Spent Foundry Sand and Compost in Blended Topsoil: Availability of Nutrients and Trace Elements

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ABSTRACT: Uncertainties concerning the fate in soil of potential contaminants in spent foundry sand (SFS), thus limiting their use in manufactured topsoils. A column experiment investigated plant growth, leaching and uptake of nutrients, trace elements, and organics from blends of SFSs and composts. Ryegrass growth was excellent with no toxicities. Very small effects on uptake and leaching of trace elements and organics were associated more strongly with compost than SFS. Large differences in macronutrient leaching were attributed to the type of compost. SFSs with low trace element content can be safely utilized for manufactured soil production however composts used could leach large quantities of nutrients.Keywords: spent foundry sand, compost, manufactured soil.

INTRODUCTION

EVERY year, the metal casting industry generates between nine and thirteen million tons of spent foundry sand (SFS), most or all of which is disposed of in landfills. Due to increased regulatory constraints and rising disposal costs, this practice is being reevaluated by individuals in the industry and regulatory agencies. According to the USEPA industrial waste division, only two percent of this material is classified as hazardous waste [1]. The physical characteristics of these sands could allow them to be beneficially reused in manufactured topsoil blends in combination with composted organic material and low value subsoil materials. Uncertainties regarding the bioavailability, solubility, and persistence of organic and inorganic contaminants potentially present in SFS have made regulators hesitant to either dewaste certain types of SFS or to develop less restrictive permitting that would allow its reuse without extensive testing and monitoring.

Most spent foundry sands are termed “green” sands and consists primarily of silica sand coated with a thin layer of burnt carbon, residual bentonite clay binders, and dust [2]. Spent green sands from most foundries will also include some sands from core molds constructed using organic-based binder systems. A binder is any material, added to virgin sand, which by means of cohesion and/or adhesion, bonds sand grains together so that they may be used for metal casting [2]. The core mold binders are the primary source of potential organic contaminants in sands whereas metals being cast are the source of potential trace element contaminants. Promising potential uses of SFS are as substitutes for virgin sand in construction activities or in manufactured soils. Any revision of regulations allowing for soil based beneficial reuse of SFS, will require characterization of potential contaminants that may be present in foundry sand as well as their behavior in a soil environment. A study conducted to determine the extent of groundwater contamination from landfills containing exclusively ferrous foundry wastes indicated the presence of a wide variety of organic compounds; however, all sample results were below the regulatory toxicity limits [2]. Extracts of pure SFS typically contained concentrations of metallic compounds below regulatory toxicity characteristic levels [2]. Furthermore, quantities of total metal content in spent and virgin foundry sand and in sandy soils were of the same order of magnitude, with total metal content of foundry sands sometimes lower than levels in sandy soils [2]. However, none of these studies investigated the behavior of SFS in a soil environment.

Sand based blended topsoils require inclusion of a large amount of organic material, usually in the form of compost. Due to the high nutrient content of composted

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organic materials, the potential exists for nutrient leaching. Nitrate losses from land application of spent mushroom substrate (SMS) compost may pose a threat to groundwater quality. Soil leachate samples collected underneath 90-cm and 150-cm deep piles of SMS at a soil depth of 90 cm contained NO_3-N concentrations as high as 50-times greater than the drinking water standard [3]. In a greenhouse column study, it was determined that soil leachate total P concentrations in biosolids amended sandy soils were not significantly different than control soils [4]. These results suggest that the potential for P leaching from manufactured soils containing biosolids is quite small.

This greenhouse column experiment was conducted to evaluate the suitability of SFS for use in manufactured soils by measurement of plant growth; and to assess potential environmental risks associated with these manufactured soils by measurement of plant uptake and leaching of nutrients, trace metals, metalloids, and organics in blended soils containing SFS, compost, and subsoil.

MATERIALS AND METHODS

Spent Foundry Sands

Spent green sands representative of three different binder systems widely used in the metal casting industry were used in this experiment. The three binder systems are: phenolic urethane no-bake (PUNB, iron foundry), furfuryl alcohol no-bake (FNB, iron foundry), and Shell (aluminum foundry). Spent sands were collected from two iron foundries (PUNB and FNB), and one aluminum foundry (Shell) in Pennsylvania and brought to Penn State University for analysis and use in the greenhouse column experiment. Prior to use in the experiment, all SFSs were passed through a 2 mm sieve to screen out foreign materials present in the sands. Any pieces of metal caught on the sieve were removed. Any SFS aggregates and core butts caught on the sieve were reduced to particles < 2 mm diameter by grinding with a mortar and pestle. Macroelement and trace element content of the SFSs was determined by strong acid digestion (EPA method 3051 and analysis by ICP, As by graphite furnace AA for As and Se), and by EPA 7471 for Hg (Tables 1 and 2). Particle size analysis of the SFSs was determined by the hydrometer method (Gee and Bauder).

Composts

Three compost materials were selected for blending with SFS: yard trimmings compost, spent mushroom substrate (SMS), and biosolids compost. These materials were analyzed for solids content (drying at 105ºC), total N (Kjeldahl), NH_4-N (ion selective electrode), organic N (subtraction of NH_4-N from total N), total P and total K (EPA 3051 digestion, ICP analysis), As, Cd, Cr, Cu, Pb, Mo, Ni, Se, and Zn (EPA 3051 digestion, graphite furnace AA for As and Se, ICP analysis for all other elements) and Hg (EPA 7471) (Tables 1–3). Although the spent mushroom substrate is not a completely composted material, in this paper the term “compost” will be used to refer to all three of these organic materials. These composts are widely available and may be sold or given away to the general public without any regulatory limitations on their distribution or use.

Topsoil and subsoil were obtained from a Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalfs) located on the Penn State University research farm located at Rock Spring, PA. Topsoil material was collected from the Ap horizon (0–20 cm) and subsoil material was collected from the Bt horizon (30–50 cm). The soil materials were analyzed for particle size distribution by the hydrometer method (Gee and Bauder).

Table 1. Macroelement concentrations in spent foundry sands and compost materials used in the greenhouse experiment.

	Al	Ca	Fe	K	Mg	Mn	Na	P	S
Material					mg kg^{-1}				
FNB	425	200	1001	55.7	909	47.6	65.1	10.7	375
Shell	1925	1020	1402	363	569	16.8	138	17.7	203
PUNB	1278	708	47480	63.7	252	286	296	< 6.0	299
SMS	314	73799	4410	27463	13089	326	2648	6129	10156
Biosolids	8602	18636	71423	1910	3784	2777	444	21705	8536
Yard	6573	38248	11693	8867	7745	1022	536	3480	2666

Table 2. Trace element concentrations in spent foundry sands and compost materials used in the greenhouse experiment.

	As	Ba	Cd	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
Material	**mg kg^{-1}**										
FNB	< 0.30	27.2	< 0.40	5.25	3.90	< 0.007	0.85	9.15	1.07	< 0.51	7.54
Shell	< 0.30	5.63	< 0.40	3.51	4.44	< 0.007	< 0.50	1.96	0.86	< 0.51	11.9
PUNB	7.50	7.95	< 0.40	51.8	137	< 0.007	6.97	26.3	2.42	< 0.53	5.32
SMS	24.8	78.4	< 0.40	20.5	78.3	0.032	3.27	8.19	4.89	0.84	153
Biosolids	5.74	451	4.36	66.0	460	1.255	16.6	22.5	148	4.04	1158
Yard	6.88	145	0.61	25.1	55.7	0.188	2.10	13.2	73.5	1.04	200

Column Establishment

Soil blends were made by combining each type of SFS with each type of compost and with subsoil at a dry weight ratio of 6.5:1.5:2.0 (SFS:compost:subsoil). All soil blends were characterized as sandy loams (Table 4). The greenhouse experiment then consisted of these nine blends and also the natural topsoil as a control. Columns for the plant growth and leaching experiment were constructed using 15-cm diameter PVC pipe cut to 30 cm lengths. The PVC pipe was glued to a flat PVC base plate with a nipple tube fitting mounted in the center. A Teflon® tube directed flow to amber glass bottles for leachate collection. The inner surfaces of the columns were lined with Teflon® sheeting to minimize potential interference from PVC constituents. A 5 cm layer of acid washed virgin sand was placed in the bottom of each column. Columns were then filled with a 21.5 cm depth of manufactured soil blend or with natural topsoil. Material was added in 3 "lifts" and columns were tamped following the addition of each lift to achieve the same extent of packing with each material. Inorganic fertilizer was added to each treatment: 68 mg N, 10 mg P, and 20 mg K per column as urea, triple super phosphate and potassium chloride respectively. The fertilizer was mixed into the upper 5 cm of each column and was further incorporated by watering. Because one objective of this experiment was to determine the amounts of N, P, and K fertility supplied by the compost materials, inorganic fertilizer addition was kept to the minimum amount needed for plant growth in the natural topsoil.

Table 3. Chemical characterization of compost materials used in manufactured soil blends.

Analyte	Yard Compost	Spent Mushroom Substrate	Biosolids Compost
pH	7.9	8.1	7.1
Soluble Salts (mmho/cm)	2.33	16.45	6.87
Organic Matter (%)	47.4	53.7	52.4
Total Nitrogen (%)	1.8	2.1	3.3
Organic Nitrogen (%)	1.8	2.1	2.8
Ammonium Nitrogen (mg/kg)	4.5	5.3	5024.5
Carbon (%)	287	29.9	29.0
Carbon/Nitrogen Ratio	15.7	14.2	8.7

After filling each column, the moisture content was adjusted to 80% of field capacity by adding de-ionized water. One day after the columns were filled, they were planted with 40 seeds of annual ryegrass (*Lolium multiflorum* Lam.). De-ionized water was added as needed to maintain sufficient moisture for ryegrass growth but not enough to cause any leaching.

Leachate Collection and Analysis

Columns were intentionally leached two weeks after planting and once each month thereafter for a total of 6 leaching events. One day prior to leaching the columns were weighed and sufficient water was added to each column to adjust soil moisture content to 80% of field

Table 4. Particle size distribution of SFSs, soils, and blends.

	Sand	Silt	Clay	Textural Class
Material	**mg kg^{-1}**			
Spent foundry sands				
FNB	975	12	13	Sand
Shell	907	57	35	Sand
PUNB	976	11	12	Sand
Hagerstown soil				
Topsoil	332	543	225	Silt loam
Subsoil	151	379	470	Clay
Blended soils (SFS+subsoil)				
FNB	781	98	121	Sandy loam
Shell	729	133	137	Sandy loam
PUNB	782	98	120	Sandy loam

capacity. Leaching was done by adding 50 ml of de-ionized water to the surface of each column every 30 minutes until approximately 500 ml of leachate had been collected. Leachate samples were analyzed immediately for pH and electrical conductance and for Al, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn by inductively coupled plasma (ICP) emission spectroscopy, and corimetrically for NO_3-N, NH_4-N, and Ortho-P using an autoanalyzer and the following QuikChem methods: 10-107-04-1-A (NO_3-N), 10-107-06-1-B (NH_4-N), and 10-115-01-1-T (Ortho-P) [6; 7; 8]. Total N and total C were analyzed by combustion using a Carlo Erba analyzer. Leachate samples from the first two leaching events were analyzed for As and Se by high resolution ICP-MS, and for Hg using EPA Method 7470 (cold vapor atomic absorption). The quantity of nutrients and trace elements leached from each column was calculated by multiplying the volume of leachate collected by the concentration of each constituent analyzed. Leachates from the first three leaching events were analyzed for the following polyaromatic hydrocarbon and phenolic organic compounds following extraction with SPME fibers with a 85µm polyacrylate coating and the method described by Doong [9]: PAHs; Acenaphthene, Acenaphthylene, Anthracene, Benzo(a)anthracene, Benzo(b)-fluoranthene, Benzo(k)fluoranthene, Benzo(a)pyrene, Chrysene, Fluoranthene, Fluorene, Naphthalene, Phenanthrene, Pyrene; Phenols: 4-Chloro-3-methylphenol, 2-Chlorophenol, 2,4-Dichlorophenol, 2,4-Dimethylphenol, 2,4-Dinitrophenol, 2-Methyl-4,6-dinitrophenol, 2-Nitrophenol, 4-Nitrophenol, Pentachlorophenol, Phenol, 2,4,6-Trichlorophenol.

Ryegrass Collection and Analysis

Ryegrass vegetative growth was clipped at a height of 4 cm whenever the grass began to flower (43 days after planting and every 2–3 weeks thereafter) for a total of 7 harvests. Clippings were dried for 48 hours at 65°C, weighed, and ground to pass a 1 mm screen. Yield data were obtained using the mass of oven dry matter collected from each column. A 5 g oven-dry composite tissue sample was prepared for analysis by determining the fractional contribution of each clipping to the total yield and adding the corresponding proportion from each clipping. When total cumulative yield was less than 5 g pot^{-1}, all of each clipping was used for the composite sample. Tissue N was determined by combustion using a Carlo Erba analyzer. Composite samples were analyzed for the following nutrients and trace elements by ICP following microwave digestion with nitric acid: P, K, Ca, Mg, S, Mn, Fe, Al, B, Cd, Cu, Mo, Na, Ni, Pb, and Zn.

Statistical Analysis

SAS 9.1 statistical software was used to perform analysis of variance (ANOVA) and means comparisons using Fisher's Least Significant Difference (LSD) Treatment effects were considered significant when $Pr > F \leq 0.05$.

RESULTS AND DISCUSSION

Ryegrass Growth and Analysis

Ryegrass grew very well in all SFS-based soil blends and greatly exceeded growth in the control topsoil (Table 5). As previously mentioned, minimal fertilizer was added to all treatments in order to assess the fertility contribution of the composts. Since topsoil yields would likely have been much greater with larger fertilizer additions, these data do not provide a valid comparison of yield potential for SFS based soil blends and natural topsoil. No differences were detected among SFS type, however, yields were influenced by compost type. Means comparison showed larger yields in blends using either SMS or biosolids compost than in blends containing yard compost. Differences in ryegrass yield among composts were most likely due to nitrogen availability. SMS and biosolids compost contained more total nitrogen, organic nitrogen, and ammonium nitrogen than the yard compost (Table 3).

As was observed with growth response, compost had a much greater effect on ryegrass tissue nutrient content than SFS (Table 4). For nearly one-half of all elements analyzed, compost type affected tissue concentrations while SFS did not. The type of sand used in the blend influenced tissue content of one-third of all elements analyzed; however, SFS type was never the only factor in determining tissue concentration of a particular element. That is, whenever tissue composition was affected by SFS it was also affected by compost which generally exhibited a larger effect than SFS. Nitrogen levels were largest in ryegrass grown on blends containing biosolids compost and were within the tissue sufficiency range (33.4–51 g N kg^{-1}) for all biosolids blends except the blend with PUNB [10]. Differences in

Table 5. Cumulative yields and tissue nutrient and trace element concentrations of ryegrass grown in SFS and compost based manufactured soil.

	Yield	**N**	**P**	**K**	**Al**	**B**	**Cd**	**Cu**	**Fe**	**Mn**	**Mo**	**Na**	**Ni**	**Zn**
Treatment	**g m^{-2}**	**mg kg^{-1}**												
Control (Topsoil)	112f*	24.1cd	5.3a	32.6d	53.5bc	25.5d	1.05a	35.3a	113b	99.7c	0.76d	141b	2.40a	103abc
PUNB + yard	784e	21.7d	3.5d	32.9d	79.7a	28.5d	0.40b	29.3a	126b	41.2c	4.16bc	371b	2.35a	57.4d
PUNB + SMS	1338abc	32.5abc	4.3bc	45.4a	65.5abc	17.6d	0.15b	26.6a	120b	48.9c	2.60c	858b	0.69b	48.2d
PUNB + biosolids	1052bcde	32.0c	2.5e	22.0e	77.1a	22.6d	0.17b	33.5a	289a	637b	4.25bc	3088a	2.25a	84.3abcd
FNB + yard	934cde	20.4d	4.3bc	32.8d	73.4ab	41.2d	0.27b	25.1a	113b	48.8c	5.83ab	224b	0.60b	61.2cd
FNB + SMS	1395ab	27.2cd	4.4b	40.5b	62.2abc	16.5d	0.12b	27.0a	106b	39.2c	3.59c	603b	0.33b	58.3d
FNB + biosolids	1587a	40.5ab	3.9cd	21.8e	48.3c	28.5d	0.11b	37.4a	110b	1055a	3.30c	3546a	0.41b	106ab
Shell + yard	852de	23.6cd	4.5b	34.6cd	66.4abc	231b	0.23b	25.3a	102b	42.5c	6.66a	163b	0.46b	60.8cd
Shell + SMS	1333abc	25.2cd	4.4b	38.2bc	68.9abc	107c	0.15b	27.4a	100b	39.5c	3.82c	399b	0.43b	60.4cd
Shell + biosolids	1230abcd	42.3a	4.2bc	33.4d	61.6abc	283a	0.08b	32.3a	140b	544b	4.02c	1313b	0.42b	128a
Mean of SFS (average of 3 composts)														
PUNB	1058a	28.7a	3.4b	33.4ab	74.1a	22.9b	0.238a	29.8a	178a	242b	3.67b	1439a	1.77a	63.3a
FNB	1305a	29.4a	4.2a	31.7b	61.3a	28.7b	0.167a	29.8a	110a	381a	4.24ab	1458a	0.45b	75.1a
Shell	1139a	30.4a	4.4a	35.4a	65.6a	207a	0.154a	28.4a	114a	209b	4.83a	625a	0.44b	83.0a
Mean of Compost (average of 3 SFSs)														
Yard	857b	21.9c	4.09b	33.4b	73.2a	100a	0.301a	26.6ab	114a	44.1b	5.55a	253b	1.14a	59.8b
SMS	1355a	28.3b	4.36a	41.4a	65.5a	46.9b	0.139b	27.0b	108a	42.5b	3.34b	620b	048b	55.6b
Biosolids	129a	38.2a	3.55c	25.7c	62.3a	111a	0.119b	34.4a	108a	745a	3.86b	2649a	1.03a	106a
ANOVA														
Source of Variation														
SFS	NS†	NS	**	**	NS	**	NS	NS	NS	**	NS	NS	**	NS
Compost	**	**	**	**	NS	**	**	NS	NS	**	**	**	**	**
SFS x Compost	NS	NS	**	**	NS	**	NS	NS	NS	**	NS	NS	**	NS

*Fisher's LSD: Within columns and sections, means with the same letter are not significantly different.
**Significant at the 0.05 level.
†Not significant at the 0.05 level.

tissue N content are likely due to the large amounts of nitrogen found in biosolids compost relative to the yard and SMS composts (Table 1). Tissue P levels were lower in samples from the blended soils compared to the topsoil, but were still within the sufficiency range (3.5–5.5 g P kg^{-1}) in all blends except the one containing PUNB and biosolids compost, which was below the range [10]. The difference in P content may simply reflect the concentrating effect of much lower biomass production on the natural topsoil. Sufficient amounts of K (20–34.2 g K kg^{-1}), Ca (2.5–5.1 g Ca kg^{-1}), and Mg (1.6–3.2 g Mg kg^{-1}) were present in ryegrass samples from all blended soils and S levels were within the sufficiency range (2.7–5.6 g S kg^{-1}) in all blends except the one made with Shell and SMS compost [10]. In this blended soil, the tissue S level was 2.6 mg kg^{-1} and was slightly below the sufficiency range.

We observed no evidence of trace element deficiencies or toxicities in ryegrass grown on the SFS and compost blends. As with macronutrients and yields, tissue trace element concentrations were affected mainly by compost type and less so by SFS, with the exception of Shell for certain elements. Almost all tissue B concentrations were above the normal sufficiency range (5–17 mg B kg^{-1}), and very large increases in B were observed in tissue grown on all blends containing Shell (Table 4) [10]. We did not measure B in the SFSs or composts and so cannot conclusively state the source of B. However, plant tissue data suggest Shell was the B source and that SMS compost was able to suppress B uptake. Tissue Mo levels from all blends were above the sufficiency range (0.5–1.0 mg Mo kg^{-1}), but well below the toxicity level of 90 mg kg^{-1} [10; 11]. Tissue micronutrient concentrations were within the specified sufficiency ranges for both Fe (97–934 mg Fe kg^{-1}) and Cu (6–38 mg Cu kg^{-1}) and were not affected by treatment [10]. Blends containing biosolids compost produced ryegrass with tissue levels of Mn and Zn above the sufficiency range (30–73 mg Mn kg^{-1}; 14–64 mg Zn kg^{-1}), but well below the toxicity levels of 600 mg kg^{-1} and 400 mg kg^{-1}, respectively [10; 11]. Tissue Al concentrations were in the normal range for all treatments and were not affected by treatment.

Tissue analysis of the nonessential elements, Na and Al, determined that Al concentrations were within the normal range (52–922 mg Al kg^{-1}) and Na levels were above the normal range (229–1107 mg Na kg^{-1}) in blends containing biosolids compost [10]. Tissue concentrations of Cd and Ni in blended soils were either lower than or not different from the control concentrations. All samples analyzed were below the detection limit of 0.25 mg kg^{-1} for Pb.

Overall the yield and plant tissue composition results indicate that blended topsoils made with SFS and composts could provide a growth media with good yield potential and the composts appear to supply adequate macronutrients for ryegrass growth. Plants grown in the constricted root environment of a greenhouse pot or column often exhibit increased uptake of micronutrients and other trace elements. In this experiment measured increases in plant tissue trace element concentrations were relatively small and in most cases could be attributed to the compost rather than to the SFS component of the blended topsoil.

Inorganic Leachate Chemistry

In this experiment we utilized a leaching frequency and intensity that exceeded that expected due to natural rainfall to simulate worst case scenario conditions and to amplify both SFS and compost effects on leachate quality. On average, the amount of water added to columns for each leaching event was equivalent to a 65 mm rainfall on columns that had been brought to 80% of field moisture capacity the day before. It is unlikely that such excessive, regular leaching would occur in a natural setting. Consequently the leachate quality and quantity results from this greenhouse are not representative of what might occur in natural systems but are useful predictors of potential effects of the various blended soil components.

Macronutrients

Similar to what we observed with plant tissues, the leachate macronutrient concentrations and total amount of macronutrients leached (N, P, K, Ca, Mg, and S) were more strongly influenced by compost than by SFS. These results correspond to, and likely can be attributed to, the generally much larger concentrations of these elements in the composts than in the SFSs (Table 1). Biosolids compost with any of the SFSs greatly increased leaching of N (total N, NO_3^-, and NH_4^+), while smaller increases were observed with SMS, and yard compost did not increase N leaching relative to the natural topsoil (Table 5). These results correspond to the total N and NH_4-N contents and the C:N ratio of the composts and expected N mineralization rates (Table 1). Further evidence of substantial N mineralization and nitrification in biosolids compost was seen in the NO_3-N leaching pattern which increased to very large concentrations in the second and third leaching event for all biosolids compost mixes (Figure 1). The corresponding pH suppression in leachates from biosolids containing blends also indicates much more nitrification was occurring in biosolids compost than in blends made with the other composts or in the topsoil (Figure 1). After the spike in leachate NO_3-N concentrations during the 2nd leaching event in the biosolids-containing blends, all treatments followed the same general trend of decreasing NO_3-N concentrations. Leachate nitrate concentrations above the USEPA Maximum Contaminant Level of 10 mg NO_3-N L^{-1} were seen in all blends, including the control; however, by the 6th leaching event NO_3-N levels from all treatments were below EPA standards [12].

The use of SMS compost resulted in increased leaching of total P, ortho-P (data not shown), and K as compared to other blends and the control (Table 5). Although the biosolids compost contained a larger concentration of P (Table 2), blends containing biosolids compost lost smaller quantities of both P and ortho-P than the other blends. Similar results were observed in a greenhouse column study of biosolids amended sandy soils where P loss from columns amended with biosolids compost was negligible and the

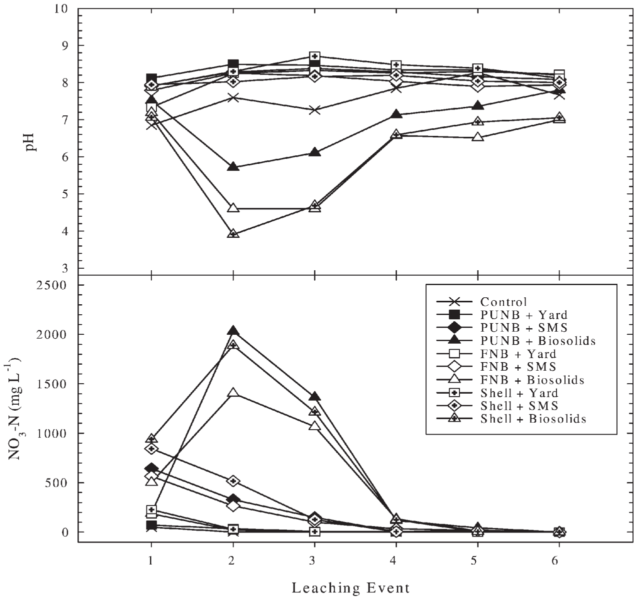

Figure 1. *Effect of SFS and compost blended soils on column leachate pH and NO_3-N concentrations.*

Table 6. Effect of SFS and compost on the cumulative nutrient loss from 6 leaching events.

	Total N	NO_3-N	NH_4-N	P	K	Ca	Mg	S
Treatment	g column^{-1}				mg column^{-1}			
Topsoil (Control)		0.33d†	11.3d	0.27e	24.7d	34.8g	14.6d	099d
PUNB + yard		0.58d	45.2d	0.53e	1699c	370g	104cd	97.0d
PUNB + SMS		1.20c	425c	16.95c	6452b	1254e	603b	554ab
PUNB + biosolids		2.87ab	2080a	0.81de	125d	2768b	928a	635ab
FNB + yard		0.62d	53.9d	5.95d	2132c	778f	211c	100d
FNB + SMS		1.22c	380c	39.43a	5976b	1343e	736b	240cd
FNB + biosolids		2.46b	1735b	1.28de	79.7d	2231c	944a	507b
Shell + yard		0.54d	77.3d	3.55de	1851c	791f	171c	25.4d
Shell + SMS		1.32c	587c	27.43b	8468a	1804d	940a	460bc
Shell + biosolids		3.08a	2057a	1.11de	141d	3233a	1027a	813a
Mean of SFS (average of 3 composts)								
PUNB		1.55a	850ab	6.10c	6.10c	1464b	545b	428a
FNB		1.44a	722b	15.6a	15.6a	1451b	630ab	283a
Shell		1.65a	907a	10.7b	10.7b	1943a	713a	433a
Mean of Compost (average of 3 SFSs)								
Yard		0.58c	58.8c	3.34b	3.34b	646c	162c	74.3c
SMS		1.25b	464b	27.9a	27.9a	1467b	760b	418b
Biosolids		2.81a	1957a	1.06b	1.06b	2744a	966a	652a
Source of Variation								
SFS		NS	NS	**	**	**	**	NS
Compost		**	**	**	**	**	**	**
SFS*Compost		NS	NS	**	**	**	NS	NS

†$LSD_{0.05}$: Within columns means with the same letter are not significantly different.
‡Results from leaching events 4–6 only, S not analyzed in leaching events 1–3.
§NS, not significant.
***Pr* > *F* ≤ 0.05.

amount of P leached was not different than control columns [4]. Differences in phosphorous leaching may also be due to differences in phosphorous-fixation capacity of the blends. Soluble iron, aluminum, and manganese can fix phosphorous in unavailable, insoluble forms [11]. Since SMS compost contains smaller quantities of Fe, Al, and Mn than biosolids and yard composts contain, blends containing SMS compost may be less able to fix P and greater amounts of P may be lost in leachates from blends utilizing SMS (Table 2). The large amount of K lost from SMS blends appears to result from the much larger amount of K present in this compost compared to the other two and to the SFSs. The amounts of Ca, Mg, and S lost in leachates varied depending on compost type (Table 5). The greatest losses were from blends containing biosolids compost, followed by blends containing SMS compost, and the smallest losses were from blends containing yard compost.

Trace Elements

Although we were able to measure SFS and compost effects on the leaching of trace elements, in most cases the concentrations and quantities leached were very small. All samples were below detection limits for mercury (< 0.0004 mg L^{-1}) and lead (< 0.025 mg L^{-1}). Leachate concentrations of Ba, Cd, Cr, and Cu (data not shown) were below the maximum contaminant levels (MCL) of 2 mg B L^{-1}, 0.005 mg Cd L^{-1}, 0.1 mg Cr L^{-1}, and 1.3 mg Cu L^{-1} set forth by EPA in the National Primary Drinking Water Standards [12]. Concentrations of Al and Fe in leachates were lower than leachate concentrations from the control treatment but were above the EPA National Secondary Drinking Water Standards of 2 mg Al L^{-1} and 0.3 mg Fe L^{-1} [12]. Secondary drinking water standards are non-enforceable guidelines regulating contaminants that may cause cosmetic or aesthetic effects in drinking water. While it is not expected that leachates from natural or synthetic topsoil should meet primary or secondary drinking water standards, these standards provide a benchmark level for comparison.

Leachate concentrations of most measured trace metals were affected by both SFS and compost type. The use of biosolids compost resulted in increased Mn and

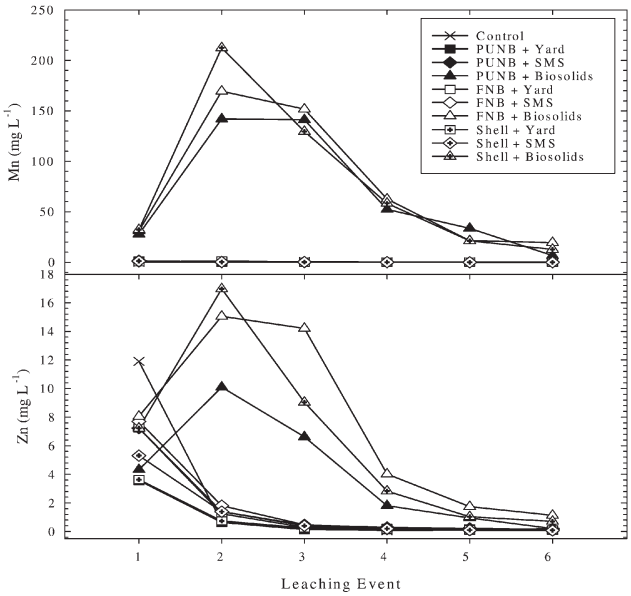

Figure 2. *Effect of SFS and compost on leachate Mn and Zn concentrations of samples collected in the greenhouse study.*

Zn leaching as compared to the other blends and the control and were above the EPA National Secondary Drinking Water Standards of 0.05 mg Mn L^{-1} and 5 mg Zn L^{-1}. These results in part reflect the much larger amounts of Mn and Zn in biosolids compost than in the other composts (Table 2). In addition, Mn and Zn solubility increase as pH decreases [13], and the greatest amount of Mn and Zn mobilization occurred during the period of leachate pH depression (Figures 1 and 2). Soil blends made with SMS compost leached greater amounts of Mo and Na than other soil blends and the control (Table 6). Mobilization of Na from blends containing SMS compost is not surprising since the SMS compost contained the greatest amount of Na (Table 2) and Na is relatively soluble in comparison to polyvalent trace metals. The larger amount of Mo loss from SMS was somewhat surprising given that biosolids compost had much greater Mo content (Table 3). Molybdenum solubility decreases as pH decreases and thus the lower pH in the biosolids compost blends may have limited Mo mobilization.

Although statistical analysis indicated SFS*compost interactions for several trace metals, this was most clear-cut when PUNB-SFS was used in combination with biosolids compost. In this particular blend, the quantity of Ni lost was nearly double the amounts lost by other blends (Table 6). Among sands, PUNB SFS contained more Ni, and biosolids compost contained more Ni than other composts (Table 3). When used together, the potential for increased Ni losses is clearly evident. As with Mn and Zn, the solubility of Ni is increased when pH is decreased and leachate pH will affect Ni concentrations [13]. It should be noted however, that despite these interactive effects, leachate Ni concentrations never exceeded 0.25 mg L^{-1}. And although ryegrass tissue Ni was greater from blends with PUNB than with other SFSs, it did not exceed tissue Ni from the natural topsoil.

Leachate As concentrations were greater than the USEPA MCL level of 10 ppb in most of the blends (Table 7). Only blends made with yard compost were at or below the MCL in both leaching events. The greatest amount of As was lost from blends containing SMS compost (Table 7). Due to the greater concentrations of arsenic found in SMS compost than in the other compost materials (Table 3), it is not surprising that leachate concentrations were greater. The feedstocks used to produce the SMS included broiler litter. It is possible this material was the source of the As since roxarsone is often included in broiler feed as a disease control agent and is associated with increased As in the litter [13]. In neutral to alkaline soils, As may be mobile in the soluble Na arsenate (AsO_4^{3-}) form [14]. Thus the high Na content in SMS compost may also have enhanced As mobility. SFS type did not affect the amount of As lost from the blends, as no differences were detected in the quantity leached.

Selenium levels in all leachates were below the National Primary Drinking Water MCL of 50 ppb (Table 7).

Organics

All leachates analyzed were below detection limits for PAHs (0.22 µg ml^{-1}) and phenols (0.44 µg ml^{-1}) with the exception of two leachate samples collected from one replicate of the blend containing PUNB and SMS compost. The second leachate of this blend contained 0.41 ppb fluoranthene and 0.22 ppb pyrene, and the third leaching contained 0.33 ppb fluoranthene. Due to the non-detectable levels of organic constituents in leachates collected from all but one blend, and the extremely small concentrations present where detected, the potential for these organics leaching from blends containing SFS and compost appears to be minimal.

CONCLUSIONS

Results from this greenhouse experiment demonstrate that manufactured soil blends containing spent

Table 7. Effect of SFS and compost on the cumulative trace element loss from 6 leaching events.

	Al	Ba	Cd	Cr	Cu	Fe	Mn	Mo	Na	Ni	Zn
Treatment						**mg column^{-1}**					
Topsoil (Control)	127a†	0.50a	0.016bc	0.09a	0.08e	75.4a	1.16c	0.02e	5.84e	0.08cd	3.02d
PUNB + yard	2.25b	0.15c	0.016bc	0.02e	0.18de	2.17b	0.33c	0.05e	367c	0.08cd	1.42d
PUNB + SMS	0.82b	0.18c	0.015c	0.04cd	0.55b	2.26b	0.26c	0.39c	974b	0.13b	2.97d
PUNB + biosolids	0.09b	0.23bc	0.015c	0.02e	0.17de	6.16b	231b	0.02e	275cd	0.35a	12.3c
FNB + yard	19.0b	0.47a	0.015c	0.04de	0.30c	12.7b	0.49c	0.17d	298cd	0.06cde	2.86d
FNB + SMS	0.58b	0.22bc	0.015c	0.06bc	0.69a	1.64b	0.60c	0.55b	830b	0.06cde	3.22d
FNB + biosolids	0.50b	0.19c	0.019b	0.02e	0.38c	3.98b	267a	0.02e	120de	0.09c	24.2a
Shell + yard	2.19b	0.43a	0.015c	0.02e	0.20d	1.68b	0.87c	0.21d	457c	0.04e	1.57d
Shell + SMS	2.86b	0.28b	0.016bc	0.08ab	0.64ab	2.53b	0.53c	0.70a	1374a	0.06de	2.38d
Shell + biosolids	2.91b	0.23bc	0.025a	0.02e	0.35c	1.73b	264ab	0.03e	332c	0.08cd	19.2b
Mean of SFS (average of 3 composts)											
PUNB	1.05b	0.18b	0.015b	0.03b	0.30b	3.53ab	77.2a	0.16c	539b	0.18a	5.55c
FNB	6.70a	0.29a	0.016b	0.016b	0.46a	6.12a	89.3a	0.25b	416c	0.07b	10.1a
Shell	2.65ab	0.31a	0.019a	0.04a	0.40a	1.98b	88.5a	0.31a	721a	0.06b	7.72b
Mean of Compost (average of 3 SFSs)											
Yard	7.82a	0.35a	0.015b	0.03b	0.23c	5.53a	0.56b	0.14b	374b	0.06c	1.95b
SMS	1.42b	0.22b	0.015b	0.06a	0.63a	2.14b	0.46b	0.55a	1059a	0.08b	2.85b
Biosolids	1.17b	0.21b	0.020a	0.02b	0.30b	3.96ab	254a	0.03c	242c	0.17a	18.5a
Source of Variation											
SFS	**†	**	**	**	**	**	NS	**	**	**	**
Compost	**	**	**	**	**	NS	**	**	**	**	**
SFS*Compost	**	**	**	**	NS	**	NS	**	NS	**	**

†LSD0.05: Within columns and sections, means with the same letter are not significantly different.
‡NS, effect not significant.
**Pr > F ≤ 0.05.

Table 8. Leachate arsenic and selenium concentrations from leaching events 1 and 2.

	Se			Se		
	Leach 1	**Leach 2**	**Quantity Leached**	**Leach 1**	**Leach 2**	**Quantity Leached**
Treatment	**μg L^{-1}**	**μg L^{-1}**	**μg column^{-1}**	**μg L^{-1}**	**μg L^{-1}**	**μg column^{-1}**
Control (Topsoil)	1.31	1.12	0.89c	<0.3	< 0.3	< 0.15d
PUNB + yard	2.79	2.09	1.76c	<0.3	< 0.3	< 0.15d
PUNB + SMS	91.7	62.3	48.6b	9.94	< 0.3	1.49bcd
PUNB + biosolids	27.0	16.17	13.4c	0.48	< 0.3	0.27d
FNB + yard	5.45	8.54	5.72c	<0.3	< 0.3	0.42d
FNB + SMS	199	144	122a	9.70	1.62	2.70abc
FNB + biosolids	28.3	15.3	14.5c	4.86	0.65	3.23ab
Shell + yard	5.46	10.1	6.82c	<0.3	<0.3	0.85cd
Shell + SMS	155	172	136a	15.2	2.11	4.07a
Shell + biosolids	31.6	15.3	14.0c	4.26	<0.3	1.21cd
Mean of SFS (average of 3 composts)						
PUNB	40.5	26.9	21.3a	3.47	< 0.3	0.58a
FNB	77.6	56.0	47.3a	4.85	0.76	2.12a
Shell	64.2	65.9	52.4a	6.49	0.70	2.04a
Mean of Compost (average of 3 SFSs)						
Yard	4.56	6.91	4.77b	< 0.3	< 0.3	0.42a
SMS	149	126	102a	11.6	1.25	2.75a
Biosolids	29.0	15.6	14.0b	3.20	0.22	1.57a

*Fisher's LSD: Within columns and sections, means with the same letter are not significantly different.

foundry sand and compost provide a good medium for annual ryegrass growth. Our results showed that the compost rather than the SFS component of the blends had the dominant effect on ryegrass growth, nutrient and trace element uptake, and nutrient and trace element leaching. Ryegrass tissue analysis indicated that most tissue trace metal concentrations were lower or the same as the control and most tissue nutrient concentrations fell within the sufficiency range for annual ryegrass. Compost selection is important due to its effects on tissue trace metal and nutrient concentration.

We also conclude that the use of SFSs with low total concentrations of trace elements (such as those generated from ferrous and aluminum foundries) in blended synthetic topsoils will not increase risk of trace element or organic contaminant transport to surrounding soils or waters. The compost component of such blends, however, could impact transport of nutrients (particularly N and P) as well as some trace elements. These potential detrimental effects could likely be avoided by selecting fully mature composts with low inorganic N levels and high C:N ratios (14:1). To fully test the efficacy and potential environmental impacts of blended topsoils containing SFS and compost in the natural environment, we plan to conduct multi-year and multi-location experiments in the field. However this short-term greenhouse study indicates the use of SFS in manufactured soils is a viable beneficial reuse strategy that could potentially be employed to reduce the volume of SFS sent to landfills.

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