	267	305	324	0.839	22.16	7.26
7	125	138	256	0.937	9.33	5.20
8	180	208	351	0.907	17.97	13.2
9	156	120	273	1.029	5.56	14.1
10	135	138	227	1.023	11.07	3.25
Cultivar						
Bluecrop	120	183		1.024	9.59	
Sierra	173		262	1.235		6.69
Analysis of variance						
Cultivar	0.0001	0.0001		0.0036	0.043	
Media	0.0001	0.0001		0.0001	0.0001	
Cultivar × media	NS	0.0126		NS	0.0061	
Contrasts						
Ash to compost ratio (5,7 vs. 6,8)	***	**	NS	NS	**	NS
Peat vs. no peat (5,6 vs. 7,8)	**	NS	NS	NS	NS	NS
Compost blend (5 vs. 9,10)	NS	NS	NS	NS	NS	NS
Clay						
Linear (2,3,4)	NS	NS	NS	***	NS	NS
Quadratic (2,3,4)	NS	NS	NS	NS	NS	NS
Berryland vs. ash-compost (1 vs. 5-10)	NS	***	NS	NS	*	NS

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

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