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Residual Compost Carryover on Soil Health and Biology in a Citrus-Supporting Ustoll

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ABSTRACT

Organic matter and its attendant benefits are vital to productivity. Residual effects of municipal compost were examined to 15-cm depth on a Cameron (Vertic Haplustoll) silty clay in which a previous experiment had implemented a cross-factorial plus control test of compost (applied; not applied) versus inorganic fertilizer (13-13-13; ammonium sulfate; urea). Eight years since the most recent application of compost, soils treated with compost and inorganic fertilizer were found to have increased organic matter (OM), protein and extractable P, Mg and Zn, and pH lowered toward neutral, relative to soils amended only with inorganic fertilizer. Broad trends across approximately 30 analytes corroborate improved soil health as quantified by the Cornell Soil Health Assessment Index.

Additional index words: soil quality, Citrus paradisi, soil change

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While it is understood that organic matter has ‘carryover’ or ‘residual’ effects, particularly with nitrogen (Endelman et al., 2010) most studies focus on the effects of current application. Studies that have examined residual or carryover effects have done so in maize (Zea maize; Eghball et al., 2004; Olsen et al., 2015), wheat (Triticum aestivum; Cogger et al., 2014; Damelash et al., 2014; Indraratne et al., 2009; Obour et al., 2017; Reeve et al., 2012), cotton (Gossypium hirsutum; Tewolde et al., 2011) and soy (Glycine max; McAndrews et al., 2006). About half of these studies have included analysis of soil health-related variables (Table 1). Residual soil effects from organic matter addition include heightened soil organic matter, total nitrogen and phosphorus (P), nitrate, extractable P and potassium. While these increases might generally be welcome, others, such as pH changes, would be conditionally favorable, or potentially harmful (increases in electrical conductivity (EC); Table 1). While some studies have examined residual effects more than a decade after the last addition of organic matter, many have done so after only three years or less (Table 1).

Because of a lack of studies in a citrus context (Table 1) and a relative lack of studies examining carryover effects of organic matter addition beyond a 3-yr lag (Table 1), here medium-term residual effects of compost application were evaluated in the eighth year (2015) following the final application of compost in a grove of grapefruit (*Citrus paradisi*). This study followed a five-year study (ending in 2007) of annual organic matter application at the same grove in which organic matter (OM), soil moisture and rooting were increased by the fifth year (Nelson et al., 2008). The goal of the present study is to report any residual soil effects of compost addition in citrus, examining a suite of 50 soil health and soil biological variables. Because of the nature of the antecedent experiment, we also examined any residual effects of inorganic fertilizer simultaneously applied with compost.

MATERIALS AND METHODS

The study was carried out in a group (26° 07’46.68”N, 97°57’16.77”W) of 29-year old ‘Rio Red’ grapefruit scions grafted onto sour orange rootstock at the South Farm of the Texas A&M University

Table 1. 'Residual' or 'Carryover' effects[z] of organic matter addition on soil variables

1st author and year	Amend-ment[y]	Sampling Depth (cm)	Lag (yr)	TC/OM	TN	TP	IN/NO_3-N	Extractable P	Extractable K	pH	EC	BD
Cogger 2014[x]	BS	10	3	+[w]	+			+		-	+	-
Damelash 2014	C	25	1	+				+				
Eghball 2004	M&C	15	3		+		+			+	+	
Indraratne 2009	M	15	17	L[v]	NL	L	L	L				
McAndrews 2006	M&C	20	1					+	+			
Olsen 2015	C	30	1				+	+				
Obour 2017	M	15	24	+				+	+	+	+	
Reeve 2012	C	10	16	+				+	+			

[z] 'Lag' time between last application of organic amendment and sampling; 'TC/OM' total carbon or organic matter; 'TN' total nitrogen; 'TP' total phosphorus; 'IN/NO_3-N' inorganic nitrogen or nitrate-nitrogen; 'EC' electrical conductivity; 'BD' bulk density.

[y] 'BS' biosolids; 'C' compost; 'M' manure.

[x] Also inspected a suite of microbial variables: bacterial biomass, aerobic bacteria, gram positive, gram negative, anaerobic bacteria, fungi, and the ratio of bacteria to fungi (all of which were increased in amended plots, save fungi).

[w] '+' increased concentration or value in soil upon sampling; '-' decreased value upon sampling

[v] 'L' likely increase based on data displayed in paper but not confirmable within the paper; 'NL' increase not likely based on data displayed in paper but not confirmable within paper.

'NL' increase not likely based on data displayed in paper but not confirmable within paper.

-Kingsville Citrus Center, Weslaco, TX. The group of trees comprised six rows (oriented North-South) with 21 trees per row. Experimental units were groups of three adjacent trees in the same row thereby providing 7 experimental units per row. Scope of inference of the study is the grove of trees itself.

The experimental area was mapped as a 'Cameron (clayey over loamy, mixed, active, hyperthermic Vertic Haplustoll) silty clay' (Soil Survey Staff, 2017). The soil in question undergoes a significant change in texture within 100 cm of the soil surface (clayey over loamy; terrace landscape of the Rio Grande river), is not dominated by any particular mineral type (mixed), is of fairly high cation exchange capacity (active), has a mean annual soil temperature above 22°C at 50 cm depth (hyperthermic), is moderately susceptible to shrink/swell behavior upon changes in moisture (Vertic) and otherwise is a typical high-organic matter soil in a semiarid climate (Haplustoll). In Weslaco, TX, the maximum average monthly temperature is 36° C (August), the minimum average monthly temperature is 9°C (January); average annual precipitation is 63 cm, with most precipitation in summer and fall (Fig. 1; USClimatedata.com).

Table 2. Treatments, Tests and Replication

------ Treatments -------		---------- Tests[z] ----------	
45.7 kg Compost	0.454 kg Inorganic N	Soil Health and Biology	Routine Soil Fertility
------- ($tree^{-1}$ yr^{-1}) -------		------------- *n*-------------	
None	None	2	6
None	13-13-13	2	4
None	$(NH_4)_2SO_4$	2	6
None	Urea	2	6
Added	13-13-13	2	6
Added	$(NH_4)_2SO_4$	2	6
Added	Urea	2	6

[z] 'Soil Health', Cornell Soil Health Testing Laboratory 'Standard' package; 'Biology', Earthfort Laboratories 'Advanced Biology' package; 'Routine Soil Fertility', Texas A&M Soil Water and Forage Laboratory 'Routine' analysis.

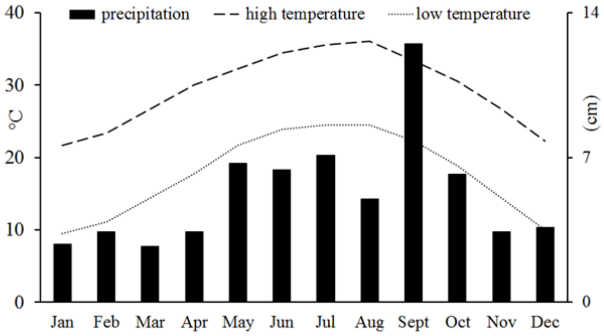

Figure 1. Average precipitation and temperature in Weslaco, TX. Source: USclimatedata.com. 19 July 2017. <http://www.usclimatedata.com/climate/weslaco/texas/

Table 3. Experimental Layout^z

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Contr^y	A	U	13	13+C	13
A+C	13	13+C	13+C	A+C	U
·	U+C	U+C	A+C	·	U+C
13+C	13+C	Contr	A	U	A+C
A	U	A+C	U	Contr	13+C
U	Contr	A	U+C	A	Contr
U+C	A+C	13	Contr	U+C	A

^{z}Six blocks; seven treatments randomly placed per block.

^{y}'Contr' control; 'A' ammonium sulfate only; 'A+C' ammonium sulfate and compost; 'U' urea only; 'U+C' urea and compost; '13' 13-13-13 only; '13+C' 13-13-13 and compost; '·' No sample collected.

As described by Nelson et al. (2008), in 2002 experimental units were assigned to one of seven treatments (Table 2) in a 3x2 cross-factorial plus control (i.e., all combinations of 3 levels of inorganic N and 2 levels of compost as well as a non-treated control). Each treatment was assigned once to each row, allowing rows to provide replication. The experimental design, therefore, was a randomized complete block design in which rows of trees served as blocks (Table 3). Blocking occurred for the sake of distributing treatments throughout the experimental area and did not occur in response to a perceived environmental gradient. One treatment factor, inorganic fertilizer, was applied at the same nitrogen rate (0.454 kg N tree^{-1} yr^{-1}) across all levels of treatment, in the form of three fertilizer types (13-13-13, slow-release urea [46-0-0], ammonium sulfate [$(NH_4)_2SO_4$; 21-0-0]; Table 2). The other treatment factor, compost from suburban yard waste (Brownsville, Texas Municipal Recycling Facility; Table 4), occurred in two levels (45.7 kg compost tree^{-1} yr^{-1} applied to 6-in depth below the canopy, and no-application; Table 2; Table 3). Compost and fertilizer treatments were applied annually from 2002 to 2007. Compost addition provided an insignificant amount of additional nitrogen (0.002 kg N tree^{-1} yr^{-1}; Nelson et al., 2008). Aspects of the experimental design and procedures and further details about general management are discussed by Nelson et al. (2008). Since activities ending in 2007, inorganic fertilization has uniformly occurred across the trees of the study.

In June 2015, eight years since the most recent compost addition, the soil was sampled for the purposes of quantifying aspects of soil quality and soil biology. Samples were taken with a 5-cm (2-in) diameter coring device attached to a drop hammer (AMS Samplers, American Falls, ID). Three subsamples, 0-15 cm (0-6 in) in depth, were obtained 1 m from the central tree of each experimental unit. The three subsamples from each experimental unit were composited and mixed in a washed bucket, forming a single, homogenized sample per experimental unit. One treatment had two experimental units in which the original central tree was missing or the experimental unit was otherwise compromised. These experimental units were not sampled, yielding a sampling total of 40 (Table 2; Table 3).

Subsamples of the homogenized composites were sent to the Texas A&M Soil, Water and Forage Testing Laboratory (College Station, TX) for 'routine' analyses: pH (Schofield and Taylor, 1955) and EC (one-part soil to two-parts deionized water slurry; Rhoades, 1982), NO_3-N (via colorimetry of a cadmium-reduced 1N KCl extract; Keeney and Nelson, 1982; Kachurina et al., 2000), and Mehlich-3 extractable P, K, Ca, Mg, S and Na (Mehlich, 1984; via Inductively Coupled Plasma).

A subset of samples (replication = 2; Table 2), chosen from the middle of the grove to eliminate edge effects, was sent to Earthfort Labs (Corvallis, OR) and the Cornell Soil Health Laboratory (Ithaca, NY) for soil biological and soil health analyses, respectively (Table 2; Table 5). While such per treatment (n=2) replication of soil health and biology data may be low, resources allowing increased replication were con-

Table 4. Compost characteristics

pH	EC	OC	NO_3-N	P	K	Ca	Mg	S	Na
	dS m^{-1}	%	------------------------------------ mg kg^{-1} ------------------------------						
7.5	0.23	12.6	41.0	580	860	12200	500	80	210

Source: Nelson et al. (2008).

Table 5. Analytes of Cornell Soil Health and Earthfort Labs used in this study

Cornell Soil Health Assessment ‘Standard Soil Health Analysis Package’

Analyte	Explanation
Texture	% mineral material as sand, silt and clay
Aggregate Stability	% mass of soil aggregates 0.25-2.0 mm in size that do not pass through a 0.25 mm sieve after a period of disturbance under a Cornell Sprinkle Infiltrometer
Plant-available Water	Difference in water content of loose soil between field capacity (10 kPa) and the wilting point (1500 kPa) in a pressure plate device
Organic Matter	%OM = (%LOI)0.7 – 0.23 %LOI= Mass lost on ignition of soil sample at 500 C for 2 hours
Active Carbon	Colorimetric observation of color loss (oxidation) of 0.02 M $KMnO_4$ after 2 min exposure to soil. Correlated with OM fraction palatable to microbes
Extractable Protein	Citrate-extractable protein upon autoclaving
Respiration	CO_2 collected, using a NaOH trap, from aerobically incubated soils
Morgan-extractable P, K, Mg, Fe, Mn, Zn	Nutrient concentrations (mg L^{-1}) in solution after exposure of soil to a sodium acetate/acetic acid solution at pH= 4.8
pH	Measured in a slurry of one part soil to two parts deionized water

Earthfort Soil Biology Analysis ‘Advanced Biology Package’

Active Bacteria		µg g^{-1}	Mass of bacteria actively respiring
Active Fungi			Mass of fungi actively respiring
Total Bacteria			Mass of bacteria actively respiring and dormant
Total Fungi			Mass of fungi actively respiring and dormant
Actinomycetes			Mass of actinobacteria
Endomycorrhizae		%	Colonization of roots
Hyphal Diameter		µm	Average diameter of fungal hyphae (bigger is better)
AFAB		µg µg $^{-1}$	Ratio of active fungi to active bacteria
AFTF			Ratio of active fungi to total fungi
ABTB			Ratio active to total bacteria
TFTB			Ratio of total fungi to total bacteria
Flagellates		# g^{-1}	Obligate aerobes (high numbers indicative of aerobic conditions)
Amoeba			
Ciliates			Facultative anaerobe (high numbers potentially indicative of anaerobic conditions)
Bacteria-Feeding	Nematodes		Consumption of indicated group and concurrent mineralization (release) of nutrients
Fungal-Feeding			
Fungal- and Root-Feeding			
Root-Feeding			
Predatory (nematode- and protozoa-feeding)			
Total			Total of above functional groups
Genera			Identification of specific nematode genera
Nitrogen Cycling Potential		kg ha^{-1}	(Calculated) function of protozoa and nematode numbers. Provides speculative nitrogen mineralization over a 3-6 month period

Sources: Moebius-Clune et al., 2016; www.earthfort.com

strained, and the cross-factorial nature of the design effectively increased replication (Mead, 1988; Pearce, 2005) of soil health and biology data when interactive effects were not evaluated.

Microscopic techniques were used by Earth Laboratories to quantify actively respiring (Stamatiadis et al., 1990) and total (Van Veen and Paul, 1979) bacteria and fungi as well as mycorrhizal colonization

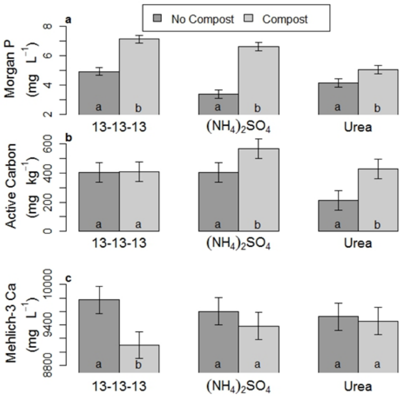

Figure 2. Interaction of compost and inorganic fertilizer eight years after last compost application. Compost means within a level of fertilizer followed by the same letter are not distinguishable at the 0.05 level.

(Rajapakse and Miller, 1992). Other techniques utilized by Earthfort include (1) the most probable number method to quantify protozoa (Stevik et al., 1998), (2) nematode extraction using the method of Baermann (1917) modified with methods of Anderson and Coleman (1977) and (3) nematode identification using Bongers et al. (1988), Goodey (1963) and Mai and Lyon (1975). Organic Matter was measured by the Cornell Soil Health Testing Laboratory using the method of Broadbent (1965). Other variables of the Cornell Soil Health Test were measured using Cornell Soil Health Laboratory standard operating procedures provided by Schindelbeck et al. (2016). These procedures are grounded in published methods (texture, Kettler et al. (2001); aggregate stability, Moebius et al. (2007); active carbon, Weil et al. (2003); plant-available water, Reynolds and Topp (2008); respiration, Haney and Haney (2010), Wolf et al. (1952), Wollum and Gomez (1970), Zibilske (1994); extractable protein, Keen and Legrand (1980), Walker (2002), Wright and Upadhyaya (1996).

Statistical Analysis. The MIXED procedure of SAS 9.4 (SAS Corporation, Cary NC) was used to perform Analysis of variance (ANOVA) with blocking according to rows of trees. CONTRAST and ESTIMATE statements evaluated (1) the (2x3) compost*fertilizer interaction, the main effects of (2) composting (three composted treatments; 4 non-composted treatments) and (3) fertilizer type (three levels across both levels of compost) and (4) differences between control (no fertilizer, no compost) and treatment (fertilizer, three treatments; fertilizer+compost, three treatments); when fertilizer and compost interacted the effect of compost was evaluated for each level of fertilizer. Separate analyses were performed for soil health and biology and routine soil fertility (Table 2). Results were considered significant at the 0.05 level. pH data were linearized to hydrogen ion concentration (H^+) using ($H^+=10^{-pH}$) before analysis; results were back-transformed for reporting.

Independent analytes (not functions of other analytes) with favorable averages were tallied according to the factor of compost addition for both the soil health and biology data set and the routine soil fertility data set. The binomial distribution was used to calculate the probability of the number of favorable averages or more favorable (inclusive 'cumulative' probability) under the compost treatment, assuming no treatment effect. The binomial distribution describes the probability of X "successes" in N trials in which the outcomes are dichotomous (either "success" or "failure"). Averages of higher concentration (but below limits specified by the Cornell Soil Health Test) and higher biological activity were considered favora-

Table 6. Main effects of compost eight years after last application

Soil Analyte		Compost	no Compost	% Difference^z	$P<$
Organic Matter	%	3.6±0.1a	2.9±0.1b	24	0.0005
Extractable Protein	mg g^{-1}	4.2±0.3a	2.4±0.2b	68	0.003
Morgan-extractable Mg	mg L^{-1}	550±4a	533±4b	3	0.02
Morgan-extractable Zn		0.49±0.04a	0.25±0.04b	92	0.004
Mehlich-3-extractable P		93±9a	61±9b	52	0.004
Total Fungi	µg g^{-1}	147±51b	226±48a	35	0.05
TAMU^y pH	-N/A-	7.95±0.02b	8.02±0.03a	<1^w	0.02
Cornell pH		7.1±0.1b	7.4±0.2a	4^v	0.05
Overall Cornell Health Index		67±2a^x	54±1b	24	0.0005

^{z}Relative to no compost.

^{y}'TAMU', Texas A&M Soil, Water and Forage Testing Lab;'Cornell', Cornell Soil Health Lab.

^{x}Means and standard errors; means followed by different letters are distinguishable at the 0.05 level.

^{w}Percent difference using pH value; 19% using H^+ concentration.

^{v}Percent difference using pH value; 132% using H^+ concentration.

Table 7. Significant main effects of inorganic fertilization between treatments, eight years after last application

Soil Analyte		13-13-13	$(NH_4)_2SO_4$	Urea	*P*<
Cephalobus (genus) Nematodes	# g^{-1}	1.4±0.1a[z]	0.2±0.1b	0.4±0.1b	0.0008
Mehlich-3-extractable P	mg L^{-1}	105±12a	67±11b	68±11b	0.05
Morgan-extractable K		458±13a	437±13a	406±13b	0.05
Active Fungi	µg g^{-1}	24±7b	32±7b	55±7a	0.02

[z] Means and standard errors; means followed by different letters are distinguishable at the 0.05 level.

Table 8. Significant differences between no-compost no-fertilizer (control) and treatment plots, eight years after last application

Soil Analyte		Control	Treatments	*P*<
Plant-Available Water	cm cm^{-1}	0.216±0.009b[z]	0.243±0.003a	0.05
Cephalobus (genus) Nematodes	# g^{-1}	0.10±0.2b	0.69±0.08a	0.05
Active Carbon	mg kg^{-1}	339±58b	414±55a	0.03

[z] Means and standard errors; means followed by different letters are distinguishable at the 0.05 level.

ble. Exceptions were ciliate and sodium concentrations, EC and root-feeding nematodes. Lower ciliate concentrations were considered favorable because ciliates are often correlated with marginal anoxia (Matthew Slaughter, Earthfort Labs., personal communication). Lower sodium and EC values were considered favorable because of detrimental effects on effective plant available water sometimes made by EC, and detrimental effects on soil structure sometimes induced by sodium. Lower root-feeding nematode counts were considered favorable because of the detrimental effects on plants expected from root-feeding nematodes. Other variables, such as fungal- and root-feeding nematodes and soil particle size separates, were not considered because of uncertainty associated with the favorability of their function.

RESULTS

ANOVA: Interaction of Fertilizer and Compost.

Fertilizer and compost interacted in their effects on Morgan-extractable P ($P<0.05$), active carbon ($P<0.04$) and Mehlich-3 Ca ($P<0.04$). Compost resulted in higher Morgan-extractable P for every level of fertilizer, but with a stronger effect under $(NH_4)_2SO_4$ than under urea (Fig. 2a). Compost resulted in heightened levels of active carbon for $(NH_4)_2SO_4$ and urea but not for 13-13-13 (Fig. 2b). Compost did not improve Mehlich-3 Ca. Rather, for the 13-13-13 fertilizer a lack of compost produced the highest Ca levels (Fig. 2c).

ANOVA: Main Effects of Compost. Within the soil health and biology data set for variables without a significant interaction, compost improved the values of OM ($P<0.002$), citrate-extractable protein ($P<0.003$), Morgan-extractable Zn ($P<0.004$) and pH ($P<0.045$; Table 6). The overall index value for soil health, assigned by the Cornell Soil Health Lab, was raised by 24% in the composted treatments ($P<0.0005$; Table 6). No soil biology analytes were significant save total fungi which was higher without compost ($P<0.05$). Within the routine soil fertility data set pH was marginally but significantly diminished ($P<0.02$) and Mehlich-3 extractable P was increased 52% ($P<0.004$; Table 6). Fungal-feeding nematodes ($P<0.06$), actively respiring bacteria ($P<0.10$) and nitrate ($P<0.09$), exhibited strong trends of increased concentration under residual compost (Table 9a, Table 9b). Weaker trends of increases under residual compost were observed in aggregate stability ($P<0.16$), actively respiring fungi:bacteria ($P<0.21$), bacterial-feeding nematodes ($P<0.15$) and overall nematode numbers ($P<0.16$). A weak trend ($P<0.18$) of *decreased* presence of actively respiring fungi under compost was observed (Table 9a).

ANOVA: Main Effect of Fertilization. Under fertilization, 13-13-13 supported greater numbers of (genus) *Cephalobus* nematodes ($P<0.0005$) and Mehlich-3-extractable P ($P<0.05$) than $(NH_4)_2SO_4$ or urea (Table 7). Morgan-extractable K was increased under 13-13-13 and $(NH_4)_2SO_4$ relative to urea ($P<0.05$). Actively respiring fungi were maximized under urea ($P<0.04$).

ANOVA: Control versus Treatments. The lack of composting and inorganic fertilizer addition accompanied lower plant-available water storage capacity ($P<0.05$), lower presence of *Cephalobus* genus nematodes ($P<0.05$) and lower biologically active carbon ($P<0.03$; Table 8).

Binomial Distribution. Among soil health and biology analytes 27 variables were judged to be independent

Table 9a. Soil health and biology response^z

				Compost	no Compost	$F_{(numdf,dendf)}$	*P*
CORNELL - Soil Health		Sand	%	35	36	$2.61_{(1,5.63)}$	0.1608
		Silt		27	24	$16.33_{(1,7)}$	**0.0049**
		Clay		38	40	$3.80_{(1,5.93)}$	0.0998
		Aggregate stability		**39**	34	$2.75_{(1,5.39)}$	0.1536
		OM		**3.6**	2.9	$46.66_{(1,4.49)}$	**0.0016**
		Plant-Available Water	cm cm^{-1}	**0.243**	0.236	$1.12_{(1,6.41)}$	0.3280
		Active Carbon	mg kg^{-1}	**464**	335	$13.99_{(1,4.3)}$	**0.0176**
		Extractable Protein	mg g^{-1}	**4.2**	2.4	$24.70_{(1,6.45)}$	**0.0021**
		Respiration (evolved CO_2)		**0.69**	0.64	$1.81_{(1,7)}$	0.2209
		pH	N/A	**7.1**	7.4	$5.94_{(1,7)}$	**0.0449**
	Modified Morgan-Extractable	P	mg L^{-1}	**6.1**	4.1	$60.82_{(1,4.55)}$	**0.0008**
		K		**442**	423	$1.86_{(1,7)}$	0.2148
		Mg		**550**	533	$10.26_{1,7)}$	**0.0150**
		Fe		**0.217**	0.200	$1.33_{(1,4.67)}$	0.3039
		Mn		**9.6**	9.3	$0.36_{(1,6.39)}$	0.5693
		Zn		**0.49**	0.25	$22.85_{(1,5.97)}$	**0.0031**
		(overall, calculated) Soil Health Index	N/A	67	54	$39.53_{(1,7)}$	**0.0004**
EARTHFORT- Soil Biology		Active Bacteria	µg g^{-1}	**36.4**	33.1	$4.65_{(1,4.45)}$	0.0905
		Active Fungi		31.2	**42.6**	$2.25_{(1,7)}$	0.1777
		Total Bacteria		1213	**2327**	$0.84_{(1,7)}$	0.3907
		Total Fungi		147	**226**	$7.35_{(1,4.36)}$	**0.0488**
		Actinomycetes		**0.783**	0.418	$0.66_{(1,7)}$	0.4441
		Active Fungi:Active Bacteria	µg µg^{-1}	0.878	1.28	$2.32_{(1,7)}$	0.2021
		Active Fungi:Total Fungi		0.214	0.199	$0.09_{(1,6.53)}$	0.7688
		Active Bacteria:Total Bacteria		0.035	0.027	$1.00_{(1,7)}$	0.3499
		Total Fungi:Total Bacteria		0.15	0.16	$0.00_{(1,5.27)}$	0.9600
		Endomycorrhizae	%	**0.332**	0.266	$1.08_{(1,7)}$	0.3326
		Hyphal Diameter	µm	2.83	**2.86**	$1.88_{(1,7)}$	0.2132
		Flagellates	# g^{-1}	5000	**1000**	$0.79_{(1,4.1)}$	0.4230
		Amoeba		34x10^4	**97x10^4**	$0.63_{(1,7)}$	0.4551
		Ciliates		**147**	194	$0.39_{(1,7)}$	0.5539
	Nematodes	Bacterial-feeding		**4.1**	2.3	$2.71_{(1,7)}$	0.1435
		Fungal-feeding		**0.9**	0.4	$5.52_{(1,7)}$	0.0511
		Fungal- & root-feeding		1.3	1.0	$0.21_{(1,7)}$	0.6593
		Root-feeding		21.8	**9.3**	$1.76_{(1,7)}$	0.2262
		Total		**28.1**	13.0	$2.53_{(1,7)}$	0.1556
	genera	*Achromadora* (non plant-feeder)		1.02	0.54	$0.80_{(1,7)}$	0.4006
		Aphelenchus (fungal-feeder)		0.705	0.695	$0.00_{(1,7)}$	0.9793
		Cephalobus (bacterial-feeder)		0.723	0.515	$1.94_{(1,7)}$	0.2059
		Rhabtididae (bacterial-feeding)		1.2	0.5	$1.47_{(1,7)}$	0.2651
		Tripyla (predatory nematode)		0.3	0.2	$1.05_{(1,5.2)}$	0.3505
		Tylenchulus (root-feeding)		21.8	9.3	$1.74_{(1,7)}$	0.2286
		(calculated) N cycling Potential	kg ha^{-1}	267	263	$0.01_{(1,7)}$	0.9162
		Total Independent Favorable Values		**20**	**7**		**0.0096**

^{z}Bolded numbers highlight values considered favorable, or P-values that were statistically significant at the 0.05 level. Favorable (higher concentration or biological activity save pH, ciliates, root-feeding nematodes) values in bold. Lack of bold across row indicates uncertainty in interpretation of improvement (e.g. soil textural size classes, fungal- & root-feeding nematodes), the value being a function of measured variables, but not an independently observed variable itself (e.g. nitrogen cycling potential, ratio of active to total bacteria), or redundancy (e.g. nematode genera versus nematode guilds).

and of sufficiently clear interpretation (see Materials and Methods) to recognize more favorable values (Table 9). Twenty of these variables were found to have values more favorable under residual compost. Assuming no treatment effect the probability of such an outcome (or greater) is <0.01 (Table 9a). Among analytes of the routine soil fertility test seven of nine values were found to be favorable under residual compost (P<0.09; Table 9b).

DISCUSSION

It is important to note that the residual effects of compost observed here occurred in plots in which compost was repeatedly applied for five years (Nelson et al. 2008). Therefore, this study did not examine the residual effects of a one-time compost application. In a six-year study of annual compost application Tewolde et al. (2011) observed changes in composted plots only in the last three years of the study and attributed this behavior to carryover from the history of cumulative additions. The study of Tewolde et al. (2011) did not concern soil change but rather cotton yield.

Regarding yields, in the plots of this study during the period of compost addition (2002-2007), yield *trends* with composting, but *not significant differences* were recorded by Nelson et al. (2008). However Nelson et al. (2008) evaluated differences in yield on a year-by-year basis. It is possible that an analysis across years would have indicated a significant difference. Despite the lack of difference in yield observed on a year-by-year basis, Young et al. (2010) recommend compost addition as economically advisable for Texas Citrus based on the data of Nelson et al. (2008). Given the 24% improvement in soil health as observed in the Cornell Soil Health Index for composted plots (*P*<0.0005; Table 6) it is possible that yield differences might exist as a function of residual composting, especially if residual composting has left trees in a healthier state. Current yields and tree health were left unmeasured in this study.

Eight years since the last imposition of compost, residual effects (i.e. $P \leq 0.05$) of compost addition are still measurable and all such effects represent improved soil conditions, save perhaps total fungi (Table 6). Chief among these differences is the 24% OM-gain induced by compost addition. Organic matter is known for its substantial cation exchange capacity, water holding capacity, provision of aggregate stability, and its importance as an energy source for the soil food web (Magdoff and van Es, 2009). Hence it should not be a surprise if beneficial soil attributes, such as increased protein content, extractable soil nutrients (Table 6; Fig. 2a), and increased biologically active carbon (Fig. 2b; Table 9a), should accompany heightened organic matter. It is likely that improvements in extractable cations stem from increased ion exchange capacity (accompanying increased organic matter contents), since evaluation of extractable cations from these plots immediately following the period of compost addition do not record improvements (Nelson et al., 2008). This is consistent with the characterization of the applied compost as nutrient deficient (Nelson et al., 2008). Sixteen- and 24-year carryover of OM from compost application was recorded by Reeve et al. (2012) and Obour et al. (2017), respectively.

Residual compost lowered pH from 7.4 to 7.1 according to the Cornell Soil Health Laboratory (*P*<0.05) and from just above 8 to just below 8 according to the Texas A&M Soil, Water and Forage Testing Laborato-

Table 9b. Conventional[z] soil fertility response[y]

			Compost	no Compost	$F_{(numdf,dendf)}$	*P*
	EC[x]	µmho cm^{-1}	397	**360**	$3.28_{(1,28.3)}$	0.0809
	pH	N/A	**7.95**	8.02	$6.58_{(1,28.3)}$	**0.0159**
	NO_3-N	mg L^{-1}	**21**	15	$3.16_{(1,28.3)}$	0.0864
Mehlich-3-Extractable	P		**93**	61	$10.53_{(1,28.2)}$	**0.0030**
	K		**475**	470	$0.07_{(1,28.4)}$	0.7930
	Ca		9400	**9700**	$5.13_{(1,28)}$	**0.0315**
	Mg		**601.4**	600.8	$0.00_{(1,28.4)}$	0.9500
	S		**22.2**	21.0	$1.29_{(1,28.4)}$	0.2649
	Na		**25.8**	26.3	$0.01_{(1,28.1)}$	0.9132
Total Independent Favorable Values			**7**	**2**		0.0898

[z] Texas A&M University Soil, Water and Forage Testing Lab ‘Routine’ soil fertility test.

[y] Bolded numbers highlight values considered favorable (higher concentration or biological activity save EC, pH, Na), or *P*-values that were statistically significant at the 0.05 level.

[x] ‘EC’, Electrical conductivity.

ry ($P<0.02$; Table 6). Both laboratories utilize a 2:1 deionized water:soil slurry in their pH measurements, and therefore the difference in pH measured by the laboratories likely has to do with the different number of samples analyzed at the two laboratories (Table 2).

Citrus yield is maximized between 5.5 and 7.0 (Yara, 2006). While even the larger change from pH 7.4 to 7.1 may seem trivial, it represents a 132% increase in the concentration of H^+ ions; the slight change on either side of pH 8 represents an H^+ increase of 19% (Table 6). Change in pH induced by compost depends on starting soil pH and the properties of compost itself as well as time since application. Liming effects that diminished over a three-year period were observed by Eghball et al. (2004) after application of composted manure (pH of compost not provided). Obour et al. (2017) record a liming effect (relative to nitrate addition) of manure 24 years after the last addition. Cogger et al. (2014) observed an acidifying effect of biosolids three years after application (initial pH of biosolids not provided). For the present experiment, the initial pH of the soil before the start of compost application was 8.3 (Nelson et al., 2008); the initial pH of compost was 7.5 (Table 4). All levels of fertilization might be expected to lower soil pH through nitrification (ammonium constitutes the nitrogen content of 13-13-13; United Suppliers, 2014). The loss or trend-of-loss of Mehlich-extractable Ca in compost treatments (Fig. 2c) may result from compost-related acidification.

Given the historic addition of nutrient-poor OM which occurred here (Nelson et al., 2008), the heightened presence of fungi might be expected under compost. However, under residual composting total fungi was diminished ($P<0.05$) and actively respiring fungi exhibited a decreasing trend ($P<0.21$; Table 9a). While some have associated higher ratios of fungal to bacterial biomass with improved soil health (Teague et al., 2011), or measured increased fungal presence in alternative systems (no-tillage, Beare et al., 1992; organic-pasture, Yeates et al., 1997), ratios of fungal to bacterial biomass may depend on the particulars of soil mesofaunal populations, and therefore may not provide a single reliable index of soil health (Strickland and Rousk, 2010). While a decrease in fungal presence under residual compost may seem anomalous, note the 68% higher extractable protein under residual compost than without ($P<0.003$; Table 6). It can be speculated that by the time of this study the organic matter added had been thoroughly processed and was more suited to the bacterial pool. Increased biologically active carbon ($P<0.02$), and the trends of increased actively respiring bacteria ($P<0.10$), bacterial-feeding nematodes ($P<0.15$) and actively respiring bacterial to fungal biomass ($P<0.21$) under residual compost are consistent with this (Table 9a). A reduction in fungal biomass and a rise in bacterial:fungal biomass was recorded by Cogger (2014) when testing the effect of biosolids three years after application (Table 1).

Cephalobus genus of nematodes and Mehlich-3-extractable P (Table 7) were more abundant ($P<0.0008$; $P<0.05$, respectively) under the 13-13-13 fertilizer treatment than under the other two fertilizer treatments (urea, $(NH_4)_2SO_4$). *Cephalobus* nematodes are bacterial feeders. It is possible that the presence of P and potassium under 13-13-13 created an environment more conducive to their reproduction than the other two treatments. This might seem a surprising effect, given 8 years of uniform fertilization since the use of different fertilizer types under Nelson et al (2008), but the longevity of P in soil is one reason that heightened levels of P are used to identify human-influenced soils more than a thousand years since enrichment (Leonardi et al., 1999). While the heightened presence of *Cephalobus* was not statistically sensitive to previous amendment with compost ($P<0.24$; Table 9a), *Cephalobus* showed sensitivity to amendment (compost or fertilization) versus control (non-amended; $P<0.05$; Table 8).

Mehlich-3-extractable P was more abundant under the only inorganic fertilizer treatment that contained P (Table 7). A similar effect, interacting with compost, also occurs for Morgan-extractable P (Fig. 2a). Of the elements studied by authors who have examined residual effects of organic matter addition, the most common observed effect has been increased extractable P (Table 1).

While some analytes showed improved values due to the main effect of compost, there is strong evidence that compost has had a larger effect on soil quality to which ANOVA is insensitive. Consider that of the 27 independently observed soil health and biology analytes with a clear interpretation based on relative value, 20 were of favorable value under previous composting (Table 9a). If the effect of residual compost was insignificant, and probability = 0.5 that any one analyte would have a higher value in the compost treatment, the probability of such a lopsided, or more lopsided, distribution would be <0.01 (via the binomial distribution). Such a probability indicates a high likelihood that compost has a larger effect on soil that would be indicated by simply the number of significant variables under ANOVA (Table 9a). Similarly, a greater number of analytes had favorable values under residual compost according to the routine soil test results ($P<0.09$; Table 9b). Combining these datasets, the overall probability associated with 27 (or greater) successes in 36 trials (assuming no treatment effect) is <0.002.

It might be suggested that a more rigorous binomial test might *exclude* variables for which 1) the difference between compost and lack of compost was small or 2) random chance is substantially likely in distributing the data as observed. Among the soil health and biology analytes, excluding values within 5% of one another results in 16 successes for compost application out of 22 eligible variables and a probability, assuming no treatment effect, of <0.03. Excluding results with P>0.4 results in 16 'successes' for compost out of 20 eligible attempts and a corresponding probability of <0.007. Excluding routine soil fertility variables (Table 9b) with estimated averages within 5% results in two favorable averages in three trials (P=0.5); excluding those with P>0.4 results in four favorable averages of six trials (P<0.35). Therefore, it appears unlikely that random chance is responsible for improved trends among biological and soil health variables, but is more likely with routine soil health variables.

Some of the variables that were less favorable under composting could have been predicted. In alignment with the trend observed in this study (Table 9b), residual compost has been observed to raise EC (Cogger et al., 2014; Eghball et al., 2004; Table 1). Other variables with more favorable values without composting are more difficult to explain (e.g. active fungi, total fungi and bacteria, aerophilic protozoa).

While composting raised the overall soil health index to 67/100 (up from 54/100 for non-composted plots; P<0.0005; Table 6) the overall quality of the soils described here is limited; such scores indicate an ongoing need to improve soil health and performance. The work of this study and Nelson et al. (2008) indicate that municipal compost, applied on an annual basis for several years, has had immediate, measurable, and lasting positive effects at the study site.

CONCLUSIONS

Eight years after the latest addition of compost detectable differences have been observed in soil OM content, soil protein content, assorted extractable ions, and overall soil health. In addition, trends across many variables indicate an effect of compost to which ANOVA is insensitive at the 0.05 level. However, overall soil health of even the healthier (composted) plots may still be improved.

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