Effect of Compost-, Sand-, or Gypsum-amended Waste Foundry Sands on Turfgrass Yield and Nutrient Content

J. P. de Koff* USDA-ARS
B. D. Lee University of Kentucky
R. S. Dungan USDA-ARS
J. B. Santini Purdue University

To prevent the 7 to 11 million metric tons of waste foundry sand (WFS) produced annually in the USA from entering landfills, current research is focused on the reuse of WFSs as soil amendments. The effects of different WFS-containing amendments on turfgrass growth and nutrient content were tested by planting perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Schedonorus phoenix* (Scop.) Holub) in different blends containing WFS. Blends of WFS were created with compost or acid-washed sand (AWS) at varying percent by volume with WFS or by amendment with gypsum (9.6 g gypsum kg^{-1} WFS). Measurements of soil strength, shoot and root dry weight, plant surface coverage, and micronutrients (Al, Fe, Mn, Cu, Zn, B, Na) and macronutrients (N, P, K, S, Ca, Mg) were performed for each blend and compared with pure WFS and with a commercial potting media control. Results showed that strength was not a factor for any of the parameters studied, but the K/Na base saturation ratio of WFS:compost mixes was highly correlated with total shoot dry weight for perennial ryegrass ($r = 0.995$) and tall fescue ($r = 0.94$). This was further substantiated because total shoot dry weight was also correlated with shoot K/Na concentration of perennial ryegrass ($r = 0.99$) and tall fescue ($r = 0.95$). A compost blend containing 40% WFS was determined to be the optimal amendment for the reuse of WFS because it incorporated the greatest possible amount of WFS without major reduction in turfgrass growth.

Waste foundry sands (WFSs) are used by the foundry industry to create the molds that cast metal products. Waste foundry sands vary depending on the type of metal cast and the type and proportion of bonding mixture used for creating the molds. In general, foundry sands contain medium or fine sand (85–95%), seacoal (2–10%), water (2–5%), and a binding agent. The binding agents used are usually bentonite clay (4–10%) or organic chemical binders (0.1–2.3%). Sands containing clay binders are referred to as "green" sands, and those using chemical binders are called "core" sands. The clay and chemical binders are used to maintain the strength of the mold during casting, and the seacoal is used to produce a reducing atmosphere and improve the metal finish (Winkler and Bol'shakov, 2000).

Waste foundry sands are disposed in landfills at a rate of 7 to 11 million metric tons per year (Lindsay and Logan, 2005) and a cost of $100 to 250 million annually (ICMA, 2008). Studies undertaken to assess the toxicity of WFS from heavy metal leaching (Ham et al., 1993; Ji et al., 2001) or plant uptake (Logan and Lindsay, 2001) have found no evidence to suggest any potential environmental or health issues. Most of this waste (up to 98%) is considered nonhazardous by the USEPA (USEPA, 2002). These results suggest their great potential for reuse in other applications.

Over 900,000 metric tons of sand are annually reused in geotechnical applications like structural fill material and as an additive to concrete and asphalt (U.S. DOT, 2003). Others have suggested the reuse of WFSs in agricultural applications as a soil amendment or manufactured soil (Jing and Barns, 1993). Land application of WFSs to amend clayey soils is unlikely due to the clay present in WFS (~4–10% bentonite) as well as the high threshold (addition of around 50% of the soil volume) that would have to be overcome to create a sandier soil (Baker, 1990; Kline, 1991; Bullock and Hassett, 1998). The use of WFS in manufactured soils is one possible option because these soils are created by blending different mineral and organic components, including sand, clay, peat, and compost, to create specified properties for a specified purpose (Koolen and

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*Corresponding author (jdekoff@uark.edu).
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677 S. Segoe Rd., Madison, WI 53711 USA

J.P. de Koff, USDA-ARS, Poultry Production and Product Safety Research Unit, Fayetteville, AR 72704. B.D. Lee, Plant and Soil Sciences Dep., Univ. of Kentucky, Lexington, KY 40546. R.S. Dungan, USDA-ARS, Northwest Irrigation and Soils Research Lab., Kimberly, ID 83341. J.B. Santini, Agronomy Dep., Purdue Univ., West Lafayette, IN 47906.

Abbreviations: AWS, acid-washed sand; DI, deionized; EC, electrical conductivity; ECEC, effective cation exchange capacity; ICP, inductively coupled plasma; WFS, waste foundry sand.

Rossignol, 1998). Initial attempts at blending WFS with organic matter have achieved some success. McCoy (1998) observed that a blend containing 65% WFS and 8% organic matter, in the form of peat (by weight), would produce a good soil for lawn establishment based on turf clipping yields.

Recent studies of the physical properties of WFSs have described high variability, with some exhibiting low saturated hydraulic conductivity (Dungan et al., 2007) and high strength values (de Koff et al., 2008) due to the presence of sodium bentonite. Because these characteristics can adversely affect root and shoot growth, more information is required that specifically looks at plant growth with this type of WFS, using suggested amelioration procedures, to better understand the potential of using this waste product as a soil amendment. Both adverse physical effects are caused by sodium bentonite present in WFSs, and a proposed process to ameliorate them is the addition of gypsum (de Koff et al., 2008) or organic matter. The purpose of adding gypsum is to exchange the dispersive sodium cation on the clay for the more flocculating calcium cation. The addition of organic matter is considered beneficial for reducing soil strength in compacted and hardsetting soils (Kubota and Williams, 1967; Harper and Gilkes, 1994). Hardsetting soils are defined by their dispersive nature when moistened and high soil strength when dry (Mullins et al., 1987; 1990). With hardsetting soils, the organic matter helps to weaken clay bridges that form between particles; clay bridges have also been observed in high-strength WFSs (Harper and Gilkes, 1994; de Koff et al., 2008).

Given the variability of WFS properties such as strength, more information is required that specifically looks at plant growth with high-strength WFS, using suggested amelioration procedures, to better understand the potential of this waste product as a soil amendment. This study focused largely on assessing the impacts of different WFS-amending techniques on turfgrass growth and nutrient content using a known high-strength WFS (WFS #6 from de Koff et al., 2008) as a soil amendment. Blends with WFS were produced using compost to find the one that could reuse the most WFS with few negative impacts on plant growth. Blends with acid-washed sand (AWS) were used in lieu of compost for comparison. The previously proposed rate of gypsum amendment was also tested to further substantiate its beneficial effects on plant growth.

Materials and Methods

Material Collection

The WFS used in this study was collected from the waste stream of an iron foundry. In producing its green sands, the foundry used sodium bentonite and organic chemical binders to bind the sands together and create molds (de Koff et al., 2008). The waste stream at this facility was a combination of green and core sands, which were homogenized in a mixer and moistened with water to reduce dust exposure. The material was collected in 20-L containers and air dried for 2 to 3 d. This material was sieved to <2 mm particle size and used for all analyses.

The compost was collected from a local composting facility that composted horse bedding with leaves and grass at a ratio of 80:20 (v/v), respectively. The organic material was composted in windrows that were turned once each month for a total of approximately 12 mo. After 1 yr, the compost was sieved to a 127-mm particle size. The compost was collected in 20-L containers and stored at room temperature 3 d before it was used for planting in the greenhouse.

The AWS was prepared using commercial play sand (River Run Products Corp., Custer, WI). About 400 mL of the sand was placed in a 1-L glass jar. The sand was saturated with 1.2 mol L^{-1} HCl (10% HCl), the screw-cap lid was replaced, and the jar was shaken by hand. The lid was unscrewed to release any built-up gas pressure, and the jar was re-closed and shaken again. This was repeated until no more gas release was necessary. The saturated sands were then allowed to stand in the sealed jars for 1 h at room temperature. After standing, deionized (DI) water was added to fill the remainder of the jar, the jar was shaken by hand, and the supernatant was poured out. This was repeated until the supernatant was transparent. The sand was transferred to 1-L beakers and dried in an oven at 40°C for about 2 d. Once dry, the sand was stored in a 20-L container at room temperature until use. After washing, the sands contained an average of 0.25% very coarse sand (particle size, >1.0 mm diameter), 1.9% coarse sand (particle size, 0.50–1.0 mm diameter), 44.7% medium sand (particle size, 0.25–0.50 mm diameter), 51.5% fine sand (particle size, 0.11–0.25 mm diameter), and 1.62% very fine sand (particle size, 0.053–0.11 mm diameter), as determined from sieving five different samples.

Greenhouse

Potting mixes were formed on a volume basis from density measurements of each starting material (moist compost, dry WFS, and dry AWS). Waste foundry sand was added to the moist compost or to the moistened acid-washed sand at a volume ratio of 0, 20, 40, 60, 65, 70, 80, and 100% of the total volume. An alternative mix containing 9.6 g gypsum kg^{-1} WFS (powdered gypsum, ACS grade 98–102%; EMD Chemicals, Inc., San Diego, CA) was also used to reduce strength in the WFS as suggested by de Koff et al. (2008). Each component was weighed and mixed on a per pot basis into 10-cm-diameter pots with four replicate pots per mixed sample. A commercial potting media was used as a control (Metro-Mix 200; Sun Gro Horticulture, Vancouver, BC, Canada). Individual mixes representing the four replicates of each treatment (17 blends including the control) were also produced for pH, electrical conductivity (EC), and nutrient analyses.

The procedure used in this greenhouse study was similar to that used by McCoy (1998) for perennial ryegrass (*Lolium perenne* L. cv. Pennlawn) growth in WFS:peat mixes. Filled pots were placed in a greenhouse set at 18°C under ambient light conditions (10–13 h daylight). Perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Schedonorus phoenix* (Scop.) Holub) seeds were planted at a rate of 30 g m^{-2} in the moistened media. The pots were watered as needed (about every 2 d) with DI water and fertilized once a week at a rate of 0.69 g m^{-2} wk^{-1} (6.9 kg ha^{-1}) N and 0.096 g m^{-2} wk^{-1} (0.96 kg ha^{-1}) P using a solution containing 7.5 mmol L^{-1} ammonium nitrate (NH_4NO_3) and 1.0 mmol L^{-1} ammonium dihydrogen phosphate ($NH_4H_2PO_4$).

Only these nutrients were supplied to prevent the replacement of exchangeable sodium by added cation fertilizers.

At around 32 d after seedling emergence, the grasses in each pot were cut to 2.5 cm height. The cuttings were dried at 65°C for 2 to 3 d, cooled under drierite, and weighed. Additional cuttings were taken every 14 d after the first cutting for a total of two additional cuttings. These cuttings were treated in the same manner as described above. Fertilizer additions occurred 4 d before each cutting.

After the last cutting, the grasses were allowed to grow for 14 d, and canopy density was determined using digital images. Digital images of each pot were taken using a Nikon Coolpix L4 camera mounted on top of a lightbox. The lightbox was constructed out of a 40-cm-diameter polyvinylchloride tub that contained two 60 W inflorescent bulbs. The distance between the camera lens and the top of the pot was kept constant at 30.5 cm.

Canopy density was determined using SigmaScan Pro 5.0 software (SPSS, Inc., Chicago, IL) on JPEG images (1600 × 1200 pixels). Hue and saturation ranges of 60 to 100 and 27 to 100, respectively, were used to identify green pixels, representing green tissue in each pot. These areas were quantified by pixel counts that were then divided by the total pot area defined by the program to provide percent coverage values.

After the digital images were taken, the grasses were removed from the pots, and a portion of the soil was saved for pH, EC, and nutrient analyses. The upper 4-cm section of roots was harvested and washed with water to remove excess potting media, dried in an oven at 65°C for 72 h, cooled under drierite, and weighed.

Chemical Analyses

Due to the low yield, cuttings and replicates of shoot dry matter were pooled for each treatment (17 treatments including control for each turfgrass species) for chemical analyses. To best identify any evidence of nutrient deficiencies, the cuttings pooled were the second and third cutting (containing four replicates each) as well as a final cutting of the total aboveground biomass taken 2 wk after the third cutting (containing three replicates). Pooling was done so that each cutting group contained the same weight of material. Pooled shoot dry matter and individual root replicates were analyzed for total nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), sodium (Na), aluminum (Al), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and boron (B). Total N was analyzed by a dry oxidation procedure called the Dumas method (Bremner, 1996). Total shoot and root nutrients were determined by inductively coupled plasma (ICP) (Thermo Scientific, Waltham, MA) analysis of extracts from an open microwave extraction using hot hydrogen peroxide and nitric and hydrochloric acids (Amacher, 1996).

The pre-plant and post-plant soil mixes were analyzed for pH, EC, organic matter content, available P, exchangeable K, Na, Ca, and Mg, and extractable nitrate-nitrogen (NO_3–N) and ammonium-nitrogen (NH_4–N). The pH and EC analyses were performed on 1:1 (soil:water) and 1:2 (soil:water) slurry samples, respectively (Rhoades, 1996; Thomas, 1996). Organic matter content was determined by weight loss after heating the sample to 360°C for 2 h (Nelson and Sommers, 1996). Available P was analyzed by ICP (Thermo Scientific) on a Mehlich III extract (Mehlich, 1984). Exchangeable K, Na, Ca, and Mg were analyzed by ICP on a 1 mol L^{-1} ammonium acetate extract (Thomas, 1982). Extractable NO_3–N and NH_4–N were determined by flow injection analysis (Lachat Instruments, Loveland, CO) on a 1 mol L^{-1} KCl extract (Mulvaney, 1996). The effective cation exchange capacity (ECEC) was calculated by summation of the base cations (Sumner and Miller, 1996).

Strength Test Analysis

Mixtures identical to those used in the greenhouse pots were constructed for strength tests. A separate mixture was constructed for each of the three strength test replicates for each potting mixture.

Values for soil strength were determined by testing the strength to rupture for the potting mixture using an adapted form of the modulus of rupture technique (Cochrane and Aylmore, 1992) used by Franzmeier et al. (1996). Discs for this test were produced by pouring each air-dried potting mixture into six 2-cm-diameter holes in a 1-cm-thick plastic plate. The samples were moistened with DI water by capillarity for ~2 h and dried in an oven at 40°C for ~48 h. Upon drying, the discs (six per replicate) were cooled in a desiccator for 30 min, removed from the plates, and ruptured using Wagner Force Dial FDK 20 and FDK 40 force gauges (Wagner Instruments, Greenwich, CT), which were able to measure forces between 1.0 and 20.0 kg. This was converted to a detection range of 0.3 to 6.9 MPa.

Statistical Analyses

The SAS GLM procedure (SAS Institute, 2004) was used for all analyses. The greenhouse experiment was conducted as a randomized, complete-block design. Each turfgrass species was analyzed separately. Transformations were made as needed to achieve homogeneity of error variances. At the end of the experiment, after the final harvest, the percent surface cover, root, and potting material were lost for one perennial ryegrass and three tall fescue experimental units, and estimates were computed by covariance analysis. The estimates were included in the analysis of variance (and regressions) to restore balance, and error variances were adjusted for the estimates before testing. Fisher's protected LSD was used for comparing means. All statistical tests were performed on transformed data. Values in text, figures, and tables are observed values unless otherwise stated.

Regressions were performed on treatment means to quantify relationships between selected measured response parameters and between response parameters and percent WFS blend content. Regression coefficients between blends within a crop were tested for differences.

At harvest, there was insufficient plant shoot material collected to preserve individual replicates for chemical analysis, so shoot material was pooled across the replicates. Chemical analyses were conducted only on two subsamples of this pooled material wherever possible. Linear regression was performed to elicit possible trends.

Results and Discussion

Analysis of Pre-plant Blends

Selected physical and chemical characteristics of the initial mixes are presented in Tables 1 and 2, respectively. The strength

Table 1. **Physical strength properties of pre-plant blends. The LSD value (P = 0.05) is for comparing those means not below detection limits.**

Mix	WFS	Strength
	% (by vol.)	MPa
Compost	0	<0.35
	20	<0.35
	40	<0.35
	60	0.4§
	65	0.5§
	70	0.5
	80	1.5
AWS†	0	<0.35
	20	<0.35
	40	<0.35
	60	0.6§
	65	0.7
	70	0.9
	80	1.5
WFS‡	100	3.0
Gypsum		0.35§
Control¶		<0.35
LSD (P = 0.05)		0.4

† Acid-washed sand.

‡ Waste foundry sand.

§ Estimate of highest probable strength value as some subsamples were below detection limits (<0.35) and estimated as 0.34.

¶ Control was a commercial potting medium.

to rupture of the mixes ranged from <0.35 to 3.0 MPa and increased numerically with increased proportions of WFS. This was expected based on previous analyses of high-strength properties of WFS that contained sodium bentonite (de Koff et al., 2008). The mixes that contained compost or AWS had strength values significantly lower than the pure WFS, and the 0 to 70% WFS blends were significantly lower than values (≥1.4 MPa) normally associated with adverse plant growth (Lipiec and Hakansson, 2000; Nabi et al., 2001). There was no difference in strength observed, however, between the two mixes at the same blending ratio, which indicated that both may have presented similar physical obstacles to clay bridge formation. The gypsum blend had a strength value numerically similar to blends containing 0 to 40% WFS but was not significantly different from those containing 60 to 70% WFS. The addition of gypsum caused a reduction in strength as Na^+ on the clay exchange sites was replaced by Ca^{2+} (U.S. Salinity Laboratory Staff, 1954). The Na^+ base saturation (i.e., the percentage of the CEC or ECEC that is bound to a particular cation) of the gypsum mix was lower, and the Ca^{2+} base saturation higher, than for the pure WFS (Table 2).

As the proportion of compost increased in the mixes, the EC, nutrient content (specifically PO_4–P, NO_3–N, and K^+ base saturation), and ECEC generally increased (Table 2). Composts are known to contain pools of soluble nutrients and salts (López-Real et al., 1989) and high CEC due to the proportion of oxygen-containing functional groups (Brewer and Sullivan, 2003).

As the proportion of WFS in the mixes increased, pH, NH_4–N content, and percent Na^+ base saturation also generally increased. The WFS was known to contain bentonite with Na^+ present on the exchange sites. Most likely, there was also ammonium present on these sites, though not to the extent of sodium. The higher pH in WFS could be caused by carbonates that were probably present because charcoal is used in the foundry process.

At planting, the mixes that contained AWS, pure WFS, and WFS:gypsum were potentially nutrient deficient in N, P, and K (McCarty et al., 2003). These deficiencies may not have significantly affected the turfgrass growth, however, because N and P were added weekly and the establishment of turfgrass is not usually dependent on K (Heydari and Balestra, 2008). The pH of all mixes, except pure AWS and the control, were significantly greater than the typical range (5.5–7.0) associated with optimal nutritional availability (Emmons, 2000).

At the termination of the study, decreases in NO_3–N (WFS:compost and control), NH_4–N, %K base saturation, and %Na base saturation were observed in the blends (Suppl. Table 1). This pattern was relatively the same for both grass species. During the growth experiment, the EC, nitrate, and ammonium levels decreased, specifically for the WFS:compost mixes and control, which was probably caused by root uptake or leaching of excess soluble nutrients not bound to exchange sites. The loss of K and Na indicated that these nutrients may have been used preferentially by the grasses during growth. Due to a concentration effect, the losses of K and Na contributed to the increase in percent Ca saturation observed for WFS:AWS and WFS:compost mixes.

Analysis of Plant Tissue

Shoot tissue of perennial ryegrass and tall fescue showed nutrient deficiencies for N, K, Ca, and S (Suppl. Table S). The threshold values for various nutrient deficiencies were based on general sufficiency ranges for turfgrass from Jones (1980). Nitrogen deficiencies (<28 g N kg^{-1} dry matter) occurred for shoot dry matter of all blends except the 0, 20 and 40% WFS:compost blends seeded with tall fescue, and 0 and 40% WFS:compost blends seeded with perennial ryegrass. Potassium deficiency (<10 g K kg^{-1} dry matter) occurred in perennial ryegrass for the 0% WFS:AWS blend. Calcium deficiencies (<5 g Ca kg^{-1} dry matter) occurred in perennial ryegrass for the 0 to 40% WFS:compost, 100% WFS, and control blends and in tall fescue for the 20 to 80% WFS:compost, 60 to 80% WFS:AWS, 100% WFS, and control blends. Sulfur deficiencies (<2 g S kg^{-1} dry matter) occurred in both turfgrasses for the 0 to 20% WFS:AWS blends. No micronutrient deficiencies in shoot dry matter were observed (Suppl. Table 3).

Overall, P and K, and in some cases N, were greater in the shoot (Suppl. Table 2) and root (Suppl. Tables 4 and 5) matter grown in WFS:compost blends than in WFS:AWS blends. This was most likely the result of the greater amounts observed in the pre-plant compost blends. Also, as with the pre-plant blends, as the proportion of WFS in the blends increased, the concentration of Na present in the shoot dry matter increased. The micronutrient contents of the roots were numerically greater than those for the shoots, although some variability, notably for Mn and B, was observed (Suppl. Tables 6 and 7). The greater micronutrient content in the roots was most likely caused by the additional polyvalent micronutrients attached to the outer root by cation exchange capacity (Hope and Stevens, 1952; Marschner, 2003) that were prevented from entering the plant.

Table 2. Chemical characteristics of pre-plant blends. Data are average values from four replicates, with values in parentheses representing the transformed mean. LSDs (P = 0.05) are for comparison of means or transformed means (if present).

Mix	WFS	pH†	EC†	OM‡	PO_4–P§	NO_3–N¶	NH_4–N¶	ECEC#	Ca††	Mg††	K††	Na††
	% (by vol.)		dS m^{-1}	%	mg kg^{-1}			cmol$_c$ kg^{-1}	% base saturation			
Compost	0	8.2	1.7	19.7	368 (19.18)	41.5 (1.62)	6.0	36.0	63.6	15.2 (3.90)	18.0	3.3 (1.80)
	20	8.4	1.4	8.6	265 (16.25)	31.0 (1.49)	6.0	27.5	59.8	16.1 (4.01)	18.1	6.0 (2.44)
	40	8.5	1.1	5.2	197 (14.02)	21.3 (1.33)	8.3	23.6	60.7	15.7 (3.97)	14.9	8.7 (2.95)
	60	8.7	1.0	2.3	97 (9.82)	11.5 (1.06)	12.3	16.6	59.2	15.4 (3.93)	11.8	13.6 (3.69)
	65	8.8	0.9	2.5	88 (9.33)	8.3 (0.91)	13.5	16.0	59.4	15.4 (3.92)	10.8	14.4 (3.79)
	70	8.8	0.8	1.8	71 (8.39)	8.0 (0.90)	14.3	14.6	58.2	15.5 (3.94)	9.9	16.5 (4.06)
	80	8.8	0.8	1.5	45 (6.68)	5.5 (0.73)	15.3	12.7	56.6	15.8 (3.97)	7.4	20.3 (4.50)
AWS‡‡	0	6.3	0.1	0.1	12 (3.39)	2.0 (0.30)	4.0	1.2	55.2	40.4 (6.35)	2.1	2.3 (1.50)
	20	8.2	0.2	0.3	10 (3.16)	2.0 (0.30)	6.5	2.5	52.0	26.9 (5.18)	2.2	18.9 (4.35)
	40	8.9	0.3	0.3	8.5 (2.91)	2.5 (0.39)	9.0	4.3	50.7	22.0 (4.69)	2.3	25.0 (5.00)
	60	9.0	0.4	0.3	8.3 (2.87)	2.0 (0.30)	10.5	5.4	50.9	20.1 (4.48)	2.3	26.8 (5.18)
	65	9.1	0.4	0.4	7.8 (2.78)	2.3 (0.35)	11.0	5.9	50.2	19.8 (4.44)	2.3	27.8 (5.27)
	70	9.0	0.5	0.5	7.3 (2.69)	2.8 (0.42)	12.8	6.2	50.7	19.4 (4.41)	2.3	27.6 (5.25)
	80	9.1	0.6	0.7	6.3 (2.50)	2.0 (0.30)	14.0	7.0	49.8	18.4 (4.29)	2.4	29.4 (5.42)
WFS§§	100	9.1	0.6	0.8	5.0 (2.24)	2.8 (0.43)	17.0	9.2	50.5	16.9 (4.11)	2.4	30.1 (5.49)
Gypsum		8.2	2.4	0.7	4.3 (2.06)	2.8 (0.43)	21.0	16.3	72.4	9.3 (3.05)	1.4	16.9 (4.11)
Control¶¶		6.6	0.6	13.8	48 (6.85)	110.5 (2.04)	6.0	9.7	29.0	50.1 (7.08)	4.7	3.9 (1.97)
LSD (P = 0.05)		0.1	0.2	1.4	– (0.87)	– (0.10)	1.3	1.4	2.3	– (0.15)	0.4	– (0.13)

† pH and EC measured from 1:1 (soil:water) and 1:2 (soil:water) slurries, respectively.

‡ Determined from weight loss after 2 h at 360°C.

§ Determined from Mehlich III extract.

¶ Determined from 1 mol L^{-1} potassium chloride extract.

Determined from base cation summation.

†† Determined from 1 mol L^{-1} ammonium acetate extract.

‡‡ Acid-washed sand.

§§ Waste foundry sand.

¶¶ Control was a commercial potting medium.

Correlations between shoot and root nutrients for all blends and turfgrasses were observed for P (r = 0.85; Suppl. Fig. 1) and K (r = 0.93; Suppl. Fig. 2). The graph for the K correlation can be identified as made up of three distinct clusters. The lower cluster, that contained the lowest overall K in roots and shoots, corresponded to all WFS:AWS and WFS:gypsum blends. The middle cluster was made up of compost blends containing 60 to 80% WFS, pure WFS, and the commercial potting media control. The highest cluster, made up of six points, had the greatest levels of K in the root and shoot matter and corresponded to compost blends that contained 0 to 40% WFS.

Shoot Growth

The overall shoot growth for the two turfgrass species (Suppl. Fig 3) was highly correlated (r = 0.95); therefore, some data presented reflect only one species, perennial ryegrass. The first cutting yielded, numerically, the greatest amount of biomass for both species: 40 to 349 mg for perennial ryegrass and 38 to 329 mg for tall fescue. This cutting encompassed 1 mo of growth, and the second and third cuttings represented 2 wk each (Table 3). The average growth rate for most mixes was significantly greater during the first two cuttings and decreased by the third (final) cut. This reduction most likely indicated that the grasses were close to an equilibrium growth rate after the second cutting because it occurred for almost all pots regardless of mix or species.

Regression analyses of total shoot dry weight on %WFS determined that there were different quadratic, linear, and intercept parameters associated with the two blending ingredients for each turfgrass species (Fig. 1a, 1b). Overall, when compared with the commercial potting media control, the mixes became similar to the control growth by the third cutting, with compost mixes containing 0 to 40% WFS exhibiting the greatest average growth (42–53 mg or 109–141% of the control for perennial ryegrass and 37–39 mg or 83–93% of the control for tall fescue) (Fig. 1a, 1b; Table 3). The mixes that had greater shoot biomass accumulation during the third cut also had significantly greater shoot biomass than the pure WFS during most of the experiment. These data indicate that the 0 to 40% WFS:compost mixes are the best blends to use for plant growth, with 40% WFS:compost as the best blend because it reuses the greatest amount of WFS.

There was no correlation between shoot dry weight and strength, indicating that strength was not a factor in this study. Instead, correlations were observed between shoot dry matter and the nutrient content of initial blends and between shoot dry matter and shoot nutrient concentrations for the same blends. Total shoot dry weight and the level of soluble nitrate present in the pre-plant WFS:compost and control blends were highly correlated for both species (r = 0.97 for perennial ryegrass, r = 0.99 for tall fescue) (Suppl. Fig. 4). Compost generally contains a large pool of plant-available and slow-release nutrients (López-Real et al., 1989; Tilman et al., 2002) that

Table 3. **Shoot and root dry weight and surface coverage (%) measurements for blends with WFS. Data are average values from four replicates, with values in parentheses representing the transformed mean. LSDs ($P = 0.05$) are for comparison of means or transformed means (if present) within grass type.**

Grass type	Mix	WFS	First cutting	Second cutting	Third cutting	Root weight	Surface coverage
		% (vol.)		mg		g	%
Perennial ryegrass	compost	0	201 (2.30)	105 (2.01)	42 (1.61)	0.90	47.8
		20	152 (2.18)	71 (1.84)	42 (1.61)	0.88	46.8
		40	110 (2.04)	67 (1.82)	53 (1.71)	0.93	52.2
		60	88 (1.95)	52 (1.69)	34 (1.49)	1.05	53.3
		65	99 (1.98)	51 (1.70)	33 (1.49)	1.04	52.3
		70	106 (2.01)	48 (1.67)	29 (1.45)	0.94	48.4
		80	89 (1.94)	45 (1.65)	32 (1.50)	0.89	51.6
	AWS†	0	40 (1.59)	13 (1.10)	5 (0.62)	0.57‡	4.2‡
		20	116 (2.06)	51 (1.69)	19 (1.24)	0.79	27.6
		40	113 (2.04)	34 (1.50)	20 (1.23)	0.99	41.4
		60	118 (2.07)	46 (1.66)	26 (1.40)	0.87	41.7
		65	95 (1.97)	40 (1.59)	29 (1.46)	0.86	50.6
		70	101 (1.99)	44 (1.64)	26 (1.40)	0.87	48.9
		80	114 (2.05)	49 (1.68)	30 (1.48)	0.83	52.0
	WFS§	100	106 (2.01)	37 (1.53)	23 (1.28)	0.70	45.8
	gypsum		107 (2.01)	44 (1.64)	24 (1.37)	0.73	39.1
	control¶		349 (2.53)	108 (2.03)	38 (1.58)	1.73	57.3
	LSD ($P = 0.05$)		– (0.13)	– (0.13)	– (0.23)	0.28	13.8
Tall fescue	compost	0	139 (2.12)	75 (1.85)	37 (1.48)	0.70	31.5
		20	121 (2.08)	61 (1.76)	38 (1.57)	0.86‡	45.7‡
		40	74 (1.86)	65 (1.81)	39 (1.58)	0.75	50.0
		60	110 (2.04)	44 (1.63)	25 (1.38)	0.77‡	49.1‡
		65	94 (1.94)	48 (1.65)	28 (1.41)	0.68	40.0
		70	87 (1.92)	57 (1.73)	32 (1.48)	0.82	50.5
		80	71 (1.84)	39 (1.59)	26 (1.41)	0.74	52.2
	AWS	0	38 (1.56)	22 (1.31)	8 (0.90)	0.43‡	1.9‡
		20	90 (1.91)	33 (1.48)	23 (1.28)	0.58	28.0
		40	97 (1.98)	29 (1.46)	17 (1.21)	0.76	32.0
		60	93 (1.95)	41 (1.61)	19 (1.27)	0.71	39.6
		65	103 (1.99)	47 (1.66)	23 (1.35)	0.72	42.9
		70	110 (2.04)	40 (1.60)	21 (1.32)	0.78	47.0
		80	102 (2.01)	44 (1.64)	20 (1.28)	0.76	48.1
	WFS	100	84 (1.91)	47 (1.64)	17 (1.21)	0.71	38.8
	gypsum		71 (1.79)	40 (1.59)	15 (1.14)	0.63	35.6
	control		329 (2.52)	110 (2.03)	42 (1.62)	1.14	53.8
	LSD ($P = 0.05$)		– (0.20)	– (0.18)	– (0.21)	0.14	11.3

† Acid-washed sand.

‡ Average of four values, which includes one estimate determined by covariance.

§ Waste foundry sand.

¶ Control was a commercial potting medium.

can improve the overall growth of turfgrasses (Loschinkohl and Boehm, 2001). Chen (1997) also observed a high correlation ($r = 0.996$) between the N derived from composts and perennial ryegrass yields in a greenhouse study, while Sikora et al. (1980) observed an increase in tall fescue growth due to compost-supplied N. There was no correlation, however, between shoot N concentration of turfgrasses grown in the previously mentioned blends and total shoot growth. This indicates that N may not have been the determining factor of shoot growth in this study.

In addition to nitrate levels, the base saturation of K relative to Na (K/Na) was also highly correlated with total shoot dry weight in perennial ryegrass ($r = 0.995$) and tall fescue ($r = 0.94$) for mixes containing compost (Suppl. Fig. 5). Mixes with K/Na ratios above 1 (0–40% WFS) were the same mixes that had yields significantly greater than pure WFS. Correlations were also observed between total shoot dry weight and the K/Na concentration in the shoot dry matter (Suppl. Fig. 6) and between the K/Na concentration in the shoot dry matter and WFS:compost blends (Suppl. Fig. 7). This is a direct indication that the K/Na ratio was a major contributing factor involved in shoot growth. In some cases, Na is believed to promote greater shoot growth in plants. This shoot growth, however, is mainly caused by cell expansion from an increase in turgor pressure (Jeschke, 1977; Nunes et al., 1984). When measuring dry weight, as was done in this study, turgor pressure and cell expansion should not factor into overall shoot weight. Helal and Mengel (1979) observed a reduction in shoot dry weight and protein synthesis under treatments with Na that were allevi-

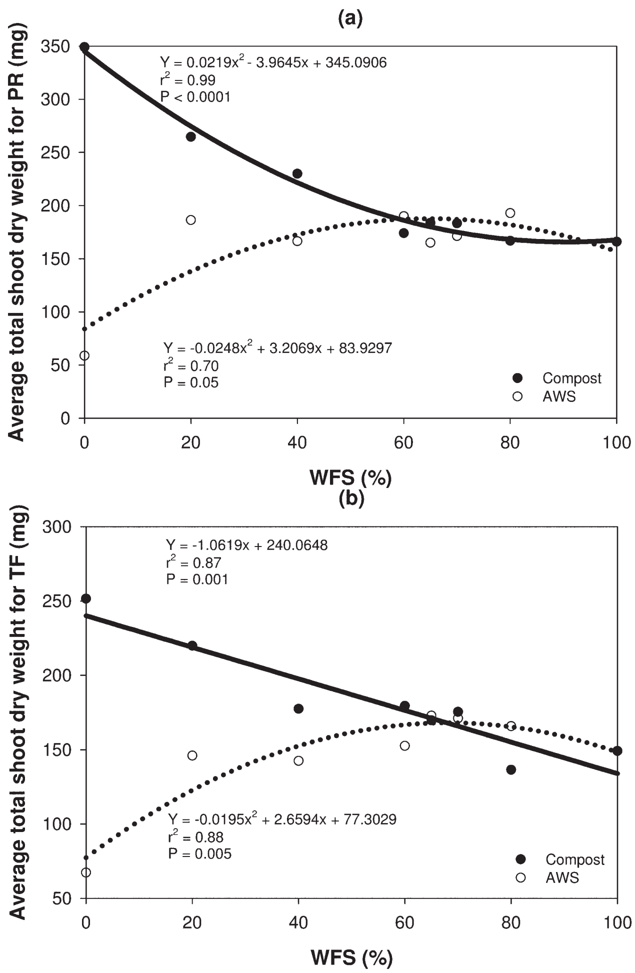

Fig. 1. Relationship between average total shoot dry weight per treatment pot after 60 d and % waste foundry sand (WFS) blends containing either compost or acid-washed sand (AWS) and grown with (a) perennial ryegrass (PR) or (b) tall fescue (TF).

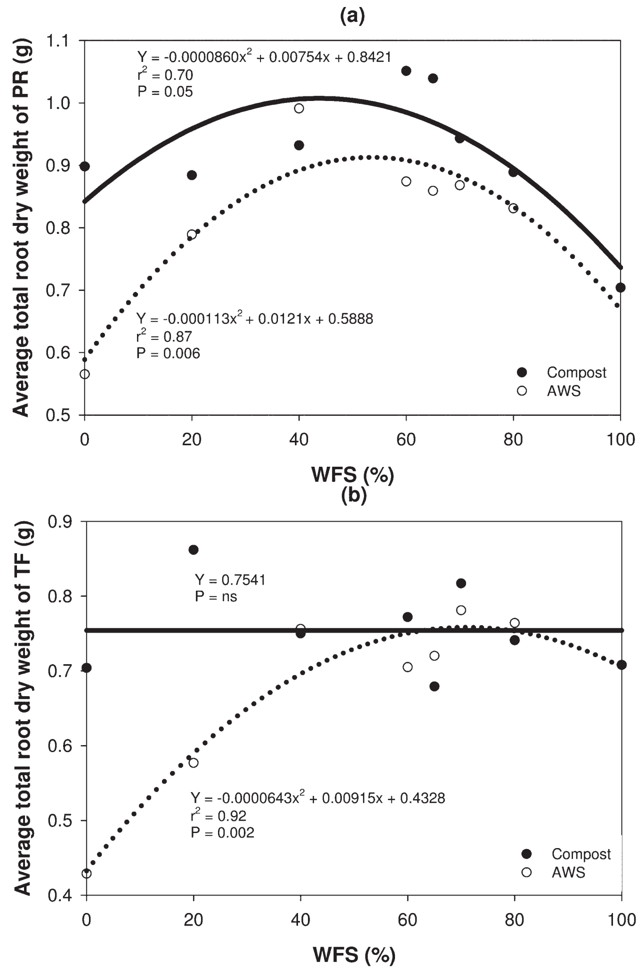

Fig. 2. Relationship between average total root dry weight per treatment pot after 60 d and % waste foundry sand (WFS) blends containing compost or acid-washed sand (AWS) and grown with (a) perennial ryegrass (PR) or (b) tall fescue (TF). Four means (1 PR, 3 TF) contained an estimate determined by covariance.

ated when K was added. This may have occurred in the current study because more K than Na was available for plant uptake in blends containing greater proportions of compost, thereby contributing to the greater observed shoot growth.

This experiment indicated that a mix containing 40% WFS and 60% compost (by volume) would allow for the reuse of the most WFS and produce greater levels of turfgrass growth than blends containing greater amounts of WFS (Fig. 1a, 1b; Table 3). At this proportion, shoot dry weight was significantly greater than pure WFS for the second and third cutting and was not significantly different from the control by the third cutting. Other studies observed similar results using different potting media. In sludge compost/soil mixes, Hua et al. (2008) observed the greatest growth rates for fescue and ryegrass at ≤40% and ≤60% compost, respectively. A study blending WFS with peat found that a mix containing 65% WFS and 35% peat (by weight) produced the best yield results for perennial ryegrass (McCoy, 1998). This is similar to the results of this study because the 40% WFS:compost blend contained 52% WFS by weight.

Root Growth

Root dry weight ranged from 0.57 to 1.73 g for mixes grown with perennial ryegrass and 0.43 to 1.14 g for mixes grown with tall fescue (Table 3). These values ranged from 0.43 to 0.99 g for mixes containing AWS and from 0.68 to 1.05 g for those containing compost. The correlation of root dry weight between perennial ryegrass and tall fescue (Suppl. Fig. 8) was less than the correlation for shoot dry weight (Suppl. Fig. 3). For both grasses, regression analyses comparing compost blends with sand blends produced regression equations with different intercept parameters. Based on regression analyses, root dry weight reached a maximum between 40 and 60% WFSs for perennial ryegrass in both the compost and sand blends (Fig. 2a). For tall fescue, the regression for compost blends was not significant, and root growth reached a maximum between 60 and 80% WFS for sand blends (Fig. 2b). There was no evident trend with respect to strength, indicating that it was not a factor in root growth in this experiment. There was also no correlation between root growth and initial nutrient content of the mixes. All blends had root dry weights that were significantly lower than the control. Others

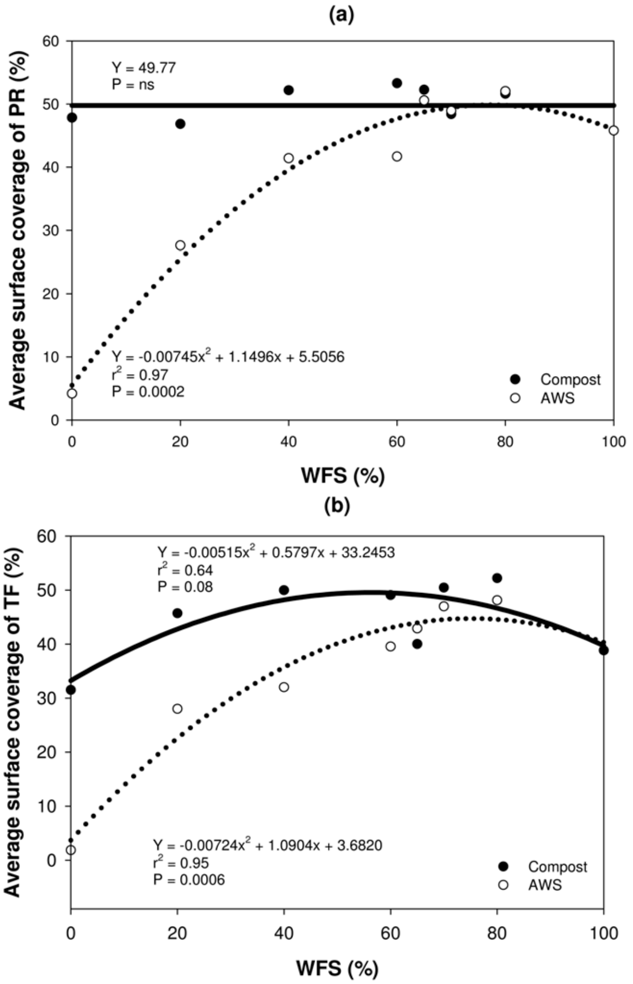

Fig. 3. Relationship between surface coverage, after third cutting and 14 d of regrowth, and % waste foundry sand (WFS) blends containing compost or acid-washed sand (AWS) and grown with (a) perennial ryegrass (PR) or (b) tall fescue (TF). Four means (1 PR, 3 TF) contained an estimate determined by covariance.

observed significant relationships for shoot dry weight and soil nutrients but none for root dry weight (Shimozono et al., 2008).

Surface Coverage

At the end of the experiment, surface coverage of mixes grown with perennial ryegrass and tall fescue ranged from 4.2 to 57.3% and 1.9 and 53.8%, respectively (Table 3). These values ranged from 31.5 to 53.3% for mixes containing compost and from 1.9 to 50.6% for those containing AWS. The average surface coverage between the turfgrass species was relatively well correlated (r = 0.93) (Suppl. Fig. 9). The regression analyses, comparing blending ingredients for both turfgrasses individually, determined different quadratic, linear, and intercept parameters for perennial ryegrass and different linear and intercept parameters for tall fescue (Fig. 3a, 3b). Based on regression, there was no change in surface coverage with increasing %WFS for perennial ryegrass grown in WFS:compost blends, but the WFS:sand blends reached maximum surface coverage at 70 to 80% (Fig. 3a). For tall fescue, surface coverage reached maxima at 40 to 60% WFS and 70 to 80% WFS for blends with compost or sand, respectively (Fig. 3b). Most of these individual mixes, however, were not different from the pure WFS and the control (Fig. 3a, 3b). Others observed higher surface coverage in potting media containing composts as compared with potting media containing no compost (Loschinkohl and Boehm, 2001). This pattern was present in this study when comparing compost mixes with AWS mixes but only for those blends containing 0 to 20% (perennial ryegrass) or 0 to 40% (tall fescue) WFS. Within the compost mix treatments, however, this trend only existed between the 0 and 20% WFS:compost blends for tall fescue. Loschinkohl and Boehm (2001) identified nutrient availability as the main cause in differences in surface coverage. The same cause was most likely present in this study as the 0 to 40% WFS blends (i.e., WFS:AWS vs. WFS:compost) represented the greatest difference in nutrient availability.

Conclusions

This study revealed a blend (40% WFS, 60% compost) that would be most advantageous for reuse of WFS while preventing adverse plant growth conditions. The use of this blend will also provide an economic incentive because it will help to save foundries the costs associated with landfill disposal. Based on density measurements and the average US landfill disposal fee of $29.50 per metric ton (Millner et al., 1998), every 10-cm application on a 1-ha area of land (or 1000 m^3) will reuse 496 metric tons of WFS and save the foundry industry $14,632.

Future research on the reuse of WFSs for turfgrass establishment should focus on field research using fertilizer and water applications typical to the situation in which it is to be reused. This research should also encompass a wider variety of WFSs containing sodium bentonite to give further representation of their effects on establishment because WFSs are highly variable. Lastly, there is interest in the reuse of pure WFSs as topdressings to reduce the thatch layer on golf courses. Therefore, research is needed in this area which may provide an additional opportunity for diverting these wastes from the landfill.

Supplemental Information Available

Seven supplementary tables and nine supplementary figures are available free of charge at http://jeq.scijournals.org.

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