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Quantifying Benefits Associated with Land Application of Organic Residuals in Washington State

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Ⓢ *Supporting Information*

ABSTRACT: This study was conducted to quantify soil C storage, N concentration, available P, and water holding capacity (WHC) across a range of sites in Washington State. Composts or biosolids had been applied to each site either annually at agronomic rates or at a one-time high rate. Site ages ranged from 2 to 18 years. For all but one site sampled, addition of organic amendments resulted in significant increases in soil carbon storage. Rates of carbon storage per dry Mg of amendment ranged from 0.014 (not significant) in a long-term study of turf grass to 0.54 in a commercial orchard. Soils with the lowest initial C levels had the highest rates of amendment carbon storage ($r^2 = 0.37$, $p < 0.001$). Excess C stored with use of amendments in comparison with control fields ranged from 8 to 72 Mg ha^{-1}. For sites with data over time, C content increased or stabilized. Increases in total N were observed at all sites, with increased WHC and available P observed at a majority of sites. Using a 50 Mg ha application rate, benefits of application of biosolids and compost ranged from 7 to 33 Mg C ha. This estimate does not account for yield increases or water conservation savings.

INTRODUCTION

Organic soil amendments derived from components of municipal solid waste offer the potential to increase soil C content while simultaneously improving soil physical and nutritional properties. Each person in the United States generates an average of 22 dry kg of municipal biosolids, 88 kg of yard trimmings, and 79 kg of food scraps annually.[1,2] Approximately 50% of the biosolids, 98% of the food scraps, and 45% of the yard trimmings are currently disposed of or landfilled. A number of recent studies have attempted to determine the best end use of each of these substrates using life cycle assessment (LCA).[2−5] This tool commonly includes sustainability factors in the analysis.[4] Traditional LCAs of organic residuals include limited consideration of benefits associated with land application. End uses frequently considered in these assessments include combustion or anaerobic digestion for energy, ash use for cement production, and land application as a substitute for synthetic nitrogen. Categories for evaluation generally include greenhouse gas emissions, water use, environmental hazards, and resource conservation.[3,4] In some cases, benefits associated with use of diverted organics are not considered in the analysis.[5]

Independently, other studies have focused on land use and management practices as a means to adapt to climate change and to meet increasing demand for food and fiber.[6−8] Soil management with an emphasis on maintaining agricultural production and ecosystem function is an integral component of these considerations.[6,8] Soils have been considered as a medium for increased water storage and terrestrial carbon sequestration.[8−12] The value of ecosystem services has been quantified with soil being an essential component of many of these services.[6,13]

The primary means to enhance soil performance for each of these functions, including net primary productivity, is to increase soil organic matter content.[6,8,10,14] Research on increasing soil carbon content has focused on altered tillage practices, crop rotations, and restoration of degraded soils.[9,15,16] Increases in soil carbon as a result of these practices have been reported. For example, fifteen years of no till resulted in increased carbon reserves ranging from 4.8 to 11.6 Mg C ha^{-1} in Nebraska in comparison to conventionally tilled fields.[15] Discussions of sustainable land management and soil C sequestration generally do not consider residuals application.

Use of organic soil amendments, derived from the organic component of municipal solid waste, has the potential to rapidly increase soil organic matter content with an associated improvement in soil quality.[14,17−19] Recycling nutrients in organic amendments offers additional benefits regarding decreased use of synthetic fertilizers and environmental impacts associated with their use.[6,13] Increases in primary productivity have also been reported following use of organic amendments.[20,21] However,

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Table 1. Sampling Sites for All Sites Included in This Study (Control Sites Received No Fertilizer Addition; Fertilizer Sites Received Agronomic Rates of Synthetic Fertilizers)

site	county	crop	soil classification	treatments	first application	application frequency	cumulative amendment loading (Mg ha^{-1})
Durfey	Yakima	cherry	Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids)	fertilizer/compost	2002	annual	105
		grape	Warden silt loam	fertilizer/compost	2002	annual	91
		hop	Warden silt loam	fertilizer/compost	2003	single	140
		pear	Warden silt loam, Esquatzel silt loam (Coarse-silty, mixed, superactive, mesic Torrifluventic Haploxerolls).	fertilizer/compost	2004	annual	84
Dryden	Chelan	pear	Cashmont sandy loam (coarse-loamy, mixed, superactive, mesic Aridic Haploxerolls)	fertilizer/compost	1993	annual	134
Wheat Fallow	Douglas	wheat	Touhey loam (coarse-loamy, mixed mesic Aridic Duric Haploxerolls	control/fertilizer/ biosolids	1994	biosolids; every 4 years	18, 27, 40
Landscape	Pierce	mixed shrubs	Puyallup find sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls)	control/compost	2001	single	224
Roadside	Pierce	mixed shrubs	disturbed site; cut and compacted glacial outwash	control/compost/ biosolids	2007	single	106, 150, 147
turfgrass	Pierce	turf	Briscot loam (coarse-loamy, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts).	control/compost	2000	single	74, 149, 224, 298
fescue compost	Pierce	turf	Puyallup find sandy loam	fertilizer/compost	1993	single	157
fescue biosolids	Pierce	turf	Puyallup find sandy loam	fertilizer/biosolids	1993	annual until 2003	67, 134, 201
vegetable rotation	Pierce	mixed rotation	Puyallup find sandy loam	chicken manure/ compost	2003	multiple	26, 68, 153

there is a paucity of data on using organic residuals to maximize soil carbon sequestration.[17,18,22]

The overlap between the benefits associated with land application of residuals and sustainability considerations in a LCA analysis of waste management has not been fully assessed from either a land management or residuals management perspective. Potential benefits need to be quantified using both perspectives. Benefits per dry Mg residual as well as per ha land applied, are important considerations in determining appropriate residuals management options. It is important to quantify the full range of ecosystem services that may be impacted by decisions on organic residuals management.[22]

This study was conducted to assess changes in soil carbon, nitrogen, plant available phosphorus, water holding capacity (WHC), and bulk density (BD) on a wide range of short- and long-term sites in Washington State where different organic residuals had been applied. These results can be used for the development of waste and land management models that more accurately reflect the benefits associated with land application of organic residuals.

MATERIALS AND METHODS

Site Descriptions. Soil samples for this study were collected from both commercial farms and replicated field trials in 2008 (Table 1). Two sites were commercial farms. All other sites were replicated field trials. Soil samples were collected at each site for total C and N, available P, BD, and WHC measurements.

Soil samples were collected for C, N, and P using a 2.5-cm diameter soil hammer probe. Unless otherwise specified, samples were collected at 0−15and 15−30 cm. At replicated study sites, a single composite sample (minimum 4 subsamples) was collected from each plot at each depth. At commercial farm sites, composite samples were collected from three different locations per field for each treatment. Samples were dried at 22−25 °C.

BD and WHC were measured on the same samples. Samples were collected using a hammer-driven core sampler. Three samples were taken in each plot or field site to a depth of 8 cm.[23] Samples were capped immediately after collection. All BD and WHC samples were stored at 4 °C prior to analysis. Bulk density was measured at the Roadside site using a modified balloon excavation method.[23] BD and WHC samples were not collected from Turf or Landscape (surface-applied treatments), and WHC was not measured from Roadside.

Laboratory Analysis. Soils were air-dried and sieved (<2 mm) prior to analysis. Aliquots of soil (25−35 mg) were weighed and analyzed for total C and N using a dry combustion CHN analyzer (Perkin-Elmer Inc., Waltham, MA). Two internal standard and duplicate site samples were also run for QA/QC. There was no attempt to distinguish between organic and inorganic C as pH of all soils was less than 7.2. The Mehlich III extract was used to evaluate available P across the range of soil types included in this study.[24] WHC was measured at 10 and 100 kPa of tension to represent an optimal range for plant growth. Details on methods for measuring WHC are given in the Supporting Information.

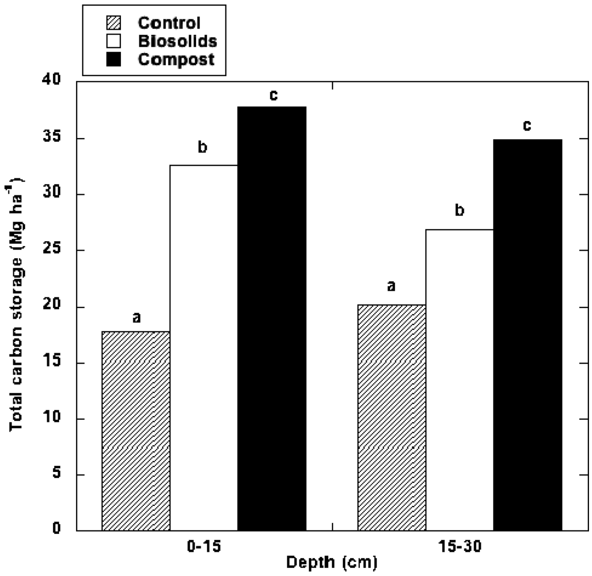

Figure 1. Total carbon storage at the 0−15 cm and 15−30 cm depths for control (n = 26), biosolids (n = 33) and compost (n = 63) amended soils sampled at these depths. Different letters indicate that means are significantly different (p < 0.01). As these data do not include side by side comparisons of biosolids and compost, results are not representative of carbon sequestration potential for similar sites and application rates for both materials.

Statistical Analysis. Statistical analysis was conducted using SPSS version 10.0.5.[25] Treatment effects were tested using ANOVA. When the F value of treatment was significant (p < 0.05), means were separated using the Waller-Duncan t test. Total carbon stored in the soil was calculated based on depth, bulk density, and soil carbon concentration.[19] Stepwise regression was used to determine the importance of different factors on select master variables.

Bulk density was only measured for the upper sampling depth, and was estimated for the lower depth. A single value for bulk density of the lower depth (1.44 g cm^{-3}) was used for all eastern Washington sites (Wheat Fallow, Dryden, and Durfey). For all western Washington sites, 1.25 g cm^{-3}, the mean of 5 random samples collected from the 15−30 cm depth of the Vegetable Rotation study, was used. Total C stored for each treatment was calculated by summing the total C stored in all sampling depths for each site.

RESULTS

Soil Carbon. Total C (g kg^{-1}) in soil varied as a result of amendment addition, site, and sampling depth (Figure 1). Across all treatments, soil C was greater at the no-till turf and landscape sites on the West side of the Cascades in comparison to disturbed sites (Roadside) or sites located on the east side of the Cascades (Table 2). Across all sites, amendments increased total C over control soils at both the 0−15 and 15−30 cm depths. A stepwise regression using data from all sampled sites identified cumulative application rate and time as the two significant factors in determining soil C concentration (r^2 = 0.63). Both application rate and time had a positive linear relationship with soil C concentrations. This indicates that composts and biosolids increase soil C concentrations in comparison to control soils across sites with different soils, tillage practices, and time since application. These results are consistent with previous studies that have shown increases in soil C concentrations with organic amendment addition.[17−19,26]

Changes over Time. A concern with use of amendments to increase soil C storage has centered on the potential for added organic matter to mineralize over a short time frame. Four of the replicated trials had soil C measures from previous samplings (Figure 2). Time since amendment application for these sites ranged from 7 years (Landscape) to 16 years (Fescue Compost). Two of the sites had multiple applications (Wheat Fallow and Fescue Biosolids). At Wheat Fallow, biosolids were applied in 1994, 1998, 2002, and 2006. Soil samples were collected prior to each biosolids application. At Fescue Biosolids, biosolids were surface applied annually from 1993 to 2002. No additional amendments have been applied since that time. For each of these sites, C concentrations in soils that received amendments were significantly higher than control or fertilized soils for all recent sampling intervals (Figure 2a−d). For Fescue Biosolids, C concentrations in the 2008 sampling were significantly higher than in the 2000 sampling for all treatments. For the two sites that received a single large application of compost (Landscape and Fescue Compost) C concentrations decreased immediately following application and have stabilized or are increasing relative to the control soils. These results suggest that increases in soil C as a result of amendment addition will persist both over time and after amendment addition, even if this is discontinued.

Likely mechanisms for persistence of elevated C concentrations in amended soils include formation of stable aggregates and increased primary productivity in comparison to conventionally managed soils.[17,20−22,27] Although not measured for this sampling, increased primary productivity as a result of amendment addition had been observed for previous samplings of the Wheat Fallow, Landscape, Fescue Biosolids, and Fescue Compost sites.[27−30]

Carbon Storage. Net total C stored (Mg ha^{-1}) for each site (C in amended soils − C in control soils) as well as the Mg of C stored per Mg of amendment were calculated for all sites (Table 2). Net C stored per Mg of amendment ranged from 0.012 for the low rate of biosolids addition to turf grass (Turfgrass site) to 0.54 Mg C per Mg compost at an orchard site. Carbon storage tended to be lower on the turf and landscape sites (0.01−0.09 Mg C per Mg amendment) in comparison to all other sites (0.10−0.54 Mg C per Mg amendment). It should be noted that total C content of biosolids and composts ranges from 0.2 to 0.35 Mg C per Mg amendment.[26,27] For several of the sites sampled, C storage per Mg amendment was similar to or greater than the C content of the added amendment. Measured excess C may be a result of higher productivity in amended soils resulting in higher C deposition.[21] Generally, C storage per Mg of amendment added was similar within sites with multiple application rates or types of amendments. However, at Durfey, a one time high compost rate stored 0.24 Mg C per Mg while similar cumulative loadings based on annual applications of lower rates resulted in 0.11−0.15 Mg C per Mg amendment. The values in this study are within the same order of magnitude as values reported in two studies of C storage for biosolids amended mine soils (0.06−0.26 Mg C per dry Mg amendment).[19,31] For this study, a significant relationship (r^2 = 0.37) was seen between C content in control sites and rate of storage per dry Mg amendment. Sites that had low organic matter stored more C

Table 2. Total Carbon Stored (Mg ha^{-1}) in Surface Horizons of Control, Fertilized, and Amended Soils, Excess Carbon (Amended − Control for All Depths Sampled), and Net C per Mg Amendment for All Sites Sampled[a]

	Mg ha^{-1}						
	rate	C storage	excess carbon[b]	net C per Mg amendment (Mg C per Mg)	total N (g kg^{-1})	available P (mg kg^{-1})	bulk density (Mg m^{-3})
				Dryden, 0−15 cm			
fertilizer		16 ± 1			0.76 ± 0.1	10.3 ± 4.3	1.2 ± 0.1
compost	134	80 ± 18*	72	0.54	4.6 ± 0.4*	34.6 ± 2.3*	1.0 ± 0.2
				Durfey, 0−15 cm			
fertilizer		21 ± 2			1.3 ± 0.1	21.7 ± 2.3	1.2 ± 0.1
compost pear	84	37 ± 2*	9	0.12	2.0 ± 0.1*	45.9 ± 3.5*	1.2 ± 0.1
compost grape	91	23 ± 1*	12	0.14	1.9 ± 0.2*	45.9 ± 5.0*	0.8 ± 0.001
compost cherry	105	26 ± 2*	16	0.15	1.8 ± 0.04*	60.7 ± 1.2*	0.9 ± 0.1*
compost hops	140	44 ± 4*	34	0.24	2.4 ± 0.6*	111 ± 18.5*	1.1 ± 0.1
				Wheat Fallow, 0−15 cm			
control		17 ± 1			0.8 ± 0.04	25.9 ± 2.9	1.3 ± 0.02
fertilizer		16 ± 0.4	−1		0.8 ± 0.01		1.3 ± 0.02
biosolids	18	22 ± 1*	8	0.43	1.1 ± 0.1*	185 ± 28*	1.2 ± 0.02
biosolids	27	22 ± 1*	9	0.34	1.1 ± 0.02*	126 ± 21.7	1.3 ± 0.03
biosolids	40	26 ± 3*	14	0.36	1.3 ± 0.1*	277 ± 18.6*	1.2 ± 0.02
				Fescue Compost, 0−15 cm			
fertilizer		36 ± 0.5			1.8 ± 0.02	227 ± 46	1.11 ± 0.01
compost	157	44 ± 1*	9	0.06	2.3 ± 0.06*	198 ± 11.7	1.1 ± 0.03
				Fescue Biosolids, 0−15 cm			
fertilizer		31 ± 1			1.5 ± 0.03	194 ± 5.6	1.0 ± 0.02
biosolids	67	36 ± 1*	6	0.08	1.9 ± 0.03*	448 ± 26*	1 ± 0.03
biosolids	134	41 ± 1*	12	0.09	2.2 ± 0.03*	530 ± 24*	1.0 ± 0.02
biosolids	202	38 ± 2*	9	0.04	2.0 ± 0.1*	605 ± 25*	1.0 ± 0.02
				Turf, 0−10 cm			
control		38 ± 5			2.4 ± 0.3	134 ± 35.5	
biosolids	74	38 ± 2	1	0.01	2.5 ± 0.1	193 ± 25	
compost	149	43 ± 6	10	0.06	3 ± 0.4	224 ± 82	
compost	224	48 ± 4	19	0.08	3.4 ± 0.3*	377 ± 82*	
compost	298	48 ± 5	18	0.06	3.4 ± 0.3*	305 ± 80*	
				Landscape, 0−20 cm			
control		24 ± 1			0.8 ± 0.02	374 ± 39	1.23 ± 0.01
compost	224	42 ± 14*	18	0.08	1.9 ± 0.1*	321 ± 16	1.07 ± 0.02*
				Vegetable Rotation, 0−15 cm			
chicken manure	11	32 ± 0.4			1.5 ± 0.02		1.3 ± 0.01
chicken manure	26	34 ± 1*	8	0.35	2.0 ± 0.03*		1.04 ± 0.01*
compost	68	36 ± 1*	6	0.1	1.8 ± 0.07*		1.2 ± 0.01*
compost	153	42 ± 1*	25	0.17	2.7 ± 0.05*		0.9 ± 0.01*
				Roadside, 0−15 cm			
control		13 ± 3			0.2 ± 0.06	38.3 ± 1	2.2 ± 0.15
biosolids inc	147	82 ± 3*	69	0.47	2.0 ± 0.6*	709 ± 73*	0.9 ± 0.15*
biosolids surface	147	12 ± 2			0.2 ± 0.03	75.4 ± 11*	2.1 ± 0.1
compost inc	150	65 ± 2*	52	0.35	2.0 ± 0.3*	135 ± 230*	1 ± 0.1*
compost surface	150	15 ± 2			0.2 ± 0.03	45 ± 4.3	2.3 ± 0.1

[a] Data on carbon storage for lower depths is presented in the Supporting Information. Net C per Mg amendment reflects increases over all sampling depths. Total N (g kg^{-1}), available P, and bulk density (Mg m^{-3}) for all sites. Means ± standard errors are shown. Means of amended soils followed by an * are significantly different from control soils ($p < 0.05$). [b] Summed over all sampling depths.

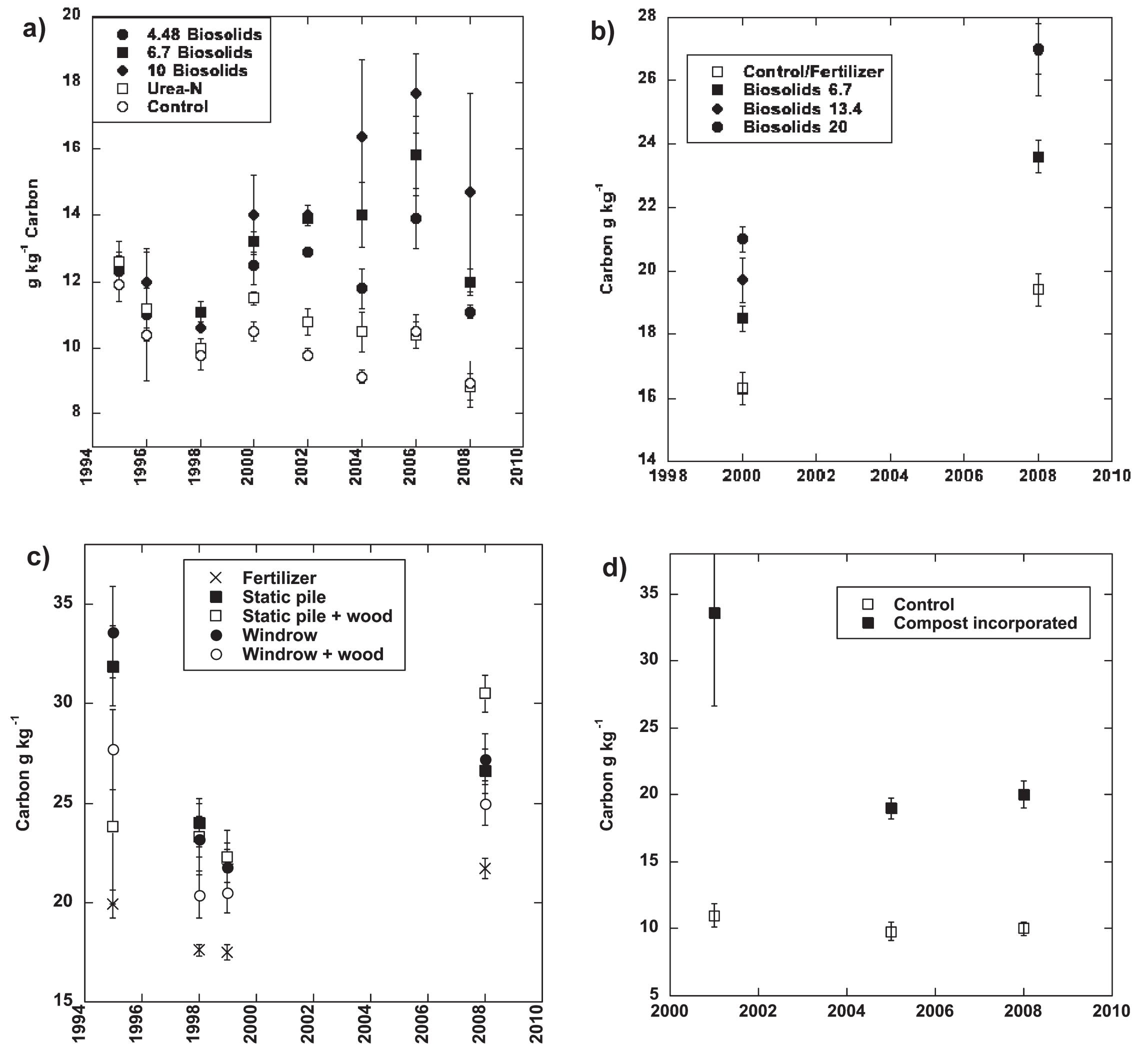

Figure 2. Changes in soil carbon (g kg^{-1}) over time at 4 replicated field trials (a: Wheat Fallow, b: Fescue Biosolids, c: Fescue Compost, and d: Landscape). Amendment history for each site is given in Table 1. For Wheat Fallow, biosolids were applied in 1994, 1998, 2002, and 2006. Soil samples from Wheat Fallow application years were collected prior to applications. Means ± standard error are shown.

per dry Mg amendment than sites that had higher organic matter before compost or biosolids amendments. The higher C sites were likely closer to equilibrium soil C concentrations than the lower C sites.

Soil N and P. Amendment application increased total soil N concentrations in comparison to control or conventionally fertilized soils for the surface depth of all sites sampled ($p < 0.0001$; Table 2). There was a similar response across all sites. Nitrogen varied based on soil C concentrations. A stepwise regression analysis showed that C concentration accounted for approximately 50% of the variability in N concentration. The persistence of N in these soils in combination with the relationship between C and N indicates that a fraction of the N added with the amendment has been conserved in the systems through partitioning to soil organic matter. Previous work has shown that composts and biosolids provide a slow release source of N for crops.[20,28−30] Across all sites, biosolids addition increased extractable P in comparison to compost, control, and fertilizer (Table 2). Compost increased extractable P at several of the sites. Values for many samples analyzed for this study were above what is generally (45−50 mg kg^{-1}) considered sufficient for plant growth.[24] These results should be taken as confirmation of the value of organic amendments as a source of phytoavailable P, rather than as a quantitative measure of phytoavailible P. Use of organic amendments in lieu of synthetic fertilizers reduces emissions associated with fertilizer production. Carbon dioxide emissions associated with the production of N and P fertilizers ranges from 1.3 to 4.7 g CO_2 per g N and 1.76−4.86 g CO_2 per g P for fossil fuel use.[32] Although a fraction of the amendment will decompose over time, these emissions are associated with the short-term carbon cycle.

Water Holding Capacity. For this study gravimetric WHC was measured to bracket the available water status of high value irrigated crops. Water content was increased in amended soils at 10 or 100 kPa at 7 of the 10 sites where WHC was measured (Table 3). Available water (the difference between 100 and 10 kPa) increased in the amended soils at three sites (Landscape, Durfey Cherry, and Durfey Hops). At the Durfey Cherry and Landscape sites, increased WHC at 10 kPa was the dominant factor increasing available water. For Durfey Hops, textural differences between the control and amended fields (Table 1) confounded the results. However, compost compensated for the

Table 3. Gravimetric Water Content at 10 and 100 kPa Pressure for All Sites Where Amendment Addition Had a Statistically Significant Effect on Soil Water Holding Capacity[a]

site	treatment and rate (Mg/ha)	texture	10 kPa	100 kPa ($g\ g^{-1}$)	difference
Landscape	control	sandy loam	0.38 a	0.17 a	0.21 a
	compost 224		0.48 b	0.17 a	0.31 b
Durfey Cherry	control	silt loam	0.31 a	0.13 a	0.18 a
	compost 105		0.48 b	0.21 a	0.27 b
Durfey Hops	control	loam	0.41 a	0.28 a	0.13 a
	compost 140	sandy loam	0.40 a	0.20 a	0.20 b
Fescue Biosolids	fertilizer	sandy loam	0.47 a	0.25 a	0.22 a
	biosolids 67		0.50 a	0.30 b	0.20 ab
	biosolids 134		0.48 a	0.30 b	0.19 ab
	biosolids 202		0.49 a	0.32 b	0.17 b
Wheat-Fallow	control	loam	0.36 a	0.09 a	0.27 a
	fertilizer		0.35 a	0.09 ab	0.27 a
	biosolids 18		0.38 a	0.1 b	0.28 a
	biosolids 27		0.36 a	0.095 ab	0.26 a
	biosolids 40		0.37 a	0.10 b	0.28 a
Vegetable	chicken manure 11	sandy loam	0.34 a	0.16 a	0.18 a
Rotation	chicken manure 26		0.40 ab	0.22 a	0.18 a
	compost 68		0.36 ab	0.16 a	0.20 a
	compost 153		0.42 b	0.23 a	0.21 a

[a] Means within a treatment and column followed by a different letter are significantly different at $p < 0.05$.

coarser texture of the amended field.[33] Prior studies have shown that organic amendments tend to increase WHC at both high and low water tensions.[14,26,33] Stepwise regression was used to test the importance of % sand, C ($g\ kg^{-1}$), total application rate, and BD on WHC. The only predictor that significantly influenced soil WHC at both 10 and 100 kPa was BD. A negative linear relationship was seen between BD and WHC at both tensions. This suggests that for the soils sampled in this study, decreasing BD was the most effective way to increase soil WHC. A stepwise regression was also carried out on BD. The variables that were included in this analysis were total application rate, C concentration, and % sand. Carbon concentration was the only significant predictor for BD with a negative linear relationship between C and BD. As has been discussed, amendments resulted in significant increases in % C across all sites. This suggests that use of organic amendments has the potential to indirectly increase soil WHC by decreasing soil BD. Although these results are not sufficient to predict water savings across a wide range of sites, they are sufficient to suggest that use of organic amendments can increase soil—water storage for certain soil types and amendments. These results are in agreement with results from previous studies.[22,26] Although it is not possible to calculate GHG benefits associated with increased soil—water, improving soil—water storage is likely to become a critical factor in the coming decades.[34] A LCA of organic residuals should include potential benefits regarding water savings in any evaluation of benefits associated with land application.[22]

■ APPLICATION OF RESULTS TO WASHINGTON STATE

A survey of residual biomass in Washington State identified annual production of 15.4 million Mg of organic biomass across a broad range of categories including agricultural wastes, manures, forestry waste, and organic components of municipal solid waste.[35] These materials have potential value as soil amendments. Restricting this to biosolids (86 290 Mg), yard waste (383 600 Mg nonwood), and food scraps (224 000 Mg) gives a total annual biomass of 694 000 Mg. Assuming that yard waste and food scraps are composted prior to land application with a 50% volume loss during the composting process, the total annual compost production from these feedstocks would be 304 000 Mg. Using a default factor of 0.1 Mg soil C sequestration per Mg of amendment, land application of these amendments in WA State would result in 39 700 Mg C sequestered in soil annually. For certain sites, this is a conservative value. Based on the results of this sampling, land application of amendments, on low C soils, could result in soil storage of 173 500 Mg C annually. Although landfilling of organics would also result in carbon storage, no additional ecosystem benefits would be associated with these materials.[36] While landfilling can be associated with CH_4 recovery and energy production, controlled anaerobic digestion prior to land application is a more efficient source of energy that also captures benefits associated with land application.[32]

The associated benefits measured in this study include the fertilizer value, improved soil tilth (bulk density), and increased water holding capacity. Previous measures on a portion of the sites have also showed increased primary productivity as a result of amendment addition. Many LCAs have taken into account the N value associated with land application. The results from this sampling provide data to support this. They also suggest that the P value of amendments may be included in all evaluations.

Increased soil—water storage was observed at a majority of the sites sampled. There are 636 000 ha of irrigated agriculture in Washington State. Irrigation requirements vary by crop requirements and natural rainfall patterns. For example, cherry production requires 10 664 m^3 H_2O ha^{-1}.[37] Yields of dry land wheat are primarily limited by insufficient water.[38] Increased water storage

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Table 4. Benefits Associated with Application of 50 Mg ha^{-1} of Biosolids or Composts to Turf, Orchard, or Dryland Wheat Sites[a]

	soil carbon	nitrogen	phosphorus	water use
	Mg C/50 Mg amendment ha^{-1}			
		orchard		
compost	12.00	0.80	0.20	1000 m^3
	(6−27)	(0.3−1.1)	(0.1−0.3)	0−5333 m^3
		turf		
biosolids	2.75	2.40	0.60	
	(0.5−4.5)	(1.6−3.8)	(0.3−0.7)	
compost	3.25	0.80	0.20	
	(3−4)	(0.3−1.1)	(0.1−0.3)	
		dryland wheat		
biosolids	19.00	3.10	0.60	
	(17−21.5)	(1.6−3.8)	(0.3−0.7)	10−20% yield increase

[a] Benefits shown include C-associated benefits with excess soil carbon and substitution for synthetic fertilizers. Actual amendment N concentrations were used for calculations if available. P values represent ranges of total P in composts and biosolids. Water benefits shown reflect potential water savings or yield increases. Mean values as well as measured or estimated ranges for values are shown.

is likely associated with increased plant available water.[14,26,33] This suggests that amendment addition would reduce irrigation water demand for certain sites and may increase yield in water limited sites.

Benefits associated with land application of biosolids and composts were calculated based on a cumulative loading rate of 50 Mg ha^{-1} for turf, orchard, and dryland wheat sites (Table 4). The mean net Mg C per Mg amendment for the Fescue Compost, both orchard sites, and Wheat Fallow sites for all application rates was used as a base for calculating cumulative benefits. The range in the data is also presented. Carbon benefits associated with N and P were calculated based on CO_2 equivalent of N and P fertilizer of 4 and 2 kg CO_2 per kg N and P.[32] Mean concentrations of N in each material (Supporting Information) were used in this estimate. Carbon-associated benefits were lowest for compost application to turf grass (4.25 Mg C ha^{-1}) and highest for biosolids application to dryland wheat (23 Mg ha^{-1}). As a basis for comparison, C sequestration rates for no till farming practices have been reported as 0.3 Mg C ha^{-1} yr^{-1}.[18] Water savings in orchard soils were estimated at 1% of available water or 1066 m^3 H_2O ha^{-1}. Actual increases in available water across the orchard sites sampled, calculated using the percent increase in available water and average water use for cherry orchards, ranged from 0 to 5333 m^3 H_2O ha^{-1} yr^{-1}.[37] This is a highly imprecise estimate but indicates the magnitude of potential water savings. For dryland wheat, potential yield increase as a result of increased soil−water content at 100 kPa was calculated using a linear relationship between available water and wheat yield.[38] Predicted yield increases ranged from 10 to 20%. Actual yield data from this site showed elevated yields in biosolids amended treatments in comparison to fertilizer for 4 of 8 harvests (Cogger, personal communication).

Results from this study suggest that land application of residuals in Washington State has the potential to result in significant C storage, replacement of synthetic fertilizers, and water conservation. Elevated C storage in comparison to conventionally managed soils persisted over time and showed a linear increase with increased amendment application rate. Ancillary benefits were observed at all sites. Total N increased in all sampled sites with increases in available P observed at several of the sampled sites. Soil BD decreased and WHC also increased at a number of the sampled sites. Calculations of benefits of residuals use on a per ha basis show significant carbon benefits as well as potential yield increases and water savings. These benefits were significantly greater than those associated with no till soil management. These results demonstrate the importance of including a broad range of benefits associated with land application of organics in a LCA and also illustrate the importance of considering land management decisions in this process.

■ ASSOCIATED CONTENT

S Supporting Information. Additional tables and methods descriptions. This material is available free of charge via the Internet at http://pubs.acs.org.

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