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Raised Beds for Vegetable Production in Urban Agriculture

Elizabeth A. Miernicki, Sarah Taylor Lovell, and Sam E. Wortman*

CORE IDEAS

- Infiltration rate, but also irrigation demand, was highest in compost raised beds.
- Compost in raised beds reduced the need for mineral fertilization across two seasons.
- Weed abundance in raised beds increased when top soil was mixed with compost.
- Crop yield was usually highest in raised beds, regardless of media composition.

ABSTRACT Raised beds are commonly used in urban agriculture, but crop production benefits have not been well studied. The objective of this 2-yr field experiment in Illinois was to determine the effects of urban production system (direct soil, raised bed with compost, or raised bed with mixed compost and soil) and fertilizer source on growing media properties, weed abundance, and vegetable crop yield. Due to the presence of compost, raised bed media had higher pH, organic matter, and nutrient concentrations. Water infiltration rate was 20× higher in raised beds with compost only compared to soil. Mixing soil with compost in raised beds reduced nutrient concentrations and water infiltration rate compared to compost-only beds. Compost-only raised beds required more irrigation than direct soil due to lower bulk density and greater porosity, but mixing soil with compost in raised beds reduced irrigation demand by 32% in year two. Compared to direct soil, compost-only raised beds reduced grass and broadleaf weed abundance by as much as 97 and 93%, respectively. Radish (*Raphanus sativus* L.), kale (*Brassica oleracea* L.), and cilantro (*Coriandrum sativum* L.) yields were highest in raised beds, regardless of growing media composition, whereas garlic (*Allium sativum* L.) and pepper (*Capsicum annuum* L.) yields were less influenced by production system. We recommend raised beds with a mix of compost and soil for vegetable production in urban agriculture.

Urban agriculture can be defined as food production within a city, town, or village that uses and contributes resources to the community (Mougeot, 2000). This local form of agriculture has the potential to increase food security for vulnerable populations (Altieri et al., 1999). Beyond the provisioning of food, urban agriculture offers associated benefits such as the recycling and reuse of organic wastes and water (Mok et al., 2014), storm water management (Ackerman et al., 2014), net carbon sequestration (Kulak et al., 2013), and increased fauna and flora biodiversity (Taylor and Lovell, 2014; Matteson et al., 2008).

E.A. Miernicki and S.T. Lovell, Dep. of Crop Sciences, Univ. of Illinois at Urbana– Champaign, 1102 S. Goodwin Ave., Urbana, IL 61801; S.E. Wortman, Dep. of Agronomy and Horticulture, Univ. of Nebraska– Lincoln, 279 Plant Sciences Hall, Lincoln, NE 68583. Received 25 June 2018. Accepted 29 Aug. 2018. *Corresponding author (swortman@unl.edu).

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One of the biggest obstacles to realizing these benefits of urban agriculture is soil contamination, which is concerning due to potential deposition and bioaccumulation of contaminants on or within crops (e.g., heavy metals) and potential inhalation or ingestion of contaminated soil particles by the grower and consumer (e.g., organic compounds and heavy metals; Madrid et al., 2008). Soil contamination can often be traced to anthropogenic sources including industrial processes (Howard and Shuster, 2015; Kim et al., 2014; Schuhmacher et al., 1997) and automobile traffic emissions (Kim et al., 2014). Common urban soil contaminants include polycyclic aromatic hydrocarbons (PAHs) (Motelay-Massei et al., 2004) and trace metals such as cadmium (Smolders, 2001), arsenic (Ramirez-Andreotta et al., 2013), and lead (Binns et al., 2004; Zhu et al., 2004). Bioavailability of soil contaminants varies across urban soils according to soil organic matter (SOM) quantity, pH, cation exchange capacity (CEC), and oxide composition found within a soil (Pouyat et al., 2010).

An additional environmental challenge for urban crop production is soil compaction (Gregory et al., 2006) and low organic matter content (Beniston and Lal, 2012). Urban soils can be severely compacted due to disturbances from construction vehicle traffic (Gregory et al., 2006) and high rates of foot traffic (Millward et al., 2011). Disadvantages of compacted soils include restricted root growth, increased bulk densities, and decreased aeration (Kozlowski, 1999). These altered soil physical properties within urban environments can reduce crop growth and yield (Wolfe et al., 1995). Moreover, soil compaction will decrease water infiltration rates (Bartens et al., 2008), which in turn may contribute to increased storm water runoff in urban areas (Pitt et al., 2008).

To improve growing conditions and reduce exposure to environmental contaminants, urban farmers and gardeners often use raised bed production systems (Sullivan et al., 2015). Two common raised bed systems used for crop production are temporary (e.g., frameless) and permanent (e.g., walled) raised beds. Temporary raised beds do not have a framework to contain the soil, which is a low cost option but is susceptible to erosion over time (Cudnik, 2004). Permanent raised beds are built above the surface where a framework is constructed and filled with soil, soilless media, or a mixture of the two (Cudnik, 2004).

Typical media used in raised beds include soil, compost, soilless media (e.g., perlite or sand), or some mixture of media. Compost is a versatile organic amendment that is capable of increasing porosity and enhancing water retention and availability to plants (Agnew and Leonard, 2003). Raised beds containing compost offer better soil conditions for water drainage (Cudnik, 2004) and generally have higher nutrient content (Lopez-Mondejar et al., 2010). Another benefit of compost as a soil amendment in urban agriculture is higher SOM levels (Marmo, 2008); soils with high SOM have higher water holding capacity due to enhanced soil aggregation and pore space distribution (Saxton and Rawls, 2006). Indeed, Weindorf et al. (2006) observed increased soil water content with increasing rates of landscape waste compost in urban soils of Dallas, TX. However, inappropriate management of nutrient-rich compost and other organic amendments may contribute to urban storm water pollution through leaching of nutrients (Lorenz, 2015).

Another challenge of urban food production, not exclusive to urban farmers, is weed management. Raised beds, especially those containing compost, are often used to reduce weeding operations in urban gardens. In general, there are fewer viable weed seeds in compost compared to mineral soils due to the thermophilic decomposition stage of composting (Grundy et al., 1998). Wiese et al. (1998) found that seeds of most weed species, except for field bindweed, were killed within a 3-d composting process at a temperature of 72°C or higher.

While raised beds and organic amendments are often promoted in urban agriculture to mitigate environmental and management challenges, less is known about effects on crop yield. Compost added to soil has significant potential to enhance crop yield (Wortman et al., 2017; Maynard, 2005), but compost feedstock and maturity, application rates and method, and crop species will influence yield response (Roe, 1998). However, most research on the effects of compost on crops has been conducted in field or greenhouse pot systems, not in raised bed production systems. The objective of this study was to determine the effects of urban production system (bed type and growing media composition), and fertilizer source on growing media chemical and physical properties, weed abundance, and vegetable crop yield.

MATERIALS AND METHODS

A field experiment was conducted in 2015 and 2016 at the University of Illinois Sustainable Student Farm in Urbana, IL (40°4'56.63"N, 88°12'40.39"W). The dominant soil type at this site is a Catlin silt loam (fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls). Cropping history for 3 yr prior to this experiment included a rotation of conventional corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.], typical for central Illinois.

The study was arranged in a randomized complete block design with a total of six treatments and four replicates. Treatments included: (i) direct soil + mineral fertilizer (DSF), (ii) direct soil + organic amendments (DSO), (iii) raised bed with imported soil and compost mixture + mineral fertilizer (RBMF), (iv) raised bed with imported soil and compost mixture + organic amendments (RBMO), (v) raised bed with compost only + mineral fertilizer (RBCF), and (vi) raised bed with compost only + organic amendments (RBCO). Experimental units were square, 1.5 m^2 permanent structures. Raised beds were constructed from nontreated cedar (*Thuja plicata* Donn ex D. Don) wood and filled with approximately 0.65 m^3 of the appropriate growing media (Table 1). In the direct soil treatments (DSF and DSO), a 9 cm tall wooden lip (also nontreated cedar wood) was installed around the plot perimeter to mimic conditions in the raised beds and mitigate any

Table 1. Summary of experimental treatments, including fertilizer type and composition of growing media.

Treatment abbreviation	Treatment description	Growing media composition at beginning of experiment
DSF	Direct soil + mineral fertilizers†	In-ground production, 100% native soil
DSO	Direct soil + organic amendments†	In-ground production, native soil plus 0.11 m^3 municipal compost‡/plot
RBMF	Raised bed, soil and compost mix + mineral fertilizer†	0.33 m^3 top soil§: 0.24 m^3 municipal compost‡: 0.08 m^3 mushroom compost§
RBMO	Raised bed, soil and compost mix + organic amendments†	0.33 m^3 top soil§: 0.24 m^3 municipal compost‡: 0.08 m^3 mushroom compost§
RBCF	Raised bed, compost-only + mineral fertilizer†	0.49 m^3 municipal compost‡: 0.16 m^3 mushroom compost§
RBCO	Raised bed, compost-only + organic amendments†	0.49 m^3 municipal compost‡: 0.16 m^3 mushroom compost§

† Fertilizer or organic amendment rate in each treatment and year were determined from pre-plant soil tests and fertilizer recommendations (Egel et al., 2017).

‡ Sourced from Landscape Recycling Center in Urbana, IL.

§ Sourced from local garden center in Urbana, IL.

Table 2. Initial properties of each growing media component prior to mixing and filling raised beds.

Media	Sand	Silt	Clay	pH	CEC†	OMC†	NO_3–N	Total N	P	K	Ca	Mg	SO_4–S	Na
		%			meq/100 g	%	mg/kg	g/kg	mg/kg		g/kg		mg/kg	
Municipal compost	55	30	15	7.8	34.2	28.6	70.8	12.9	215	1.45	4.34	1.02	82	60
Mushroom compost	68	19	13	7.7	37.7	36.1	0.1	13.5	28	2.18	5.15	0.65	389	227
Topsoil	23	48	29	5.8	20.7	3.8	9.3	1.8	15	0.14	2.75	0.50	12	10

† CEC, cation exchange capacity; OMC, organic matter content.

potential confounding effects of the aboveground physical environment. The DSO treatment received a 0.11 m^3/plot (equivalent to 230 Mg/ha) surface application of municipal compost, which was incorporated via rototiller. Initial chemical and physical analyses of soil and composts (detailed methods below) are reported in Table 2.

A total of five crops were grown in rotation including cilantro (*Coriandrum sativum* var. Calypso), kale (*Brassica oleracea* var. Toscano), garlic [*Allium sativum* var. Music (2015); German Red (2016)], pepper (*Capsicum annuum* var. Lunchbox Red), and radish (*Raphanus sativus* var. Red Meat). Crop species were chosen to represent a diversity of crop types, including leafy, root, and fruiting crops. Specific cultivars were chosen for their unique properties (e.g., 'Red Meat' radish has white exterior and dark pink interior flesh) as a potential strategy for increasing net revenue per unit area in land-limited urban production systems. Experimental units were divided into four 0.19 m^2 quadrants, crop location was randomized among quadrants, and then crops rotated clockwise among quadrants in year two of the experiment. Radish followed kale and cilantro followed garlic in the same quadrants within each year using an intensive double cropping approach. Kale and pepper seedling plugs were transplanted into plots, but all other crops were direct seeded by hand on appropriate planting dates. All crops and cover crops were planted in two rows per quadrat spaced 25 cm apart. Seeding rates were 394 seeds/m for cilantro, 39 seeds/m for radish, and 33 cloves/m for garlic. Transplanting rate was 10 plants/m for pepper and kale. Soybean (79 seeds/m) and hairy vetch (118 seeds/m) (*Vicia villosa* Roth) cover crop seeds were planted in the organic fertility treatments (DSO, RBMO, and RBCO) and followed garlic and pepper, respectively. Cover crop green manure was incorporated into the soil using a hand trowel at termination, but cash crop residues were removed from plots at the conclusion of the growing season.

Crops were irrigated using drip irrigation (Indiana Irrigation Co., Onward, IN, USA; DripWorks, Willits, CA, USA). Two emitter lines were used per plot in 2015, and a third emitter line was installed in 2016 to improve soil coverage. Irrigation system assembly enabled irrigation schedules unique to growing media composition (direct soil, raised bed with soil and compost mix, and raised bed with compost only). Volumetric surface soil moisture (TH_2O portable soil moisture meter; Dynamax Inc., Houston, TX, USA) and tensiometers (Irrometer Company, Inc., Riverside, CA, USA) were used to determine irrigation scheduling. In 2015, direct soil treatments (DSO and DSF) received a season-long total of 3300 L/plot, and all raised beds treatments received a total of 3200 L/plot. In 2016, direct soil treatments received a season-long total of 2100 L/plot, raised bed with soil and compost treatments received 1700 L/plot, and compost only raised beds received 2500 L/plot.

Soil sampling was performed using JMC soil probes consisting of a 1.9 cm bore (Clements Associates Inc., Newton, IA, USA) and an AMS soil probe consisting of a 2.54 cm bore (AMS Inc., American Falls, ID, USA). Soil sampling occurred pre-plant (spring) and post-harvest (fall) each year. Two cores per quadrant were collected to a depth of 20 cm for a total of eight cores per experimental unit. Samples were sent to Ward Laboratories in Kearney, NE and analyzed for

Table 3. Summary of nitrogen fertilizer rates and types for treatments and crops requiring fertilization in 2015 and 2016 (rates determined from pre-plant soil tests and crop nutrient removal estimates). All fertilizers were surface applied and immediately incorporated into the soil.

Year	Treatment†	Crop quadrants	Application rate‡	Fertilizer type
2015	DSF	All crops	56 kg N/ha	Urea
		Radish	27 kg N/ha	Urea
	DSO	Radish	7.3 Mg/ha	Compost
2016	DSF	Cilantro	42 kg N/ha	Urea
		Kale	42 kg N/ha	Urea
		Garlic	42 kg N/ha	Urea
		Pepper	84 kg N/ha	Urea
		Radish	24 kg N/ha	Urea
	DSO	Cilantro	2.8 Mg/ha	Compost
		Kale	2.8 Mg/ha	Compost
		Garlic	2.8 Mg/ha	Compost
		Pepper	5.6 Mg/ha	Compost
	RBMF	Cilantro	20 kg N/ha	Urea
		Kale	20 kg N/ha	Urea
		Garlic	20 kg N/ha	Urea
		Pepper	37 kg N/ha	Urea

† DSF = direct soil + mineral fertilizers; DSO = direct soil + organic amendments; RBMF = raised bed, soil and compost mix + organic amendments; RMBO = raised bed, soil and compost mix + organic amendments; RBCF = raised bed, compost-only + mineral fertilizer; RBCO = raised bed, compost-only + organic amendments.

‡ Dry weight basis.

soil pH (1:1 water dilution), SOM (Walkley–Black method), cation exchange capacity (CEC; sum of cations method), total N (Kjeldahl method), NO_3–N (KCl extraction), P (Bray-1), SO_4–S (calcium phosphate extraction), and K, Ca, Na, and Mg (ammonium acetate extraction). Nitrogen fertilizer application rates (Table 3) for all treatments were determined from pre-plant soil NO_3–N concentrations and generalized crop N removal estimates for leafy (56 kg N/ha) and fruiting crops (112 kg N/ha). No other nutrient fertilization was necessary during the experiment, as soil test values exceeded crop sufficiency values for the crops grown (Egel et al., 2017).

Water infiltration rate was measured using an infiltrometer (Turf-tec International Tallahassee, FL, USA) in pepper and kale quadrants of each experimental unit at the beginning of each year. The infiltrometer uses a modified double-ring approach to measure time required for water in the inner ring to infiltrate the growing media. After saturating the media, inner and outer rings were filled completely with water and the change in inner ring water depth was recorded over 10 min to calculate millimeters of water infiltrated per hour. Bulk density was measured by collecting one soil sample per experimental unit (in a random quadrant) to a depth of 7.6 cm at the beginning of each growing season using a 93.3 cm^3 metal cylinder. A 50-mL subsample of soil was oven-dried for 24 h at 105°C to estimate dry weight of the original sample, and bulk density was calculated as oven dry weight of soil (g) divided by the volume of soil (cm^3). Soil porosity was calculated using bulk density data and assuming an average particle density of soil of 2.7 g cm^{-3} [% porosity = 1– (bulk density/particle density)].

Grass and broadleaf weed emergence was recorded every 2 wk from within a 900 cm^2 quadrat located in the center of each plot (including equal portions of each crop quadrant). After counting, all weeds within the quadrat and the plot were removed by hand. All crops were harvested by hand, separated by marketable and cull, counted, and fresh weights were recorded.

All data were analyzed with ANOVA using the GLIMMIX procedure in SAS (SAS Institute, 2013). Normality of data was assessed using the UNIVARIATE procedure in SAS, and if necessary, data were *ln*-transformed. Treatment, year, and their interaction were treated as fixed effects, and replication was a random effect. If there was no interaction between treatment and year, data were pooled across years. The Tukey-Kramer multiple comparisons test was used to determine differences among least squares means at a significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

Chemical Properties of Growing Media

Organic matter content, pH, CEC, total N, NO_3–N, P, SO_4–S, Ca, Mg, and Na in growing media were usually higher in raised beds than in direct soil, which was related to the proportion of compost in raised bed growing media (Tables 4–6). Properties of growing media in each treatment, at least in the first season, reflected the properties of its primary components, and in the case of compost included alkaline pH, high CEC, high organic matter content (OMC), and high concentrations of plant macronutrients (Table 2). Potassium was greatest in compost only raised beds in year one, but concentrations were greatest in DSO in year two (Tables 4 and 5). Potassium decline in the raised beds between years one and two was likely due to a combination of crop removal and leaching potential unique to this cation. Charge of a cation and its hydrated radius determine adsorption ability to a soil colloid, and the charge and hydrated radius of potassium are less than other cations found in compost and soil (e.g., Ca^{2+}). If calcium levels are high relative to potassium, as they were in raised beds, calcium can displace potassium due to soil colloid cation selectivity, and displaced potassium cations can be leached (Brady and Weil, 2002).

Though typically used for container or seedling plug production, compost can be an effective growing media, but chemical characteristics and suitability can vary depending on feedstock (Clark and Cavigelli, 2005). The abundance of OMC in compost media is generally a benefit to growers because it serves as a reservoir of plant essential nutrients and CEC; however, plant availability of nutrients stored in OMC

Table 4. Chemical characteristics of soil or growing media in each treatment prior to planting in 2015. Different letters within columns indicate significant differences between mean values (n = 4) according to the Tukey-Kramer multiple comparisons test (α = 0.05). SE = standard error of the least squares means.

Treatment†	pH	OMC§	NO$_3$–N	K	S	Ca	Mg
		%	mg/kg			g/kg	mg/kg
DSF	7.5 d	3.5 d	6.7 d	257.3 c	9.7 d	2.41 d	258.6 d
DSO	7.6 c	5.2 c	11.6 d	396.6 b	16.3 c	2.88 c	397.9 c
RBMF	7.7 bc	11.5 b	26.7 c	332.5 bc	31.7 b	4.10 b	755.6 b
RBMO	7.8 abc	12.0 b	32.2 c	374.1 b	33.5 b	4.41 ab	822 ab
RBCF	7.9 a	20.1 a	44.8 b	637.3 a	54.3 a	4.53 a	870.9 a
RBCO	7.8 ab	19.8 a	58.5 a	693.4 a	67.0 a	4.50 ab	890.0 a
SE	0.03	-‡	2.1	22.9	-‡	0.09	19.8

† DSF = direct soil + mineral fertilizers; DSO = direct soil + organic amendments; RBMF = raised bed, soil and compost mix + organic amendments; RMBO = raised bed, soil and compost mix + organic amendments; RBCF = raised bed, compost-only + mineral fertilizer; RBCO = raised bed, compost-only + organic amendments.

‡ Data were transformed for analysis and backtransformed for presentation, but standard errors cannot be backtransformed.

§ OMC, organic matter content.

Table 5. Chemical characteristics of soil or growing media in each treatment prior to planting in 2016. Different letters within columns indicate significant differences between mean values (n = 4) according to the Tukey-Kramer multiple comparisons test (α = 0.05). SE = standard error of the least squares means.

Treatment†	pH	OMC§	NO$_3$–N	K	S	Ca	Mg
		%	mg/kg			g/kg	mg/kg
DSF	7.7 b	3.3 d	7.5 d	207.5 b	7.7 d	2.36 d	303.4 d
DSO	7.7 b	5.0 c	15.5 cd	293.1 a	13.6 c	2.83 c	425.1 c
RBMF	7.9 a	9.7 b	18.3 bc	191.8 b	23.1 b	3.83 b	708.9 b
RBMO	7.9 a	10.5 b	26.7 b	204 b	23.9 b	3.88 b	735.6 ab
RBCF	7.8 a	28.3 a	41.9 a	185.5 b	32.1 a	4.38 a	771.8 ab
RBCO	7.8 a	28.0 a	48.9 a	219.8 b	32.4 a	4.54 a	813.8 a
SE	0.03	-‡	2.1	10.4	-‡	0.06	19.3

† DSF = direct soil + mineral fertilizers; DSO = direct soil + organic amendments; RBMF = raised bed, soil and compost mix + organic amendments; RMBO = raised bed, soil and compost mix + organic amendments; RBCF = raised bed, compost-only + mineral fertilizer; RBCO = raised bed, compost-only + organic amendments.

‡ Data were transformed for analysis and backtransformed for presentation, but standard errors cannot be backtransformed.

§ OMC, organic matter content.

depends on compost maturity, C:N, and nutrient mineralization rates (Cogger, 2005). Clark and Cavigelli (2005) found that food waste compost was a better growing media than horse bedding compost because the food waste compost did not immobilize N, and it had lower pH and electrical conductivity. Alkaline pH (>8) in compost growing media is not uncommon (Rippy et al., 2004; Zhang et al., 2013) and can limit availability of some plant essential nutrients (e.g., Fe). Elevated salts and greater electrical conductivity in compost can be toxic to germinating seedlings, and sensitivity varies by species (Sánchez-Monedero et al., 2004); thus, compost should be analyzed prior to use as a sole source of growing media in raised beds, especially when crops will be direct seeded. However, mixing compost with other components (e.g., top soil), as was done with the RBMF and RBMO treatments in this study, can help to alleviate potentially negative physiological effects of compost properties on plants (Moldes et al., 2007).

Total N in the compost-only (RBCF and RBCO) and compost-plus-soil (RBMF and RBMO) raised bed treatments was 6.9× and 2.9× greater, respectively, than in direct soil (Table 6). A substantial total N supply in raised bed media does not necessarily equate to an abundance of plant available NO$_3$–N or ammonium, as this depends on timely mineralization of organic N sources (Cogger, 2005). However, NO$_3$–N in the compost-only raised beds (RBCF and RBCO) was 5.6× and 4.0× greater than direct soil treatments (DSF and DSO) in 2015 and 2016, respectively. Similarly, NO$_3$–N in compost-plus-soil raised beds (RBMF and RBMO) was 3.2× and 2.0× greater than direct soil in 2015 and 2016, respectively. As a result of elevated NO$_3$–N and sufficient mineralization of organic N, supplemental fertilizer application was not necessary in the RBCF treatment in either year (according to pre-plant soil tests). Nitrogen fertilizer was only needed in year two of the RBMF treatment, and the required rate was just 25% of the applied rate in the direct soil treatment (data not shown). Depending on feedstock, compost can displace mineral N fertilization requirements in potting media (Sánchez-Monedero et al., 2004); indeed, pre-plant soil nitrate tests across both years of this study suggested

Table 6. Chemical characteristics of soil or growing media in each treatment pooled across 2015 and 2016 due to an insignificant ($p > 0.05$) treatment-by-year interaction effect. Different letters within columns indicate significant differences between mean values (n = 8) according to the Tukey-Kramer multiple comparisons test (α = 0.05). SE = standard error of the least squares means.

Treatment†	Na	CEC‡	P	Total N
	mg/kg	meq/100 g	mg/kg	g/kg
DSF	51.5 b	15.1 d	141.1 b	1.76 d
DSO	58.3 ab	18.8 c	159.5 b	2.61 c
RBMF	63.2 a	26.9 c	157.9 b	4.85 b
RBMO	64.7 a	28.2 b	167.1 b	5.25 b
RBCF	64.0 a	30.5 a	347.9 a	12.04 a
RBCO	63.9 a	31.1 a	329.5 a	12.28 a
SE	9.2	0.9	12.1	0.37

† DSF = direct soil + mineral fertilizers; DSO = direct soil + organic amendments; RBMF = raised bed, soil and compost mix + organic amendments; RMBO = raised bed, soil and compost mix + organic amendments; RBCF = raised bed, compost-only + mineral fertilizer; RBCO = raised bed, compost-only + organic amendments.

‡ CEC, cation exchange capacity.

Table 7. Physical properties of soil or growing media in each treatment pooled across 2015 and 2016 due to a lack of treatment-by-year interaction effect. Different letters within columns indicate significant differences between mean values (n = 8) according to the Tukey-Kramer multiple comparisons test (α = 0.05). SE = standard error of the least squares means.

Treatment†	Bulk density	Soil porosity	Water infiltration
	g/cm^3	%	mm/h
DSF	1.30 a	52 c	226 c
DSO	0.87 b	67 b	2017 b
RBMF	0.85 b	68 b	1520 bc
RBMO	0.89 b	67 b	1832 b
RBCF	0.32 c	89 a	4596 a
RBCO	0.35 c	87 a	4290 a
SE	0.04	1.0	806

† DSF = direct soil + mineral fertilizers; DSO = direct soil + organic amendments; RBMF = raised bed, soil and compost mix + organic amendments; RMBO = raised bed, soil and compost mix + organic amendments; RBCF = raised bed, compost-only + mineral fertilizer; RBCO = raised bed, compost-only + organic amendments.

compost-only growing media would be a sufficient source of season-long plant available N. Though not practiced in this study, soil NO_3–N testing pre-plant and again during early crop vegetative growth can be useful for monitoring timely mineralization of organic N in certain immature composts (Clark and Cavigelli, 2005). If deemed necessary after soil testing, an in-season mineral fertilizer application can quickly alleviate physiological stress and also help to speed mineralization of organic N in the compost (Raviv et al., 2005).

Phosphorus in compost-only raised beds (RBCF and RBCO) was 2.2× greater than in direct soil (DSF and DSO) and compost-plus-soil raised beds (RBMF and RBMO; Table 6). Phosphorus fertilization was not needed in any treatment during the 2 yr of this experiment, as soil and media concentrations remained above sufficiency levels for the crops grown (>35–40 mg P/kg; Egel et al., 2017). Soil P well in excess of sufficiency levels, as was observed in all treatments of this study (ranging from 141 to 348 mg P/kg), is susceptible to runoff with water as surface sediment and surface water pollution (Moseley et al., 2008). However, P fertilization and compost amendment are also possible strategies for immobilizing soil lead in urban gardens as lead-phosphate precipitates (e.g., pyromorphites) and reducing bioavailability to plants and humans (Wortman and Lovell, 2013); thus, additional research is needed to determine the optimum concentration of P in compost-amended urban garden soils to balance crop productivity and human and environmental health.

Physical Properties of Growing Media

Bulk density was greatest in DSF followed by DSO, which suggests improvements in a soil physical property can be achieved after a single compost amendment of urban soils (Table 7). Beniston et al. (2015) reported similar results where the addition of organic matter reduced compaction within urban surface soils. Bulk density was lowest and porosity was greatest in the compost-only raised beds (RBCF and RBCO), which contributed to the fastest water infiltration rate among treatments. Despite the potential benefits of compost as a growing media, poor water holding capacity has been identified as a challenge (Rogers, 2017). Water infiltration rate was 20× higher in compost-only raised beds (RBCF and RBCO) than in direct soil without organic amendment (DSF; Table 7). Infiltration rates were similar among RBMF, RMBO, and DSO treatments, which were on average 7.9× higher than in DSF. Water movement downward in the soil profile is influenced by porosity and bulk density (Agnew and Leonard, 2003). Pitt et al. (1999) observed increases in water infiltration rates due to compost applications. High water infiltration rates may be a desirable characteristic of urban farms and gardens as it may help to reduce storm water runoff (Wortman and Lovell, 2013). However, increased rates of water infiltration through raised beds may lead to greater water use requirements and nutrient leaching. Mazuela et al. (2005) found that leaching compost with eight times its volume in distilled water was enough to leach 98% of salts through a 25-cm column; however, leaching dynamics in field-based raised bed production systems with tap or well water for irrigation have not been studied.

Weed Abundance

Broadleaf weeds were most abundant in direct soil plots (DSF and DSO) each year (Table 8). Weed emergence was relatively low in the compost-only raised beds (RBCF and RBCO). Despite low populations across all treatments in 2015, grass weeds were most prevalent in the RBMO treatment. In 2016, grass weed emergence was greatest in the DSF treatment (Table 8). Results demonstrate the value of compost in raised beds, as weed abundance decreased as the proportion of compost in

Table 8. Broadleaf and grass weeds emerged per m^2 every 2 wk during 2015 and 2016. Different letters within columns indicate significant differences between mean values (n = 4) according to the Tukey-Kramer multiple comparisons test (α = 0.05). SE = standard error of the least squares means.

Treatment†	Broadleaf		Grass	
	2015	2016	2015	2016
	plants/m^2/2 wk			
DSF	46 a	70 ab	1 b	33 a
DSO	58 a	109 a	1 b	9 a
RBMF	11 b	16 bc	4 ab	6 a
RBMO	13 b	42 bc	7 a	3 a
RBCF	4 b	9 c	1 b	1 a
RBCO	5 b	11 c	1 b	3 a
SE	1.7	5.1	0.4	3.9

† DSF = direct soil + mineral fertilizers; DSO = direct soil + organic amendments; RBMF = raised bed, soil and compost mix + organic amendments; RMBO = raised bed, soil and compost mix + organic amendments; RBCF = raised bed, compost-only + mineral fertilizer; RBCO = raised bed, compost-only + organic amendments.

the treatment increased. The thermophilic phase of aerobic, windrow composting (where core temperatures can exceed 60°C)– which was used to produce compost used in this study– is lethal to many weed species and seed viability approaches 0% after 1 mo of composting (Tompkins et al., 1998; Larney and Blackshaw, 2003). However, weed abundance increased between 2015 and 2016 in all treatments, which demonstrates the potential for rapid weed infestation even when initial weed abundance is low. A "zero seed rain" management strategy– preventing weeds from producing seeds– can be labor intensive, but may be necessary to maintain low weed seedbank abundance in the long-term (Brown and Gallandt, 2017).

Crop Yield

Garlic yield was not influenced by production treatments across both years (Table 9). Pepper yield was highly variable, due in part to disease issues (data not shown), but was usually greater in direct soil than in raised bed treatments (Table 9). Radish, cilantro, and kale yields were generally greater in raised beds (particularly compost-only raised beds) than in direct soil (Table 9).

We had hypothesized that garlic and radish yields would be greatest in raised beds due to the abundance of soil nutrients and loosely textured media (Abbey et al., 2002). However, root crop yield response to compost and other organic amendments can be less pronounced relative to grain, fruiting, and vegetative crops (Wortman et al., 2017). Filippini et al. (2012) found that 4 Mg ha^{-1} of vermicompost and chicken litter compost was insufficient for increasing garlic yield, but 8 Mg ha^{-1} did increase yield compared to a non-fertilized direct soil control. In a different study, a 1:1 mix of soil and vermicompost increased garlic yield nearly three-fold compared to soil alone (Argüello et al., 2006). However, the soil control in Argüello et al. (2006) had extremely low organic carbon, whereas the direct soil in our study had greater SOM and initial plant essential nutrient concentrations (Table 2).

Reduced pepper yield in raised beds was surprising, and may have been the result of excessive N fertility. Nitrate concentrations in the compost-only raised beds remained high through both years of the experiment, and abundant mineral N can lead to excessive vegetative growth relative to flower and fruit development in pepper and other fruiting crops (Wortman, 2015). Consistent with this explanation, pepper yield was greatest in direct soil treatments (Table 8) where soil NO_3–N concentrations were lowest (Tables 4 and 5). Arancon et al. (2004) found that growing peppers in

Table 9. Fresh crop weight yield in each treatment in 2015 and 2016 [data were pooled across years for garlic and cilantro due to an insignificant (p > 0.05) treatment by year interaction effect]. Different letters within columns indicate significant differences according to the Tukey-Kramer multiple comparisons test (α = 0.05). SE = standard error of the least squares means.

Treatment†	Crop yield							
	Garlic	Pepper		Radish		Kale		Cilantro
		2015	2016	2015	2016	2015	2016	
	kg/m^2							
DSF	3.41 a	1.77 a	1.32 abc	0.58 c	-‡	4.67 b	1.18 bc	2.14 b
DSO	3.83 a	1.27 ab	2.48 a	4.59 bc	-‡	4.28 b	0.93 c	1.73 b
RBMF	3.39 a	0.95 ab	2.11 ab	8.15 ab	4.31 a	10.20 a	2.62 ab	2.10 b
RBMO	3.32 a	0.49 b	0.54 bc	8.70 ab	3.84 a	9.81 a	4.66 a	2.76 ab
RBCF	3.25 a	0.45 b	0.46 c	7.88 ab	5.47 a	10.11 a	3.98 a	3.72 a
RBCO	3.15 a	0.92 ab	1.15 abc	10.43 a	3.16 a	11.34 a	3.69 a	3.62 a
SE	0.11	0.08	0.13	0.33	0.26	0.20	-§	0.26

† DSF = direct soil + mineral fertilizers; DSO = direct soil + organic amendments; RBMF = raised bed, soil and compost mix + organic amendments; RMBO = raised bed, soil and compost mix + organic amendments; RBCF = raised bed, compost-only + mineral fertilizer; RBCO = raised bed, compost-only + organic amendments.

‡ No data due to poor seedling emergence.

§ Data were transformed for analysis and backtransformed for presentation, but standard errors cannot be backtransformed.

100% vermicompost reduced marketable yield by nearly 50% compared to a more balanced mix of vermicompost with peat, bark, and perlite. Moreover, the yield loss in 100% vermicompost occurred despite increases in mineral N and microbial biomass N. Among other benefits, mixing compost with topsoil in raised beds may help to reduce mineral soil N and increase yield of fruiting crops like pepper, but that was not always realized in this study (Table 9).

Radish yield was greatest in the RBCO treatment in 2015. However, in 2016, radish yields were similar across measured treatments and no yield data could be collected from direct soil plots due to poor seedling emergence. Similar to peppers, previous research suggests that a mix of compost with other soilless media will increase radish yield relative to compost alone. Gajdoš (1997) found that a 1:2 compost/peat mix was necessary to maximize radish root dry matter yield. However, results of this study suggest that radish yield benefits from raised bed production, regardless of media composition. There is a negative relationship between crop seedling emergence and force required to penetrate the soil surface after germination, especially for small-seeded vegetable crops (Hegarty and Royle, 1978). Given the greater porosity and lower bulk density of compost compared to top soil, compost-based raised beds may be more suitable for direct seeding small-seeded vegetable crops. Mixing top soil and compost in raised beds could maintain low surface resistance to emerging seedlings, but also help to retain moisture near the surface necessary for consistent germination.

Cilantro yield was 90% greater in compost-only raised beds compared to direct soil across both years. Similarly, kale yield was 140 and 264% greater in compost-only raised beds compared to direct soil in 2015 and 2016, respectively. Kale yield in raised beds was not influenced by growing media composition or fertilizer source (Table 9). Yield benefits of growing kale and cilantro in compost-based raised beds are consistent with results of Wortman et al. (2017), where we demonstrated that leafy vegetable crops are most responsive to organic soil amendments in the first season after application. Yield benefits of leafy crops in compost-based raised beds may be due to increased mineral N (Tables 4 and 5), which has been shown to increase shoot:root biomass partitioning (Wortman and Dawson, 2015). Lettuce (*Lactuca sativa* L.), another common leafy crop, also exhibits yield gains proportional to increasing N fertilizer rates (until an upper yield limit is reached; Pavlou et al., 2007).

CONCLUSION

Results of this study document the agronomic benefits of raised bed vegetable production for urban agriculture. Raised beds, with compost or compost-plus-soil growing media, have greater OMC, CEC, and concentrations of essential plant macronutrients. Compared to direct soil, raised bed media was also characterized by reduced weed abundance, lower bulk density, greater porosity, and greater water infiltration rates, which may help to mitigate storm water runoff in urban areas. However, elevated NO_3–N and P concentrations in raised bed media may be susceptible to leaching and runoff, potentially contributing to eutrophication of surface waters even if storm water runoff is reduced. Mixing compost with an equal amount of top soil in raised beds reduced nutrient concentrations, water infiltration rate, and irrigation water use, which may help to mitigate potentially negative environmental impacts of urban crop production. Crop yield was increased in raised beds compared to direct soil for three of the five crops tested, and leafy crops benefited most from raised bed production. With few exceptions, yield was not influenced by differences in growing media or fertilizer type within raised beds. As a result, we recommend urban gardeners and farmers use a mix of compost and top soil in raised beds and fertilize with organic amendments. Given the potential benefits of compost and top soil mixes in raised beds, future research should evaluate additional mixing ratios as well as other sources of locally available organic amendments, including composted municipal biosolids.

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