1   *Article*

2 3 Compost Quality Recommendations for Remediating Urban Soils

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12   **Abstract:** Poor soil health is a critical problem in many urban landscapes. Degraded soil restricts
13   plant growth and microorganism activity, limiting the ability of urban landscapes to perform much
14   needed ecosystem services. Incorporation of approximately 33% compost by volume into degraded
15   soil has been proven to improve soil health and structure over time while avoiding the financial
16   and environmental costs of importing soil mixes from elsewhere. However, additions of high
17   volumes of compost could potentially increase the risk of nutrient loss through leaching and
18   runoff. The objective of our study was to consider the effects of different compost amendments on
19   soil health, plant health and susceptibility to nutrient leaching in order to identify ranges of
20   acceptable compost characteristics that could be used for soil remediation in the urban landscape.
21   We conducted a bioassay with Phaseolus vulgaris (Bush Bean) to measure the effect of nine
22   composts from different feedstocks on various plant health parameters. We collected leachate prior
23   to planting to measure nutrient loss from each treatment. We found that all compost amendments
24   improved soil health. Nutrient-rich, manure-based composts produced the greatest plant growth,
25   but also leached high concentrations of nitrate and phosphorus. Some treatments provided
26   sufficient nutrients for plant growth without excess nutrient loss. We concluded, when
27   incorporating as much as 33% compost by volume into a landscape bed, the optimal compost will
28   generally have a C:N ratio of 10-20, P-content <1.0% and a soluble salt content between 1.0 and 3.5
29   mmhos/cm. These recommendations should ensure optimal plant and soil health and minimize
30   nutrient leaching.

31   **Keywords:** compost; compost quality; soil remediation; urban soil; nutrient leaching

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33   1. Introduction

34   Healthy soils have the potential to provide critical ecosystems services through processes
35   including nutrient cycling, water infiltration, pollutant containment and carbon sequestration in
36   addition to providing habitat for plants, animals and microorganisms. An important indicator of soil
37   health is good soil structure. Healthy soil forms aggregates, creating pore space that can be filled by
38   air and water and ease the growth of plant root systems. This process is made possible by the organic
39   matter in the soil and the organisms that consume and transform it, providing the binding agents
40   that help form soil aggregates [1-2].
41   Urban soil is generally characterized by the disturbance inflicted upon it by human activity
42   such as burying of construction materials, soil importing, contamination and compaction, which can
43   lead to imperviousness and soil sealing. Urban soil also tends to lack OM and, as a result, exhibits
44   little to no microbial activity [3-5]. These characteristics make urban soil a poor habitat for plants and
45   debilitate the growth of healthy urban ecosystems. To correct for this, the common practice in the
46   landscaping industry is to remove and replace soils with specified soil mixes. These soil mixes are

47   mined off-site and shipped to the desired location. This practice is costly and wasteful and does not
48   address the underlying problem.
49   Compost amendment has been shown to improve physical, biological and chemical properties
50   of many types of soil. It can decrease bulk density and increase porosity, OM content, microbial
51   biomass, available water holding capacity, and structural stability [2,6]. However, compost is a
52   highly variable product, which makes it difficult to assess quality and is, therefore, less appealing to
53   landscape managers. Moving forward standardized testing protocols like the Test Methods for the
54   Examination of Compost and Composting (TMECC), developed by the U.S. Composting Council [7]
55   will be crucial in advancing the use of compost in the landscaping industry.   In order to reap the full
56   benefits of soil remediation with compost, one must fully understand the qualities of the compost
57   being used, the qualities and limitations of the site and the desired outcomes.
58   A twelve-year study was completed at Cornell University in 2015, to measure the impacts of a
59   soil remediation strategy on various soil quality indicators [8]. This strategy (The Scoop & Dump
60   Method) consisted of physically fracturing compacted soils and incorporating large amounts of
61   compost (33% by volume) to a depth of approximately 45 cm with the use of a backhoe or excavator.
62   After planting bark mulch was added to the soil surface. The study found that, over time,
63   remediated soils exhibited improved bulk density, increased active C and increased mineralizable
64   N, as well as improved aggregate stability and available water holding capacity. Chen et al. (2014)
65   and Rivenshield & Bassuk (2007) discussed similar effects of compost on soil health, however, only
66   one type of compost was tested in each of these studies [1,9]. In this study, we sought to gauge the
67   effects of different composts from different feedstocks on soil and plant health.
68   We conducted a bioassay with *Phaseolus vulgaris* (Bush Bean) to measure the effect of composts
69   from different feedstocks (animal manure, green waste, food scraps) at different concentrations (33%
70   and 50% by volume) on various plant health characteristics (dry shoot weight, leaf area and leaf
71   greenness). We also collected leachate from each treatment during the experiment to measure
72   nutrient (N and P) loss from our different compost-amended soils.
73   Nutrient leaching is a concern when high levels of compost are applied to landscapes before
74   plant establishment or any time plants are unable to utilize large amount of N and P [2,10]. Organic
75   amendments are often applied at N-based rates, which can lead to applications of P in excess of plant
76   needs and increase the likelihood of nutrient loss in leachate or runoff [11]. Our objective was to
77   consider soil health, plant health and susceptibility to nutrient leaching in order to identify a range
78   of acceptable compost characteristics that could be used for soil remediation in the urban landscape.
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80   **2. Materials and Methods**

81   *2.1 Compost Selection*

82   In the autumn of 2017, we collected seventeen composts from around New York State (Table 1).
83   We collected composts from a variety of common compost feedstocks (e.g. manure, green waste,
84   food scraps) and from a diversity of compost producers (e.g. farms, institutions, municipalities,
85   private companies etc.). Approximately 75 liters of compost were collected from each location. We
86   collected two different batches of compost from four of our producers. These batches were either
87   prepared differently or a single company collected feedstocks from different locations. Most
88   compost producers used a turned-windrow method of compost production [12].
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95   **Table 1.** Seventeen composts collected from around New York State. Those in bold were selected for
96   further experimentation.

Compost ID	Location	Major Feedstocks
BOO	**Greenwich, NY**	**Dairy Manure**
VA	Johnstown, NY	Dairy Manure
CV	Homer, NY	Dairy Manure
CC	**Trumansburg, NY**	**Food Scraps/Green Waste**
CU	**Ithaca, NY**	**Horse Manure/Green waste**
DL	**Stanfordville, NY**	**Horse Manure/Green Waste**
WCE	**Wolcott, NY**	**Poultry Manure**
OCJ	Jamesville, NY	Green Waste
OCS	Syracuse, NY	Green Waste
OH	Utica, NY	Green Waste
ORC	Orangeburg, NY	Green Waste (NY)
OR	**Orangeburg, NY**	**Green Waste (NJ)**
FF	**Staten Island, NY**	**Food Scraps**
FY	Staten Island, NY	Green Waste
BS	Bethlehem, NY	Green Waste (Screened)
BL	**Bethlehem, NY**	**Green Waste**
CG	**Ithaca, NY**	**Green Waste**

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98   A sample of each of the seventeen composts were brought to the Cornell University Nutrient
99   Analysis Lab to be tested for C:N ratio by finding total carbon using the Combustion with CO_2
100   Detection and Total Kjeldahl Nitrogen. The compost samples were also tested for soluble salt content
101   by measuring electrical conductivity using the slurry method as well as for OM% using the Loss on
102   Ignition Method (LOI) all according to the Test Methods for the Examination of Composting and
103   Compost (TMECC) protocol [7]. Based on those results we narrowed our study down to nine
104   composts that represented a wide range of measured characteristics to use in our bioassay. Those nine
105   composts were BOO, CC, CU, DL, WCE, OR, FF, BL and CG (Table 2).
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107   **Table 2.** This data table shows the mean of two samples of each of the 9 composts tested at the
108   Cornell Nutrient Analysis lab. Most of the tests shown above were taken according to the TMECC
109   protocol [7]. nitrate and ammonium content were found using a KCl extraction.

Primary Feedstock	ID	Organic Matter (%)	Total Ash Content (%)	Total N (%)	Organic N (%)	NH4 (mg/kg)	NO3 (mg/kg)	P2O5 (%)	K2O (%)	Ca (%)	Mg (%)	Total Carbon (%)	C: N	Soluble Salts (mmhos/cm)	pH
YARD WASTE	CG	35.27	78.33	0.82	0.82	10.94	5.15	0.22	0.57	5.20	0.75	22.32	27.26	1.01	8.25
	OR	72.91	78.76	2.83	2.83	2.06	19.85	0.53	1.53	4.33	0.70	71.63	25.40	1.32	7.52
	BL	65.60	81.58	2.93	2.91	2.86	242.88	0.73	1.79	4.88	0.94	55.62	17.22	2.64	7.54
FOOD SCRAPS	FF	25.50	95.39	1.62	1.61	2.98	100.90	0.63	0.84	4.16	1.10	20.82	13.13	0.85	8.06
	CC	24.23	95.70	1.64	1.60	5.98	410.80	0.82	1.41	2.22	0.57	17.40	11.53	1.94	7.66
MANURE	DL	84.80	88.97	3.99	3.92	8.20	626.18	1.03	2.52	8.46	2.49	64.70	15.91	3.21	8.15
	CU	83.23	138.11	3.38	3.34	13.17	439.74	2.20	4.42	7.44	1.98	54.01	15.95	2.21	7.29
	BOO	52.59	82.34	2.50	2.46	4.08	366.34	1.07	2.25	4.54	0.78	42.03	16.37	3.41	7.67
	WCE	50.68	39.44	6.49	6.18	3104.04	22.18	6.33	3.33	11.1	0.84	35.61	5.49	17.59	6.73

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112   *2.2 Soil Amendment and Testing*

113   We collected an Arkport sandy loam soil (56% sand, 37% silt, 6% clay) from the Bluegrass Lane
114   Turf and Landscape Research Center in Ithaca, NY and sifted that soil through a 2.0 cm sieve. This soil
115   was mixed with each of the selected composts to make the media for our bioassay. The Arkport soil
116   and the eighteen compost-soil mixes were all sent to the Cornell Soil Health Lab for testing prior to the
117   bioassay and then twice more during the course of the experiment (Table A1). The samples were
118   stored in refrigeration at 4°C (40°F) prior to processing. Samples were analyzed for physical, biological

119 and chemical indicators including available water holding capacity, aggregate stability, OM%,
120 Autoclave Citrate Extractable (ACE) soil proteins, root pathogen pressure, soil respiration, pH, active
121 C and extractible phosphorous using the Comprehensive Assessment of Soil Health: The Cornell
122 Framework [13].
123   The OM% was determined by Loss on Ignition (LOI). Samples were dried at 105°C and weighed.
124 The samples were then ashed for two hours at 500°C and weighed again and the percent of mass lost
125 was calculated. Nutrients like phosphorous were extracted from soil mixes by shaking with Modified
126 Morgan's solution. After shaking, the extraction slurry was filtered and the filtrate was analyzed on an
127 inductively coupled plasma emission spectrometer (ICP, Spectro Arcos).
128   We also measured soluble salts by making a 1:1 soil:water suspension by volume. The suspension
129 was left to settle for one hour after which electrical conductivity of the supernatant was measured with
130 a calibrated conductivity meter.
131   Available water holding capacity was tested by placing the soil on two ceramic plates and wetting
132 them to saturation. The ceramic plates were then inserted into two high pressure chambers, one
133 extracting the water to field capacity (10 kPa), the other to the permanent wilting point (1500 kPa).
134 After each sample was weighed, oven-dried at 105∘ C to a constant weight, and then weighed again.
135 The soil water content at each pressure was calculated, and the available water capacity was calculated
136 as the difference between water content at 10 and 1500 kPa pressures [14].
137   To test for aggregate stability, soil was air-dried and shaken for 15 seconds on a Tyler Coarse
138 Sieve Shaker to separate out aggregates of 0.25 - 2.0 mm size for analysis. A single layer of those
139 aggregates was spread on a 0.25 mm sieve which was placed below a rainfall simulator. The simulator
140 was run for 5 minutes and delivered 12.5 mm of water as drops to each sieve. The soil material that fell
141 through during the simulated rainfall event, and any stones remaining on the sieve was collected,
142 dried and weighed, and the fraction of stable soil aggregates was calculated [13].
143   The Autoclaved Citrate Extractable (ACE) Protein Index indicated the amount of protein-like
144 substances that are present in the soil OM. To extract the proteins, soil samples were placed into a glass
145 tube with a sodium citrate buffer and shaken for 5 min at 180 rpm. A sample of the slurry was
146 centrifuged at 10,000 x gravity to remove soil particles. A subsample of this extract was used in a
147 standard colorimetric protein quantification assay (BCA) to determine total protein content of the
148 extract. The Cornell Soil Health Lab used the Thermo Pierce BCA protein assay. Extractable protein
149 content of the soil was calculated by multiplying the protein concentration of the extract by the volume
150 of extractant used and dividing by number of grams of soil used [15].
151   To test for active C, air dried soil was placed in a centrifuge tube with a 0.02 M potassium
152 permanganate (KMnO4) solution, which is deep purple in color. The soil and KMnO4 were shaken for
153 exactly 2 minutes to oxidize the active C in the sample which causes the solution to lose some of its
154 color. The more active C found in the soil, the more color is lost. This color change was measured with
155 a spectrophotometer and a simple formula was used to convert absorbance to active C in units of mg C
156 per kg of soil [16].
157   Soil respiration was measured by placing a sample of air-dried soil in a glass jar. A trap assembly
158 filled with an alkaline CO_2 - trapping solution (9 ml of 0.5 M KOH) was placed in the jar as well.
159 Deionized water was then pipetted into the jar to rewet the soil and the jar sealed tightly and incubated
160 undisturbed for 4 days. After incubation, the conductivity of the trap solution was measured. Trap
161 electrical conductivity declined linearly with increasing CO_2 absorption. CO_2 respired was calculated
162 by comparing the conductivities of the original trap solution, and a solution representing a trap
163 saturated with CO_2 [13, 17].

164 *2.3 The Bioassay*

165   Our nine selected composts were each combined with the sieved Arkport sandy loam soil to serve
166 as the growing media for the bioassay. We made six repetitions of the following treatments, 100% soil,
167 100% compost for each of the nine composts, 50% of each compost with 50% soil by volume and 33%
168 of each compost with 77% soil by volume.

169   For every repetition we used a #1 size nursery pot with a volume of 2.78 L (0.73 gallons).   The
170 50% mixes were made by filling three pots to the first rim with soil (gently packed) and three pots with
171 compost (gently packed). All six pots were combined in a large tub and mixed roughly with hands or
172 trowel until evenly mixed. Then each of the six pots were refilled with the mixture distributed evenly
173 by volume. For the 33% mixture a similar protocol was used. This time four pots were filled with soil
174 and two pots were filled with compost and combined in the large tub. Both soils and composts were
175 nearly completely dry when mixing took place with moisture contents below 5.0% for all media.
176   The bioassay was conducted in the greenhouse with *Phaseolus vulgaris* 'Provider' (bush bean) as
177 our indicator species. Prior to planting, all treatments underwent a simulated heavy rain event. All
178 pots were fully saturated, brought to container capacity (field capacity) and leachate was collected for
179 later nutrient analysis. After that initial leaching, two *Phaseolus vulgaris* seeds were planted in each pot.
180 Once the beans began to show true leaves if both plants had successfully germinated, one was
181 disposed of. Pots were arranged in the greenhouse using a completely randomized design with six
182 replicates and kept at 70°F and 16-hour days with overhead High Pressure Sodium High Intensity
183 Discharge (HID) lamps.   After germination, beans were watered with 150 ml of clear water every
184 other day for the remainder of the experiment, excluding a second simulated heavy rain event
185 conducted towards the end of the bioassay, for the purpose of collecting leachate. 150 ml of water was
186 enough to keep the plants well-watered as they grew without allowing for more than slight leaching
187 from the bottom of the pots.
188   Beans were harvested 39-42 days after they were planted. Soil was gently loosened around the
189 roots to remove the plant to salvage as many roots as possible and collect a sample of the soil for
190 testing. A SPAD 502 Plus Chlorophyll Meter (Konica Minolta, New Jersey, USA) was used to measure
191 the "greenness" of the leaves. Leaf area was measured by taking a sample leaf from the second round
192 of mature leaf growth from each plant and running it through a LI-COR 3100 leaf area meter (LICOR,
193 Inc., Lincoln, NE). Shoots were separated from roots and placed in labeled paper bags and dried at
194 70°C for approximately two weeks after which dry shoot weight was measured.

195 *2.4 Leachate Testing*

196   Leachate was collected from each pot prior to planting and tested for nitrate, ammonium and
197 soluble reactive phosphorus (SRP). Prior to planting the bean seeds, the media in each pot was
198 saturated by putting each pot in a 5-gallon bucket, slowly filling the bucket with water until the water
199 sat just above the level of the media in the pot and allowing it to soak for five minutes. Once pots were
200 fully saturated, (bubbles no longer appeared at the surface and the pots sat on the bottom of the
201 bucket) pots were placed upon plastic trays and left for 24 hours to reach "container capacity" (or field
202 capacity). Container capacity of each pot was measured with a ThetaProbe Soil Moisture Sensor
203 (Delta-T Devices Ltd, Cambridge, UK) and recorded. Any liquid in the tray was poured off and the
204 trays were rinsed. We then poured 150 ml of clear water through the media and 40 ml of the leachate
205 that came through the pot into the tray was collected.   The 40 ml of leachate was then frozen for future
206 analysis.
207   Leachate samples were thawed overnight prior to testing.   Prior to phosphorus (P) testing, 20 ml
208 of each sample was collected and filtered through 45μm filters.   After filtering, samples were fed
209 through an OI Analytical Phosphorus Analyzer Model 3000 (Xylem, Rye Brook, New York) using the
210 Ascorbic Acid Method of phosphate analysis [18]. Nearly all the leachate samples that were collected
211 exhibited some coloration most likely due to high levels of tannins in the OM. This posed a challenge
212 when using a colorimetric method of nutrient analysis because the pigment in the samples could
213 possibly interfere with the absorption of the color reagent being measured. For the phosphate analysis
214 we diluted the darkest of our samples to overcome that interference. The darkest samples also showed
215 levels of phosphorous that were well above the range of the instrument's rating curve so dilution was
216 necessary to receive an accurate reading. We diluted all WCE (poultry manure) compost mixes at a
217 ratio of 100:1 and both the 100% BOO (cow manure) and 100% CU (mixed horse manure and green
218 waste) at a ratio of 10:1 with deionized water.

219   To measure Nitrate and Ammonium in the leachate, we used the colorimetric methods developed
220   by Hood-Nowotny et al., (2010) [19]. This protocol was conducted using a Synergy™ HT Multi-Mode
221   Microplate Reader (BioTek® Instruments Inc., Winooski, VT). Ammonium was quantified by a
222   colorimetric method based on the Berthelot reaction [20]. Nitrate was estimated after persulfate
223   oxidation by reduction of nitrate to nitrite by Vanadium (III) chloride and a colorimetric determination
224   of nitrite by an acidic Griess reaction [21]. Dilutions were necessary once again and the dilutions
225   differed between the first and second leach events. Dilutions also differed for Nitrate and Ammonium
226   tests to ensure that the reading fell within the range that could be accurately read by the micro-plate
227   reader. Occasionally two different dilutions were made for a single treatment and an average was
228   taken of the two readings.

229   *2.5 Statistical Analysis*

230   Statistical analyses were conducted using JMP pro 14.0 (SAS Institute Inc., NC, USA). Tukey HSD
231   was used to compare mean values of the six repetitions in the bioassay and leachate collections. Linear
232   regression analyses were conducted to determine correlation between compost and amended soil
233   characteristics and plant growth as well as nutrient leaching.

234   **3. Results**

235   *3.1 Soil Quality*

236   Compost amendment improved soil health regardless of feedstock type (Table 2) according to
237   the Comprehensive Assessment of Soil Health completed at the Cornell Soil Health Lab [13]. Soil
238   health tests were conducted on samples taken immediately after the incorporation of compost.
239   Aggregate stability, OM percentage, soil respiration, ACE soil protein index and active C content
240   increased for all amended soils compared to the control. Aggregate stability increased from 34.7% in
241   the control soil to a minimum of 41.43% in the 50% DL treatment and a maximum of 68.50% in the
242   33% CU treatment. OM increased from 2.2% in the control to a minimum of 3.15% in the 33% OR
243   treatment and 8.85% in the 50% BL treatment. ACE soil protein index score increased from 5.10 in
244   the control soil to a minimum of 10.70 with the amendment of 33% CU compost and a maximum of
245   23.40 with the addition of 50% CC compost. Respiration increased from 0.40 mg CO_2 in the control to
246   a minimum of 0.72 mg CO_2 in the 33% OR and a maximum of 1.98 mg CO_2 in the 50% CG treatment.
247   Active C increased from 317.0 mg/kg in the control soil to a minimum of 487.58 mg/kg with the
248   amendment of 33% DL compost and a maximum of 1160.90 mg/kg with the addition of 50% BL
249   compost. Some of the amended soil mixes showed increased root pathogen pressure (50% CC, 50%
250   and 33% CU). Manure-based compost mixtures generally exhibited higher values for root pathogen
251   pressure, P and K content and soluble salt content and lower values for active C. For other soil
252   characteristics like respiration, aggregate stability, available water holding capacity etc. feedstock
253   type did not appear to have a noted effect.
254   Surprisingly, twelve of the eighteen amended soil mixes exhibited either no improvement or
255   slightly decreased available water holding capacities. AWHC of amended soils ranged from 16.2% to
256   36.7% compared to soil alone, which was 22.0%.   We surmise this may be due to the larger particle
257   size of the nine composts which reduced bulk density and available water, but more research would
258   be required to verify this. All compost amendments increased the soluble salt content of the soil,
259   from 0.03 of soil alone to 0.126 mmhos/cm, at the lowest (33% FF) to 2.924 mmhos/cm, at the highest
260   (33% WCE).   All but six of the amended soil mixes displayed extractable P concentrations higher
261   than 25 mg/kg MMP (Modified Morgan Phosphorus), making them potential sources of nutrient loss
262   (Jokela et al. 1998; Moebius-Clune et al. 2016). The mixtures that did not were both concentrations
263   (33% and 50%) of CG and OR compost as well as the 33% concentrations of the DL and FF composts.
264   However, these mixes also showed the least impressive plant growth. The amended soil with the
265   highest available P concentration was amended with 50% BOO containing as much as 180.137 mg/kg
266   MMP, increased from the unamended soil concentration of 5.3 mg/kg of MMP.

Table 3. Unamended and amended soil characteristics. The soil used in all mixes is an Arkport sandy loam. Samples were taken immediately after mixing. Tests followed the *Comprehensive assessment of soil health: the Cornell framework manual* protocol by Moebius-Clune.

Major Feedstock	ID	Compost Conc. (%)	AWHC	Aggregate Stability (%)	OM (%)	ACE soil protein index	Root Pathogen Pressure	Respiration (mg)	Active C (mg/kg)	P (mg/kg)	K (mg/kg)	pH	Soluble Salts (mmho/cm)
Control Soil	S	0	0.22	34.70	2.20	5.10	4.00	0.40	317.00	5.30	20.10	5.40	0.03
Yard Waste	CG	50	0.20	63.58	4.80	15.35	3.00	1.98	753.37	18.85	300.12	6.90	0.42
	CG	33	0.20	60.12	3.74	11.67	3.00	1.44	562.00	12.32	178.98	6.74	0.25
	OR	50	0.22	48.68	4.52	18.26	3.33	0.90	732.10	22.59	338.02	6.51	0.25
	OR	33	0.19	50.40	3.15	12.78	3.33	0.72	553.14	11.60	182.86	6.19	0.20
	BL	50	0.37	62.91	8.85	20.26	3.75	1.15	1160.90	130.82	955.36	7.09	0.88
	BL	33	0.24	57.14	4.97	15.81	3.00	0.83	918.15	49.00	429.28	6.75	0.51
Food Scraps	FF	50	0.21	49.89	5.38	11.83	4.00	1.29	827.78	46.09	315.95	7.26	0.15
	FF	33	0.20	50.13	3.57	13.15	3.75	0.99	629.33	24.89	199.10	6.92	0.13
	CC	50	0.24	51.49	6.64	23.40	6.67	1.31	951.82	126.33	1192.96	6.67	1.12
	CC	33	0.20	57.88	4.55	18.20	3.00	1.13	758.68	69.08	700.34	6.67	0.76
Manure	DL	50	0.27	41.43	5.74	16.01	3.25	1.32	707.30	59.62	621.65	7.13	0.54
	DL	33	0.20	48.99	3.70	11.61	3.50	0.95	487.58	21.11	314.55	6.29	0.35
	CU	50	0.19	64.05	5.24	14.39	5.00	1.08	570.86	149.41	1017.41	6.85	0.82
	CU	33	0.18	68.50	4.07	10.70	5.75	0.94	487.58	68.36	572.86	6.48	0.57
	BOO	50	0.24	58.54	5.40	15.92	3.00	0.98	664.77	180.14	1330.43	6.91	0.90
	BOO	33	0.19	60.38	4.31	11.79	4.00	0.85	579.72	130.63	965.05	6.25	0.81
	WCE	50	0.17	64.12	6.91	53.25	5.80	4.90	918.15	1021.00	2515.26	6.69	2.04
	WCE	33	0.16	63.34	5.81	30.27	4.33	4.91	538.97	637.04	1780.03	7.05	2.92

BL leaf compost was the finest in texture with 63.2% of the compost particles smaller than 2.0mm, followed by CC with 60.1% smaller than 2.0mm. OR and DL composts were the coarsest in texture with 33.5% and 32.3% of compost particles being larger than 1.0 cm, respectively (Figure 1).
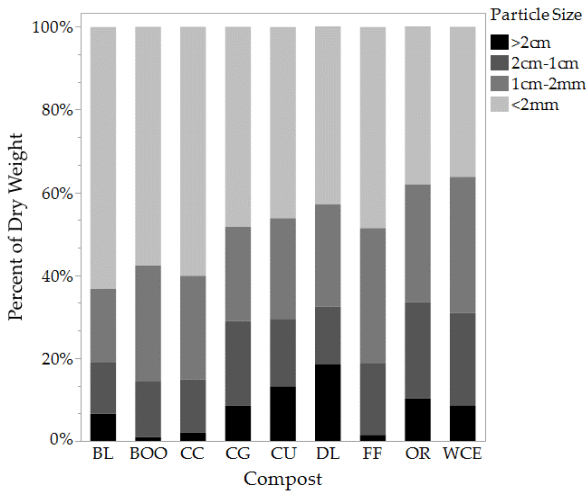

Figure 1. Composition of the compost particle size (>2cm, 2cm-1cm, 1cm-2mm, <2mm) by dry weight.

3.2 Relationship of Compost to Plant Quality

The compost characteristics that had the greatest effect on plant growth were C:N ratio (Figure 2-A), soluble salt content (Figure 2-B), Phosphorus (P) content (Figure 2-C) and Potassium (K) content. Soluble salt content of the amended and unamended soil had relatively strong positive correlations with both bean shoot weight and leaf area with r^2 values of 0.57 and 0.51, respectively. Extractable P of the amended soil had a strong, positive correlation with plant growth. Leaf area and shoot weight had r^2 values of 0.636 and 0.698, respectively, with increasing available P (Figure 2-C). The positive correlation between K content of amended soils and plant growth was also strong with r^2 values of 0.597 for leaf area and 0.652 for shoot weight. OM% of the composts and amended soils, alternatively, showed nearly no correlation with plant growth (Figure 2-D).

When composts with a C:N above 25:1 were incorporated into the soil, plant growth and chlorophyll concentration were reduced compared to the control. Shoot weight was reduced by as much as 80.9%, leaf area was reduced by as much as 77.3% and Leaf SPAD (greenness) was reduced

by as much as 67.9% (33% OR compost) (Figures 3-5). Beans grown using composts with a C:N close to 15:1 displayed the greatest shoot weight and leaf area (Figures 3 and 4). C:N ratio and nitrate concentration of the compost had the greatest effect on chlorophyll concentration (Figure 5).

Manure-based composts outperformed the woody green waste-based composts, in terms of plant growth (Figures 3-5). The only plant health parameter that did not differ based on compost type was root length. We suspect the size of the pot may have constrained root growth. BOO and CU had the greatest shoot weights (Figure 3), leaf areas (Figure 4) and shoot lengths. The treatments displaying the highest leaf SPAD (chlorophyll concentration) were the 33% CC, with a measurement of 35.6 and the 0% compost (control soil), at 35.5 (Figure 5). We suspect that the bean plants grown in soil alone had highly concentrated chlorophyll because those plants were stunted in size with abnormally small leaves. CG and OR performed poorest in all categories. We do not have plant growth measurements for the poultry manure compost (WCE) because the bean seeds were unable to germinate at any compost concentration. WCE compost had a soluble salt content of 17.585 mmhos/cm, a C:N ratio of 5.87, ammonium concentration of 3104.04 mg/kg and a P concentration of 63,260 mg/kg. We excluded the WCE compost from our analysis as an extreme outlier. Poultry manure compost is generally marketed for use as an agricultural fertilizer rather than as a soil amendment in landscape beds.

(A)   (B)

Figures 2. **(A)** shows the relationship between dry shoot weight of the bean plants and C:N ratio of
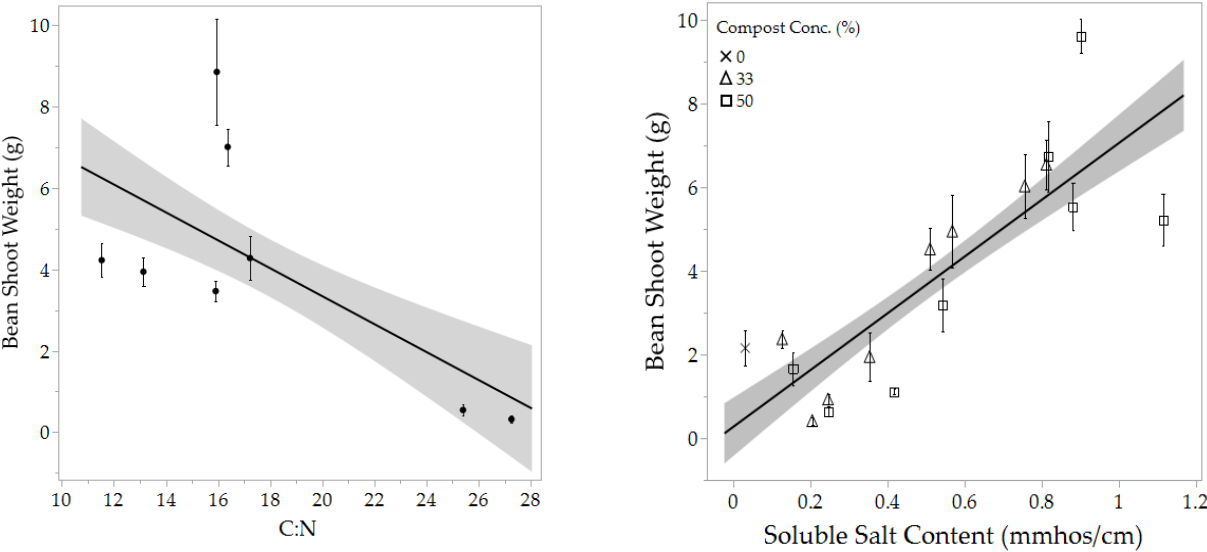
eight of the nine compost types (excluding WCE). The black line represents the line of best fit; R^2=0.359. **(B)** displays the relationship between dry shoot weight of the bean plants and soluble salts concentration of the amended and unamended soil for all compost types (excluding WCE); R^2=0.570. **(C)** displays the relationship between extractable (available) phosphorus content of the amended and unamended treatments and bean dry shoot weight; R^2=0.698. **(D)** displays the relationship between dry shoot weight of the bean plants and OM% of the amended and unamended treatments (excluding WCE); R^2=0.157. The 100% compost treatments were excluded from Figures 2B-D for ease of interpretation. In all figures the shaded area denotes a 95% confidence interval. Each point represents the mean, error bars denote standard error (n=6).

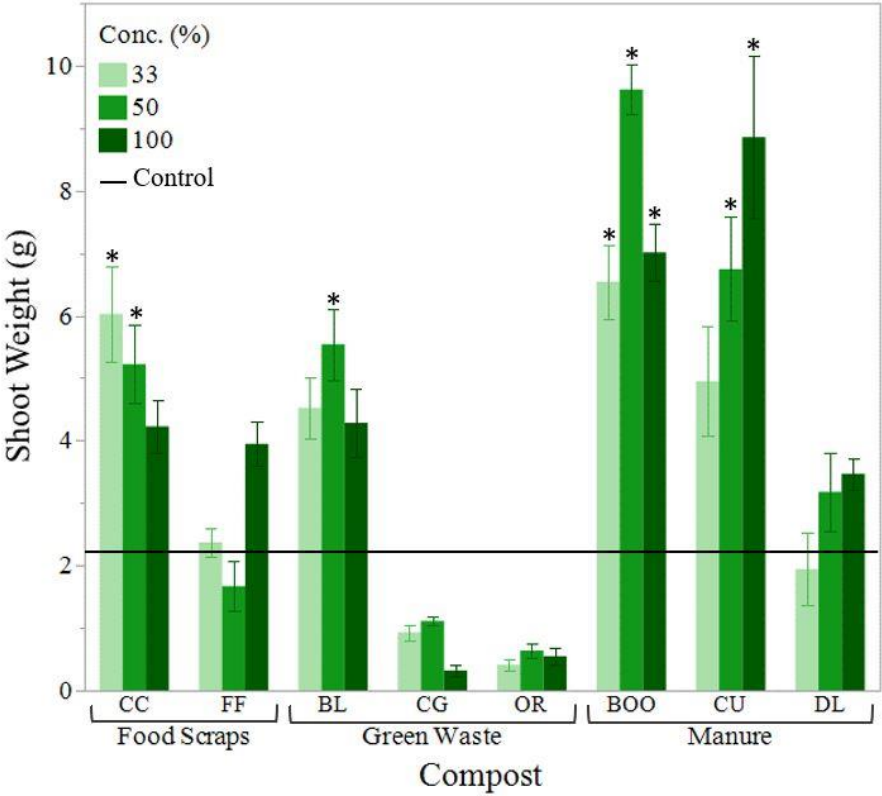320   (C)

321
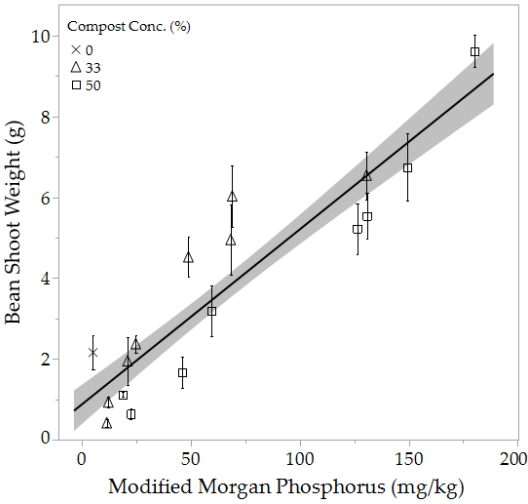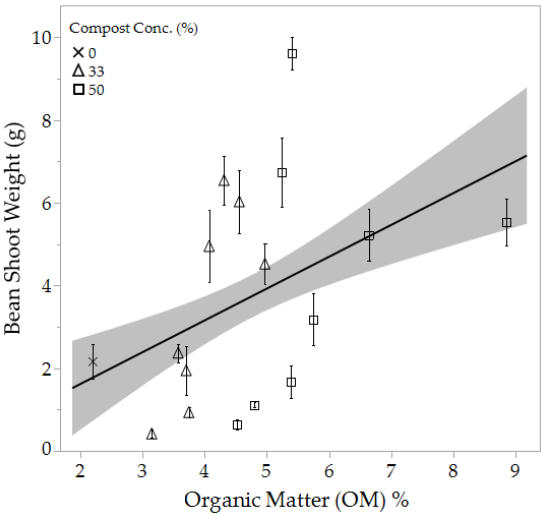
322   **Figure 3.** Mean bean plant dry shoot weight in grams by compost type. Compost concentration of the
323   growing media shown from dark to light (100%, 50%, 33% compost). Horizontal solid black line
324   indicates the mean shoot weight of the control (soil). Error bars denote standard error (n=6). Stars (*)
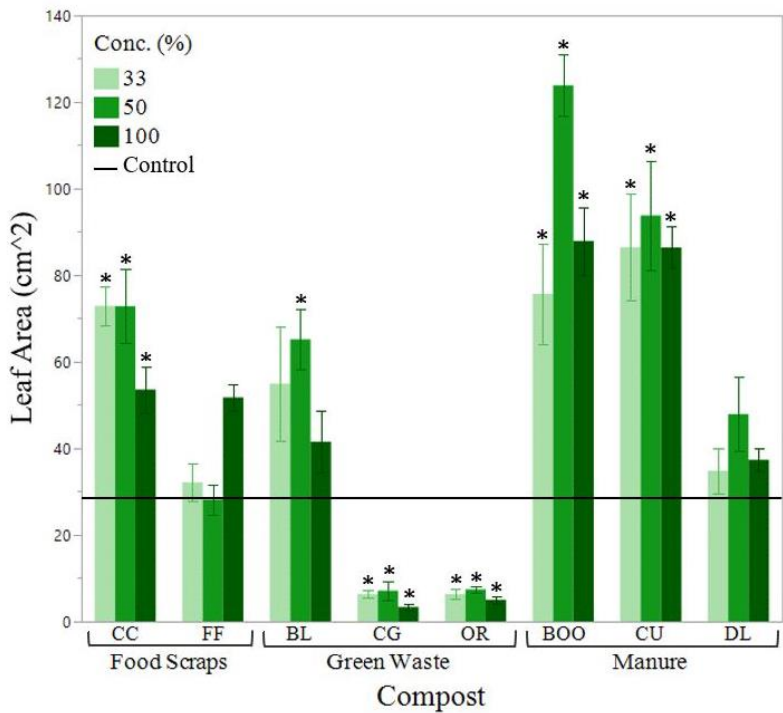325   indicate significant difference from the control (α=0.05).

Figure 4.   Mean bean plant leaf area in cm2 by compost type. Leaf area was taken for the second round of growth on bean plants. Compost concentration of the growing media shown from dark to light (100%, 50%, 33% compost). Horizontal solid black line indicates the mean shoot weight of the control (soil). Error bars denote standard error (n=6). Stars (*) indicate significant from the control (α=0.05).
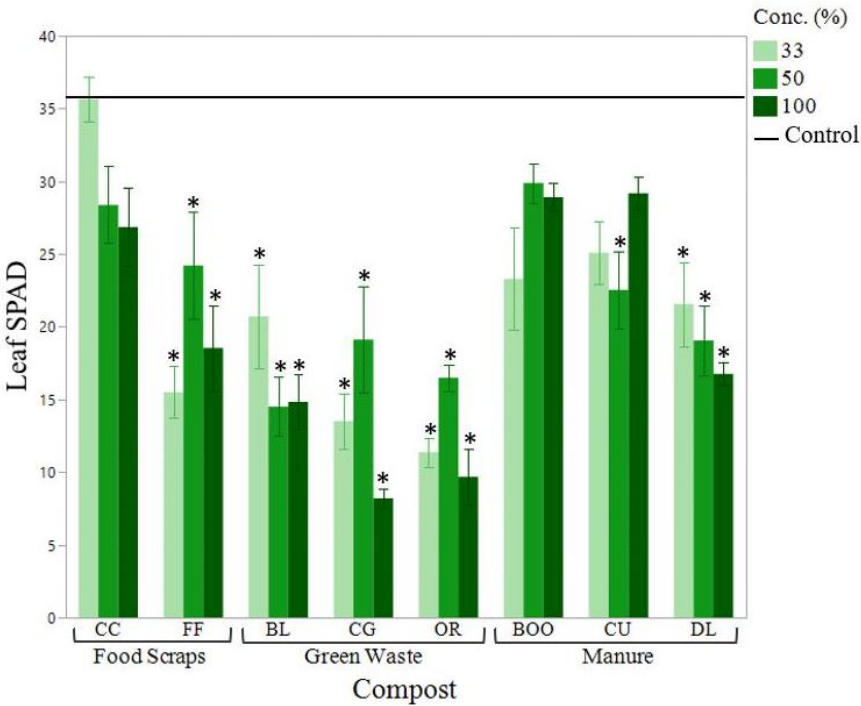

Figure 5. Mean bean leaf SPAD (greenness) by compost type. SPAD was taken using the second round of growth on bean plants. The mean of four separate measurements with the SPAD-meter was calculated for each plant. Compost concentration of the growing media shown from dark to light (100%, 50%, 33% compost). Horizontal solid black line indicates the mean shoot weight of the control (soil). Error bars denote standard error (n=6). Stars (*) indicate significant from the control (α=0.05).

3.1. Nutrient Leaching

337   We found a relatively strong positive correlation between extractable P content of composts and
338   amended soils and SRP content of leachate (Figure 6-A). The same was not true for leached N, which
339   displayed a weak correlation between nitrate found in the compost and nitrate content of the
340   leachate (Figure 6-B). Three of the four manure-based composts used (BOO, CU, WCE) leached
341   significantly higher concentrations of SRP than the rest of the composts (Figure 7-A). The composts
342   that leached the greatest concentration of nitrate were CC and BOO followed by CU (Figure 7-B).
343   And the WCE compost was the only one to show significant amounts of ammonium leaching. We
344   excluded WCE from our analyses as an outlier. The 100% CU compost treatment leached the highest
345   concentration of SRP at 32.395 mg/kg SRP, while the 33% CU compost treatment leached only 3.985
346   mg/kg SRP.   The 100% CC (food scraps) compost leached 340.417 mg/kg NO_3, while the 33% CC
347   compost treatment leached a far lower concentration, at 54.533 mg/kg NO_3. Planting directly into
348   100% compost is not recommended.   The leachate measured was collected prior to planting. It is
349   possible that the high concentrations of nutrients found in the leachate would decrease significantly
350   after even a short period of time, especially with the presence of actively growing plants to utilize
351   some of the nutrients.

352   (A)   (B)
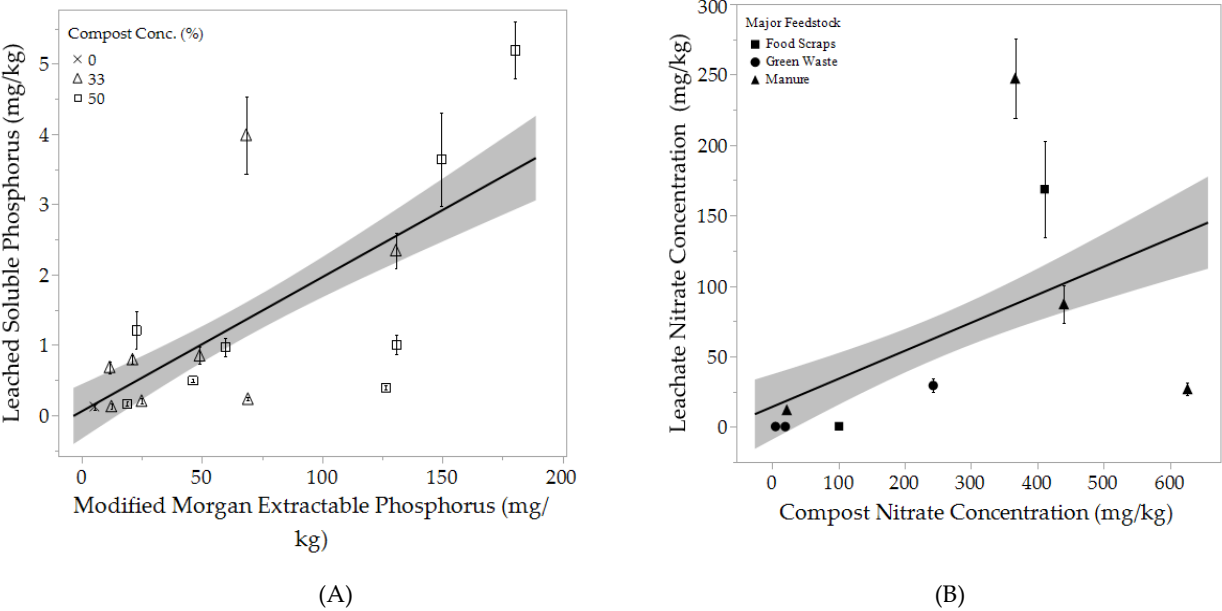
Figure 6. (A) displays the relationship between extractable (available) phosphorus content of the
amended and unamended soil with concentration of soluble reactive phosphorus found in leachate.
The black line represents the line of best fit; R^2=0.417.   The 100% compost treatment is excluded for
ease of interpretation. **(B)** displays the relationship between nitrate concentration in the composts
alone (100% compost). The manure-based compost in the lower left-hand corner is the WCE poultry
manure compost which leached very little nitrate because the nitrogen in the compost was primarily
in the form of ammonium. The black line represents the line of best fit; r2=0.161. In both graphs the
shaded area denotes a 95% confidence interval. Each point represents the mean, error bars denote
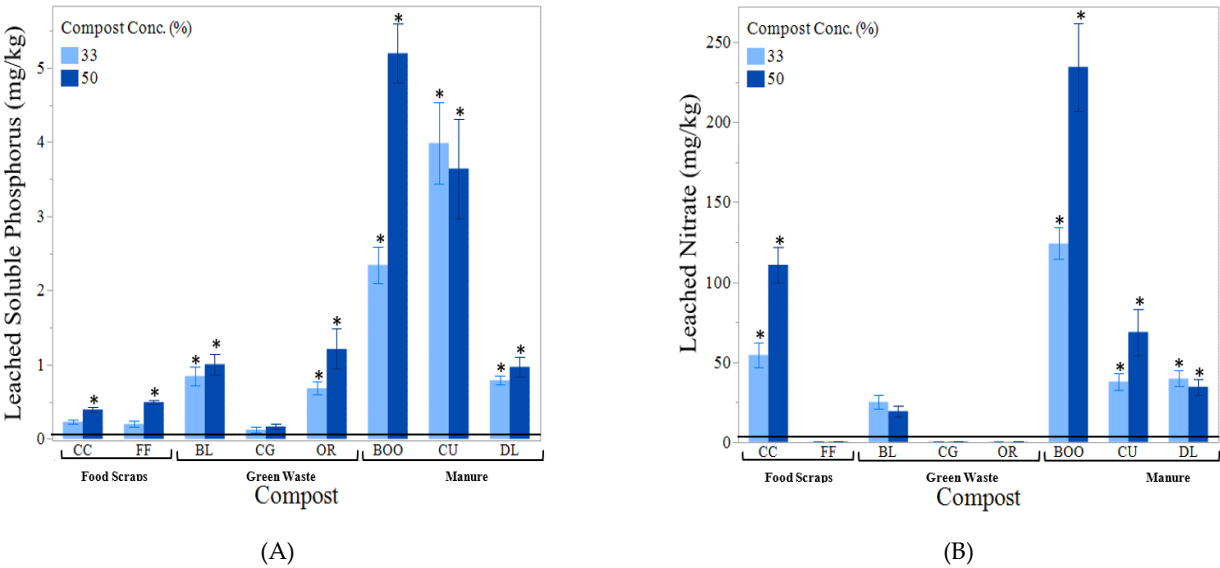standard error (n=6).

362

363   (A)   (B)

Figure 7. (A) shows mean soluble phosphorous found in leachate by compost type. Compost concentration of the growing media shown from light to dark (33% and 50%compost). The horizontal solid black line indicates the mean soluble phosphorus found in the leachate from the control (soil) equaling 0.122 mg/kg. **(B)** shows mean soluble Nitrate found in leachate by compost type. The horizontal solid black line indicates the mean nitrate found in the leachate from the control (soil) equaling 5.91 mg/kg. WCE compost and 100% compost concentration were excluded from both graphs. Error bars denote standard error (n=6). Stars (*) indicate significant from the control (α=0.05).

4. Discussion

4.1 Testing Compost Quality

The composts selected for this experiment were chosen to encompass a range of compost characteristics and feedstocks. We wanted to choose composts that were commercially available and made from common feedstock sources to best reflect what landscape managers would have access to. We used C:N ratio, OM and soluble salt content as qualities to narrow down our composts from 17 to 9, anticipating that those characteristics would be the strongest indicators of compost quality.

The initial compost quality parameters that must be met are those that indicate safety, such as contamination, maturity and traits like smell and presence of inert particles (trash). Those quality parameters apply to all compost regardless of their eventual use. Once those criteria are met, focus shifts to secondary quality parameters determined by the compost's end use [22,23]. All nine composts used in the experiment tested well for maturity (above 6) when tested with a Solvita® Basic Field CO_2 test. However, the CG and WCE composts showed signs of immaturity. The CG (woodchips) and WCE (poultry manure) were included in the experiment to illustrate the extreme ends of the spectrum in terms of C:N and nutrient content. The woodchips were not, in fact, compost as they never underwent the composting process. The WCE poultry manure compost was composted but did not undergo a sufficient curing period. It was, instead, rapidly dried to prevent it from losing nutrients because it was intended to be marketed more as a fertilizer than as a compost. We believe its immaturity was one of the main reasons the bean plants failed to germinate in any of the WCE mixes.

As for the secondary quality parameters, the intended end-use was urban or disturbed soil remediation with 33-50% compost by volume. These soil to compost ratios had been found to improve soil health and reduce bulk density over time [8,9]. At these volumes the main compost characteristics of concern were C:N ratio, soluble salt content and nutrient content (N-P-K). Nutrient content is not often included in compost specifications, although it is generally included in compost laboratory testing. We found that if nutrient leaching is a concern, nutrient recommendations are important considerations when specifying a compost.

398   When testing compost, a recognized, consistent test protocol is critically important if one is to
399   successfully adhere to written compost specifications and recommendations for use. We recommend
400   compost producers and practitioners seek out labs that use TMECC, which was developed, with the
401   assistance of many laboratories, by the U.S. Composting Council and modeled after the American
402   Society for Testing and Materials (ASTM) [7]. Compost is an extremely variable product.
403   Standardization of testing is a good way to mitigate uncertainty and increase universal
404   understanding of a complex product that is often made from a mix of feedstocks and by a variety of
405   processes.

4.2 Soil Health

407   All compost amendments carried out in this experiment improved soil health according to the
408   Comprehensive Assessment of Soil Health completed at the Cornell Soil Health Lab [13]. These
409   improvements included increased OM, active C, ACE (Autoclave Citrate Extractable) soil proteins,
410   respiration and nutrient content. These results either directly indicated an increase in microbial
411   activity or suggested a potential for increased microbial activity. OM%, a measure of the
412   biomass-derived carbonaceous material in the soil, is the main energy source for microorganisms.
413   Active C is the portion of that food source that is the most easily accessible for microorganisms. Soil
414   proteins represent the large pool of organically bound N in the soil OM that can be mineralized by
415   microbes and made available for plant uptake [13]. In our experiment, we measured an increase in
416   OM from 2.2% in the control to as much as 8.85% with the addition of 50% BL compost and we found
417   slight positive correlations between increased OM% and respiration, aggregate stability and
418   available water holding capacity (AWHC). Treatments with 50% compost tended to show higher
419   values for those characteristics than those with 33% compost.

420   Soil Respiration is a measure of carbon dioxide released from the soil due to microbial
421   metabolic activity. The measurement of soil respiration integrates both abundance and activity of the
422   microbial community. That activity includes nutrient cycling into and out of soil OM pools and N
423   transformations like mineralization and nitrification. In our experiment respiration increased with
424   the addition of all compost types at all concentrations. Increased OM, active C, and soil proteins,
425   increased microbial activity. The greatest respiration in our experiment, was observed in the CG
426   compost treatments (50% and 33%) at 1.98 and 1.44 mg CO_2, respectively. The CG compost did not
427   display the highest OM%, protein content or active C content, however. We suspect the increased
428   microbial activity might be due to the immature nature of the CG compost. There may have been
429   more microbial activity because there was more potential for further decomposition.   The 50% BL
430   and 50% CC treatments displayed the highest OM% at 8.85% and 6.64%, respectively. They
431   displayed the highest values for the ACE soil protein index at 20.26 (50% BL) and 23.40 (50% CC) as
432   well as the highest active C contents at 1160.90 mg/kg (50% BL) and 951.82 mg/kg (50% CC). They
433   correspondingly showed high levels of respiration at 1.15 mg CO_2 in the 50% BL treatment and 1.31
434   mg CO_2 in the 50% CC treatment.

435   That increased microbial activity then influenced soil aggregate stability, water retention,
436   nutrient cycling, and cation exchange capacity (CEC) [8, 9, 24-29]. Both 50% BL and 50% CC showed
437   increased AWHC and increased aggregate stability. Compost can also inoculate soil that has been
438   depleted of its microbial community. Pérez-Piqueres et al. (2006) found that incorporation of good
439   quality composts may increase microbial biomass and enhance soil enzyme activity, although to
440   what extent, depends on the compost and soil type [30]. We believe it is likely some inoculation
441   occurred in our experiment because respiration increased by a minimum of 81.25% and a maximum
442   of 396.0% with the addition of compost (from 0.4 mg CO_2 in the soil alone to 0.72 mg CO_2 in the 33%
443   OR and 1.98 mg CO_2 in the 50% CG) shortly after incorporation.

444   Aggregate stability increased by 19.4% to 97.4% with the addition of compost. Feedstock type
445   did not seem to correlate with increased aggregate stability. Aggregate stability is greatly influenced
446   by microbial activity as aggregates are held together by microbial products like polysaccharides,
447   exudates and fungal hyphae. In our experiment certain treatments that displayed greater aggregate
448   stability also showed greater plant growth such as BL, CU and BOO treatments (Figures 3 and 4). CG

449 treatments also displayed a high percentage of aggregate stability, but still displayed poor growth,
450 most likely because large pieces of woody material were mistaken for aggregates during laboratory
451 testing.

452   Available water holding capacity either stayed the same or decreased slightly in the majority of
453 our compost amended treatments. AWHC decreased by a maximum of 27% in the 33% WCE
454 compost treatment. These results contradict most findings in the literature which cite increased
455 AWHC with increased OM [1,6,8]. Saxton and Rawls (2006) found that soil OM between 0.5% and
456 8.0% has been proven to increase AWHC in silt loam soils [31]. However, despite OM% increasing
457 for all eighteen of our treatments, only five displayed an increase in AWHC (33% and 50% BL, 50%
458 CC, DL, BOO). The 50% BL (leaf compost) treatment displayed the greatest AWHC increase (68% up
459 from the control), this treatment also showed the greatest OM%, 8.85%. The composts that displayed
460 increases in AWHC (BOO, BL, CC) had larger percentages of fine particles (<2mm). BOO, BL, and
461 CC composts contained 57.6%, 63.2% and 60.1% particles that were <2mm by dry weight,
462 respectively (Figure 1). The treatments with the lowest AWHC were amended with OR, CU and CG
463 composts which all displayed higher percentages of larger particles. OR, CU and CG composts
464 contained 33.45%, 29.56% and 29.06% particles >1cm by dry weight (Figure 1). With larger pores,
465 water most likely drained away by gravity as it could not be held by adhesion as it is in finer soils.
466 We took our soil quality measurements immediately after incorporation. Over time, perhaps, once
467 the compost could be broken down further by microorganisms, we might see different results,
468 however further research is necessary to confirm this. In subsequent soil tests taken four and seven
469 months later AWHC measurements fluctuated for all treatments (Appendix A).

470   Amending urban soil with compost is a simple solution that could immensely improve the
471 health of urban landscapes. Not only does compost improve the biological, chemical and physical
472 health of the soil, it contributes to maintenance of that health long-term. Sax et al. (2017) found
473 increases in active C and aggregate stability over the course of their 12-year study and continual
474 decreases in bulk density over that same time period [8]. In urban areas, where landscapes get heavy
475 use and often receive little regular fertilization, the long-term N availability that compost provides is
476 particularly important [32]. Sæbø and Ferrini (2006) suggest an annual top-application of compost
477 because it serves a dual purpose, providing nutrients and OM and assisting with weed suppression
478 [25].

479   Considering only soil health, it appears nearly any compost would improve compacted soil
480 with low OM, low microbial activity and high bulk density. But it is important to consider plant
481 health and nutrient retention as well.

482 *4.3 Plant Health*

483   Compost benefits plant growth indirectly, through remediating the soil and directly by
484 providing nutrients immediately and continuously as it is transformed by microorganisms.
485 However, because compost is a variable product, practitioners are often hesitant to utilize it as a
486 nutrient source. Most compost specifications do not include nutrient recommendations, but we
487 found nutrient content was an important consideration, not only for determining plant growth, but
488 also to gauge to what extent nutrients might be lost after application.   C:N ratio, soluble salt content
489 and P and K content were the compost characteristics that appeared to have the greatest effect on
490 plant growth.

491   The composts that performed the best in terms of plant health were BOO (cow manure-based
492 compost), CU (horse manure and green waste compost), CC (food and green waste compost) and BL
493 (leaf compost) (Figures 3-5). These four composts had C:N ratios ranging from 11.5 - 17.2. Their
494 soluble salt content ranged from 1.9 - 3.4 mmhos/cm. Their phosphorous content ranged from 0.73%
495 - 2.20% and their K content ranged from 1.4% - 4.4% (Table 1). These results indicated that compost
496 quality is not necessarily feedstock dependent.

497   The C:N ratio range that proved optimal in this experiment was in line with what is often
498 recommended in the literature for finished compost. According to Sikora and Schmidt (2001) the
499 C:N ratio considered optimal for compost is based on the C:N ratio of stable soil OM which generally

falls between 10 and 15 [33]. Chatterjee et al. 2013 stated in their review that the ideal ratio for a compost used as a growing medium was 12–18 [34].We found that a C:N ratio equal to or greater than 25 in the finished compost resulted in stunted growth and pale green color, most likely due to N immobilization which was confirmed by Brady and Weil (1999) [35]. Because we did not include a compost in our experiment with a C:N ratio between 17 and 25 we were unable to determine a maximum C:N ratio that would still allow enough available N for plant growth. Sikora and Szmidt (2001) and Sullivan et al. (2003) found that in composts with a C:N of 20 or less, 5 to 15% of total N became plant-available during the first year after application [33,36]. Because we chose beans as our bioassay species, we also must consider the effects of nodulation, which occurred in all treatments over the course of the bioassay. Despite nodulation, many plants exhibited yellow leaves and stunted growth suggesting that nodulation did not make up for low N in some of the treatments.

Mupondi et al. (2006) and Warman and Termeer (1996) both utilized bioassays in the greenhouse to evaluate the use of compost mixes on plant germination and growth. Both found that a mix of nutrient-rich material composted with a carboniferous material resulted in the strongest plant growth. The compost that performed the best for Mupondi et al. was a pine bark and goat manure blend with a C:N ratio of 16, which is in line with our findings. Mupondi et al. found that composted pine bark alone immobilized N and resulted in stunted plant growth, much like our CG woodchips [37,38]. Warman and Termeer saw plant growth decline when greater than 50% compost was utilized in the growing media whereas many of our bioassay plants thrived in up to 100% manure-based compost [39]. Nutrient levels of the compost and nutrient requirements of the desired plants or crops will vary, but the literature seems to agree that a combination of nutrient-rich and carboniferous feedstocks provide for the best growing media.

A low level of salinity is important in compost because it indicates the presence of nutrients in the form of cations and anions that are required for plant growth. High salinity, however, can inhibit germination and plant growth [40]. The treatments in this experiment with soluble salt content below 0.5 mmhos/cm resulted in poor growth and greenness, particularly when low salinity coincided with high C:N. We did not have sufficient data to offer a maximum safe soluble salt content based on our bioassay because we lacked a treatment with a soluble salt content between 3.4 mmhos/cm and 17.6 mmhos/cm which inhibited germination completely. The composts that performed the best in our study had soluble salt contents from 1.9 - 3.4 mmhos/cm. Much depends on plant selection and in urban landscapes the use of salt-tolerant plants is encouraged due to regular salting of roads and walkways in cities located in regions with cold winters. Much of the literature agrees that compost amendments that increase the soil soluble salt levels higher than 4 mmhos/cm can pose a risk to healthy plant growth [41], but many standard compost specifications set the maximum electrical conductivity levels as high as 10 mmhos/cm [42].

We found strong positive correlations between P and K content and plant growth. This is not surprising because P and K are vital macronutrients. P is necessary for various plant processes such as photosynthesis, respiration, N fixation, root development, maturation, flowering, fruiting, and seed production [43]. We used the Modified Morgan method [44] of phosphorus extraction to measure available P in our growing media. This method tends to be less sensitive then other extraction methods such as Mehlich III, Bray-Kurtz P1 and Olsen [45,46]. However, we still found extremely high levels of Modified Morgan phosphorus (MMP) in our treatments. The recommended 33% treatment of the composts that showed the best performance (BOO, CU, CC, BL) showed a range of MMP from 49.0 – 130.63 mg/kg MMP.   Jokela et al. (1998) found the optimal range of MMP for field crops to be from 4.0 to 7.0 mg/kg. 4.0 mg/kg MMP was cited as the critical value and additions of P fertilizer were recommended for soil with MMP levels up to 7.0 mg/kg. In their paper, Jokela et al. characterized soil with MMP above 20 mg/kg as excessive [47]. All but three of our treatments (30% and 50% CG and 33% OR) exceeded 20 mg/kg MMP. Consequences of excess available P are far reaching, and P can remain in the soil far longer than N. For this reason, compost testing, site analysis and thoughtful timing of compost amendments are important considerations. Although the soil remediation method we are testing calls for 33% compost by volume, it may be

551 wise to use 25%, if P leaching is a concern on the intended site. Amendments of 25% compost by
552 volume have been shown to improve bulk density in compacted sandy loam soil [9].
553   Our results displayed both the positive and negative impacts compost amendment can have on
554 plant growth. Type of compost and amount of amendment will depend on the needs of the plants,
555 but compost is undoubtedly a sustainable, affordable nutrient source for plants in the landscape.

556 *4.4 Nutrient Leaching*

557   Compost is less susceptible to nutrient losses during large rain events than inorganic fertilizers
558 that are completely soluble, but the soluble nutrients in compost are still of concern [48]. Site and soil
559 assessment are important steps to take prior to compost amendment, as are compost laboratory
560 tests.
561   In a drier area with deeper soil, composts made with a mixture of manure and some
562 carboniferous bulking agent could be used safely. However, on a site with well-drained soil,
563 particularly moist conditions, or a high risk of runoff, manure-based compost is most likely too high
564 in P and will result in nutrient pollution.   Hurley et al. (2017) suggest that ≤0.2% P be the definition
565 of low P compost. Low P composts are primarily derived from yard or green waste, as opposed to
566 composts derived from food scraps, manure, or biosolids [49]. The CG woodchips contained the
567 lowest concentration of P of the composts we tested, with 0.22%. All non-manure-based composts
568 used contained <0.9% P. Finding a compost with ≤0.2% P might be a challenge for compost users if
569 leaching is a concern.
570   Timing of compost incorporation is crucial, particularly when compost amendment is occurring
571 before the landscape is installed. It would be unwise to leave the amended soil unplanted for long
572 stretches of time because available nutrients will be lost without established plant uptake. Most
573 compost specifications do not include N content, outside of the C:N ratio, and P content is generally
574 omitted as well. When incorporating compost into soil at such large volumes it is necessary to
575 include nutrient ranges in specifications to make informed management decisions.
576   Borken et al. (2004) found composts rich in N can cause excessive nitrate leaching during the
577 first one to two years after application. In their experiment, Borken et al. measured N leaching in a
578 forested area and observed that the mineral soils acted as a significant sink for $NO-3$ and dissolved
579 organic N [26]. This experiment confirmed that where there was deeper soil to catch nutrients as
580 they leach, N and P-rich composts may be safer to use.
581   Amlinger et al. (2003) discouraged the use of very large amounts of compost as a soil
582 amendment, especially in well-drained soils. Nutrient leaching from compost-amended soils could
583 exacerbate existing eutrophication problems, which threaten the health of coastal and freshwater
584 systems [48,51]. This danger is elevated when composts are applied in late autumn and winter when
585 plants are not actively growing. Spring is the best time to apply compost, when plants can take up
586 dissolved nutrients, so they don't end up polluting groundwater [50].
587   We found a direct correlation between the concentration of MMP in the media and the
588 concentration of soluble reactive phosphorus (SRP) found in the leachate ($r^2=0.79$). According to
589 Pote et al. (1996) the soil P extraction test that will best predict SRP loss depends on soil type. In their
590 study using Captina silt loam, they found the distilled water and acidified ammonium oxalate
591 (Sheldrick, 1984) extraction methods were the most accurate indicators of SRP in the leachate,
592 although all the methods they used showed statistically significant correlations [52]. In 1999, Pote et
593 al. came out with another study using three more ultisols to see if different methods would be more
594 accurate with different soil types. They found several tests were good predictors (with an $r^2 > 0.90$)
595 for all three soils, including Mehlich III, Modified Morgan, Bray-Kurtz P1 and Distilled Water
596 [45,46]. This confirms our results that MMP in the compost would be a good indicator of potential P
597 leaching and a P extraction would be a valuable addition to regular compost laboratory analysis and
598 specification.
599   We did not find a compost measurement that correlated strongly with nitrate leaching on its
600 own. We know that a higher C:N ratio results in increased N immobilization and therefore reduces
601 the threat of leaching. Increased C:N was negatively correlated with nitrate concentration in the

602 leachate. However, the r^2 was only 0.079. We assessed this relationship based solely on the 100%
603 compost treatment, because we did not test for C:N in the soil mixes.   Nitrate concentration in the
604 compost was only slightly positively correlated with nitrate concentration in the leachate with an r^2
605 of 0.145. We believe that a larger sample size could result in stronger correlations, however, more
606 research is necessary to better predict likelihood of nitrate leaching from compost.
607

608 **5. Conclusions**

609   Compost is a valuable renewable resource for rebuilding depleted soils, reducing compaction
610 and reinvigorating disturbed landscapes. Our objective was to identify a range of acceptable
611 compost characteristics that could be used for soil remediation in the urban landscape. We analyzed
612 composts made from combinations of three main feedstocks, animal manure, green waste and food
613 scraps. We wanted to take into account soil health, plant health and the potential of nutrient leaching
614 in our recommendations. Although all nine composts used in this experiment improved soil health,
615 the green waste composts received the highest scores from the Cornell Soil Health Lab. We also
616 found that the higher compost concentration (50%) tended to improve soil characteristics more than
617 the lower concentration (33%).
618   We found very different results when we evaluated plant growth. The nutrient rich composts
619 made from cow and horse manure and food scraps produced the largest, greenest plants. The
620 woody composts were detrimental to growth, immobilizing all N that might otherwise be available
621 to the plant. However, those nutrient rich composts that boosted plant growth, leached high levels of
622 nitrate and SRP.
623   Taking all the information collected from our research and experimentation into consideration
624 we came up with recommended ranges for the ideal compost for urban soil remediation. The main
625 concerns were C:N, P% and soluble salt content. We found the ideal ranges were 10 – 20 for C:N
626 ratio, 0.2% – 0.9% P and a soluble salt content between 1.0 and 3.5 mmhos/cm (Appendix B).
627 Composts that exhibit these characteristics tend to be combinations of several feedstocks, some
628 richer in N and P like manure, food waste or grass clippings and others richer in carboniferous
629 material. Moreover, these levels produced good plant growth with minimal nutrient leaching. There
630 are a wide variety of composts available for growers and landscapers with distinct nutrient contents,
631 nutrient leaching potential, bacterial community composition, and other qualities that vary by the
632 feedstocks used and the process through which the compost was produced [34,53]. It is important to
633 test compost qualities using a standard testing protocol such as the TMECC protocol.
634   When using compost as a soil amendment the safest approach is to understand site conditions
635 soil type and drainage, which will help improve plant growth and minimize nutrient leaching. As
636 we learn more about compost properties and streamline and standardize testing and regulations, we
637 believe the knowledgeable incorporation of compost will play a critical role in improving soil and
638 plant growth in disturbed urban soils.
639

651 **Appendix A**

Table A1. Unamended and amended soil characteristics for all three samples taken during the bioassay. The soil used in all mixes is an Arkport sandy loam. Tests followed the *Comprehensive assessment of soil health: the Cornell framework manual* protocol by Moebius-Clune.

Feedstock	ID	Sample #	AWHC	Aggregate Stability (%)	OM (%)	Respiration (mg)	Active C (mg/kg)	P (mg/kg)	Soluble Salts (mmho/cm)
	S	1	0.220	34.700	2.200	0.400	317.000	5.300	0.03
SOIL	S	2	0.182	40.866	2.66	0.291	310.977	4	0.22
	S	3	0.168	67.746	2.73	0.567	359.271	6.3	0.25
	CG50	1	0.197	63.584	4.802	1.984	753.366	18.845	0.417
	CG50	2	0.242	56.342	5.69	1.390	728.769	20.3	0.69
	CG50	3	0.218	81.818	6.65	1.715	808.968	22.8	0.62
	CG33	1	0.204	60.122	3.743	1.441	562.003	12.318	0.245
	CG33	2	0.204	43.374	4.47	1.135	617.963	10.6	0.33
	CG33	3	0.161	77.819	3.88	1.233	652.097	12.4	0.4
	OR50	1	0.220	48.680	4.515	0.902	732.103	22.591	0.247
	OR50	2	0.302	55.222	6.56	1.605	1028.794	27.1	0.40
GREEN	OR50	3	0.211	78.935	7.31	1.353	869.973	27.8	0.67
WASTE	OR33	1	0.186	50.402	3.146	0.725	553.144	11.601	0.204
	OR33	2	0.205	47.412	4.61	0.759	594.348	11.5	0.45
	OR33	3	0.191	76.355	4.97	1.226	700.901	13.9	0.39
	BL50	1	0.367	62.907	8.848	1.147	1160.897	130.815	0.881
	BL50	2	0.274	50.260	9.69	0.838	1168.281	109.2	0.77
	BL50	3	0.302	68.047	10.78	1.275	1147.111	95.5	0.6
	BL33	1	0.243	57.139	4.967	0.831	918.150	49.004	0.510
	BL33	2	0.295	41.167	6.17	0.689	942.956	46.3	0.64
	BL33	3	0.192	70.600	7.32	0.786	922.263	40.5	0.56
	FF50	1	0.211	49.885	5.382	1.292	827.785	46.092	0.154
	FF50	2	0.223	57.685	7.77	1.07	779.630	67.6	0.57
	FF50	3	0.188	83.870	6.43	1.134	822.912	54.9	0.45
	FF33	1	0.199	50.134	3.571	0.994	629.334	24.886	0.126
	FF33	2	0.226	56.231	5.02	0.816	621.596	28.7	0.40
FOOD	FF33	3	0.188	80.545	5.04	1.006	660.812	29.9	0.45
WASTE	CC50	1	0.237	51.487	6.636	1.310	951.816	126.332	1.115
	CC50	2	0.195	50.330	7.77	0.823	814.143	166.3	1.85
	CC50	3	0.187	72.802	7.1	1.091	871.716	140.3	0.75
	CC33	1	0.201	57.883	4.555	1.126	758.681	69.081	0.756
	CC33	2	0.160	49.1409	5.62	0.596	588.899	97	1.11
	CC33	3	0.168	76.201	4.21	0.800	704.387	64.5	0.63
	DL50	1	0.266	41.428	5.742	1.317	707.297	59.616	0.543
	DL50	2	0.205	73.659	6.67	1.170	872.271	71	0.85
	DL50	3	0.232	86.613	7.5	1.403	1047.76	58.3	0.39
	DL33	1	0.202	48.989	3.701	0.952	487.58	21.113	0.353
	DL33	2	0.236	56.306	6.16	0.979	632.495	27	0.55
	DL33	3	0.201	86.261	5.24	1.474	801.996	20.6	0.36
	CU50	1	0.193	64.051	5.236	1.083	570.862	149.407	0.816
	CU50	2	0.307	58.349	6.21	0.851	748.75	133.3	0.69
MANURE	CU50	3	0.248	75.342	7.3	1.062	749.705	163.3	0.57
	CU33	1	0.181	68.502	4.070	0.945	487.584	68.362	0.568
	CU33	2	0.275	32.728	4.98	0.645	648.843	66.8	0.61
	CU33	3	0.204	67.496	4.16	0.985	653.840	58.4	0.43
	BOO50	1	0.244	58.535	5.397	0.984	664.772	180.137	0.901
	BOO50	2	0.202	65.401	9.39	0.746	799.892	355.7	1.18
	BOO50	3	0.151	80.034	8.13	0.942	697.415	285.7	0.89
	B0033	1	0.189	60.379	4.309	0.849	579.722	130.627	0.812
	B0033	2	0.164	56.759	5.8	0.711	642.522	113.1	0.79
	B0033	3	0.152	78.561	5.03	0.694	570.175	102.8	0.51

Appendix B

Scoop and Dump Compost Specification (For planting beds)

After critical root zone protection has occurred, grade and remove all plants and debris from the surface. Spread 6 inches of compost over the surface of the soil. Loosen the soil to depth of 18 - 24 inches, using a backhoe or excavator to dig into the soil through the compost. Lift and then drop the loosened soil immediately back into the hole. The bucket then moves to the adjacent soil and repeats the process until the entire area indicated has been loosened. Scoop and Dump so that the backhoe is working away from soil that has already been amended.

Compost

Compost for amending planting media shall be a stable, mature, humus-like material produced from the aerobic decomposition and curing of organic biomass residues. The compost shall be a dark brown to black color and be capable of supporting plant growth with appropriate management practices in conjunction with addition of fertilizer and other amendments as applicable, with no visible free water or dust, with no unpleasant odor, and meeting the following criteria as reported by laboratory tests. Recommended test methodologies are provided in Test Methods for the Examination of Composting and Compost (TMECC) from the United States Composting Council (USCC).

1. The ratio of carbon to nitrogen shall be in the range of 10:1 to 20:1.

2. Stability shall be assessed using the Solvita® procedure or the Carbon dioxide evolution rate procedure described in the Respirometry section of the TMECC (05.08-B). The carbon dioxide evolution rate must be <8 mg CO2-C per g OM per day. The Solvita® protocol is specified by the Solvita® manual (version 3.5). The compost must achieve a maturity index of 6 or more. Woods End Research Laboratory, Mt. Vernon, Maine, or approved equal shall conduct stability tests.

3. Maturity shall be assessed with a biological assay procedure described in TMECC 05.09-A. Seed emergence and seed vigor shall be ≥80% relative to a positive control.

4. Chemical contaminants shall meet the US EPA Class A standard, 40 CFR § 503.13, Tables 1 and 3 levels. (Arsenic = 41ppm, Cadmium = 39ppm, Copper = 1,500ppm, Lead = 300ppm, Mercury = 17ppm, Molybdenum = 75ppm, Nickel = 420ppm, Selenium = 100ppm, Zinc = 2,800ppm) [54].

5. Biological contaminants shall meet the US EPA Class A standard, 40 CFR § 503.32(a) levels (Salmonella <3 MPN/4grams of total solids or Fecal Coliform <1000 MPN/gram of total solids) [54].

6. Organic Matter (OM) content shall be at least 24 percent (dry weight). One hundred percent of the material shall pass a 1.0 inch (2.6 cm) screen. Debris such as metal, glass, plastic, wood (other than residual chips), asphalt or masonry shall not be visible and shall not exceed one percent dry weight. Organic content shall be determined by weight loss on ignition for particles passing a number 10 sieve as follows. A 50-cc sub-sample of the screened and mixed compost is ground to pass the number 60 sieve. Two to three grams (0.001g) of ground sample, dried to a constant weight at 105 degrees C is placed into a muffle furnace. The temperature is slowly raised (SC/minute) to 450C and maintained for three hours. The sample is removed to an oven to equilibrate at 105C and the weight is taken. Organic matter is calculated as loss on ignition.

7. pH: The pH shall be between 6.0 to 8.2 as determined from a 1:1 soil-distilled water suspension using a glass electrode pH meter American Society of Agronomy *Methods of Soil Analysis*, Part 2, 1986.

8. Salinity: Electrical conductivity of a one to five soil to water ratio slurry extract shall not be lower than 1.0 mmhos/cm or exceed 3.5 mmhos/cm (dS/m) for use in blending.

9. Phosphorus: Percent P_2O_5 shall be below 1.0% dry matter; preferably lower if C:N ratio is also low or if leaching is a concern.

10. The compost shall be screened to 1.0 inch (2.6 cm) maximum particle size and shall contain not more that 3 percent material finer than 0.002mm as determined by hydrometer test on ashed material.

11. Nutrient content shall be determined by the Cornell University Soil Testing Laboratory or equivalent laboratory and utilized to evaluate soil required amendments for the mixed soils. Chemical analysis shall be undertaken for Nitrate Nitrogen, Ammonium Nitrogen, Phosphorus, Potassium, Calcium, Aluminum, Magnesium, Iron, Manganese, Lead, Soluble Salts, Cation Exchange Capacity, soil reaction (pH), and buffer pH

Parameters	Recommended Ranges	Units	References
pH	6.0 - 8.2	-	[55]
C:N	10 - 20	ratio	[33,34,56]
Organic Matter	>24	% dry matter	[55]
Soluble Salts	1.0 - 3.5	mmhos/cm	[55, 57]
Total N	0.5 - 3.5	% dry matter	[58]
NO3-N	100 - 1,000	mg/kg	[56]
NH4-N	<500	mg/kg	[56]
NH4:NO3	<10	-	[56]
P2O5	<1.0	% dry matter	[55,56,59]
K20	1.0 - 3.0	% dry matter	[55,59]
Particle Size	100% passing through 3 cm sieve 85% passing through 2 cm sieve 40-60% passing through 2mm sieve	% dry matter	[55]

Recommendations to Reduce Nutrient Leaching Based on Site Analysis

When incorporating large quantities of compost at once, loss of soluble nutrients by leaching may be a concern. Compost is far less susceptible to nutrient losses than inorganic fertilizers that are completely soluble, but the soluble nutrients in compost are still vulnerable to leaching in the event of a large rain event. Nitrogen (N) and phosphorus (P) are the limiting nutrients in the eutrophication process of aquatic ecosystems. Efforts to reduce anthropogenic sources of N and P to combat eutrophication and the proliferation of toxic algal blooms have proved successful. When incorporating large volumes of compost into soil, particularly manure-based composts, it is crucial to understand the physical, chemical and biological characteristics of the soil as well as the geographic and hydrologic qualities of the intended site. Once that site analysis is complete, a compost can be selected that fits the limitations of the site. If nutrient leaching is a concern and the remediation site displays one or more of the following characteristics:

- Soil texture is sandy, very well-drained
- Soil depth is shallow (<24inches)
- Site/soil is very wet, site is located in a wet climate, site is located at the bottom of a slope or amendment is being applied during a rainy season
- Slope of site is >4:1 (25%)
- Compost application is occurring more than one week before plant installation

the following modifications to the above specification are warranted [60,61].   Limit composts to those with a C:N between 15:1 and 20:1 and a phosphorus content <0.5%. Consider using a compost that contains little to no animal manure. Additionally, consider using 25% compost by volume, instead of 33% compost by volume.

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