



# Long-term remediation of compacted urban soils by physical fracturing and incorporation of compost



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## ARTICLE INFO

### Keywords:

Scoop & Dump  
Soil health  
Soil remediation  
Soil quality  
Soil active carbon  
Soil potentially mineralizable nitrogen

## ABSTRACT

On the Cornell University campus a long-term study has measured the impacts of a soil remediation strategy on plant growth and soil quality using the Cornell Soil Health Test. The Scoop & Dump (S&D) process of soil remediation consists of physically fracturing compacted urban soils, incorporating large quantities (33% by volume) of compost with the use of a backhoe, and annually top dressing with mulch. This study was designed to investigate the impact of this remediation technique for the amelioration of compaction and degradation of soils in the urbanized environment.

The study finds that over a 12-year period remediated soils exhibit improved (reduced) bulk density ( $R^2 = 0.50$ ) ( $P < .0001$ ) ( $n = 30$ ), increased active carbon ( $R^2 = 0.61$ ) ( $P < .0001$ ) ( $n = 30$ ) and increased potentially mineralizable nitrogen ( $R^2 = 0.61$ ) ( $P < .0001$ ) ( $n = 30$ ). When S&D soils were compared to unamended (Unam) soils, improvements were found in aggregate stability (S&D = 72.41%, Unam = 34.90%,  $P < .0001$ ,  $n = 30$ ), available water holding capacity (S&D = 0.22%, Unam = 0.15%,  $P < .0001$ ,  $n = 30$ ), total organic matter (S&D = 8.43%, Unam = 3.23%,  $P < .0001$ ,  $n = 30$ ), potentially mineralizable nitrogen (S&D = 27.53 mg/kg, Unam = 3.11 mg/kg,  $P = 0.0005$ ,  $n = 30$ ), active carbon (S&D = 1022.47 mg/kg, Unam = 361.60 mg/kg,  $P < .0001$ ,  $n = 30$ ), and reduction in bulk density (S&D = 0.89 g/cm<sup>3</sup>, Unam = 1.47 g/cm<sup>3</sup>,  $P < .0001$ ,  $n = 30$ ). Application of the S&D process provides an alternative to using specified soils and has potential for improving long term soil quality using locally sourced materials and simple methods.

## 1. Introduction

In the United States, urban lands have been projected to increase from 3.1% to 8.1% (392,400 km<sup>2</sup>) between 2000 and 2050 (Nowak and Walton, 2005) with a concomitant predicted increase of urban dwellers globally from 3.6 billion to 6.3 billion in the same time frame (United Nations, 2012). Soils found in urbanized landscapes often exhibit biogeochemical processes that are distinctly altered when compared to natural landscapes. As a result of urban development, soil quality is typically diminished resulting in reduced ecosystem services and less successful landscape plant establishment.

In the urbanized environment, it has been shown that soils make up 64% of the terrestrial carbon sink followed by vegetation making up an additional 20% (Churkina et al., 2010). In these environments, soil damage is often highly pronounced because of multiple stresses such as compaction, contamination, frequent land use and burying of anthropogenic waste materials. Characteristics of urban soil include: high soil bulk density, low organic matter, poor structure, high pH, low water

holding capacity, decreased aggregate stability, inadequate soil volume for root proliferation and decreased microbial biomass and activity (Jim, 1998; Scharenbroch et al., 2005). These diminished properties compromise soil health and create an inhospitable environment to support plant growth. It has been shown that within the first two years of new street tree plantings mortality can be as high as 34% in the city environment (Nowak et al., 1990). Urban soil limitations have been shown to account for 80% of issues relating to maintenance of urban vegetation (Layman et al., 2016; Patterson et al., 1980). As a result, strategies are needed to address specific soil limitations in order to support the development and longevity of urban forests.

Soil health is the quantifying of the varying physical, chemical and biological aspects of soil that allow it to be a medium for supporting plant life and a provider of ecosystem services. Studies have been conducted to identify and determine soil quality indicators. These indicators are a series of specific tests that elucidate soil function and determine suitability as a substrate for plant growth. The soil health test has been designed so that indicators are responsive to management and

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<http://dx.doi.org/10.1016/j.ufug.2017.03.023>

Received 1 December 2015; Received in revised form 3 March 2017; Accepted 19 March 2017

Available online 04 April 2017

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correlate with plant growth and health (Scharenbroch and Catania, 2012; Schindelbeck et al., 2008). The concept of soil health is important because it integrates many aspects of soil science and provides a conceptual framework that can be understood by a range of audiences from homeowners to professional scientists.

The objective of this study is to investigate the long-term effects of incorporating large volumes of compost into compacted urban soils, and to measure soil quality indicators compared to unamended sites over time. The Cornell Soil Health Test was used to study these sites and to demonstrate its practicality in urban ecosystems. Using a chronosequence methodology allowed for investigating the long-term effects of this technique (Gugino et al., 2009).

The Scoop & Dump (S & D) technique is a novel approach to addressing soil compaction by conducting mechanical loosening and deep compost incorporation. This study quantitatively investigates the benefits of the S & D technique and its applied use in the field. The S & D technique is easy to conduct but seldom recognized as a rehabilitation tool for homeowners, arborists, farmers and green industry practitioners. A past study by Kaj Rolf first investigated the effects of soil loosening using a pneumatic air tool to enhance the soil environment around trees (Rolf, 1992). A series of recent studies have investigated biogeochemical effects of mechanical disturbance and deep compost incorporation using a similar technique to S & D known as Profile Rebuilding (Chen et al., 2014a,b, 2013; Layman et al., 2010). In combination, the findings of previous studies and the results presented in this paper provide the research necessary to promote these methods for restoration of compacted soils and as a tool for remediation.

## 2. Materials and methods

### 2.1. Study sites and sampling protocols

The selected study sites were on the Agricultural Quad of the Cornell University campus in the City of Ithaca, New York. Soils in this area have been subjected to an extended period of prolonged human use and were either unclassified or considered human-influenced soils.

Study sites included planting beds where compost was incorporated with a backhoe at the time of site establishment and that have been annually mulched since landscape installation. These sites have been installed annually since 2001 at various locations around campus. At the time of landscape establishment, compost was spread across an entire study site to a depth of approximately 15.24 cm on top of resident urban soils. Cornell University compost made from a mix of food waste, animal bedding and manure as well as greenhouse medium and plant residues was incorporated into the soil. A Bobcat E35 Compact Excavator with a 45.72 cm bucket was used to systematically scoop the compost and resident soil to 38–45.75 cm depth, lifting the material approximately 1.22 m into the air and dumping the mixed substrate back to the ground. This process created a heterogeneous soil/compost mixture with physically fractured soils and compost incorporated into the soil profile. After the initial soil mixing, sites were minimally smoothed over with iron rakes and then trees and shrubs were planted directly into the remediated soils. After planting, shredded bark mulch was applied to a depth of approximately 5–7.5 cm across the entire site. Mulch has been added annually to each site during April to May each subsequent year to a depth of 7.5 cm.

Study sites were selected to represent a cross section of time from 2001 to 2012 allowing for the Scoop & Dump (S & D) method of soil restoration to be observed in a chronosequence. Study sites and year of remediation treatment included landscapes adjacent to the buildings CCC (2012), Mann Library (2010), Roberts Hall (2009), Plant Sciences (2007), Centennial-Mann North (2004) and Fernow Hall (2001). For chronosequence analysis all six sites were used. Additional sites were selected adjacent to S & D sites that had similar land use histories and disturbances as study sites. These were used to compare S & D soils to unamended sites and functioned as a control group. These sites

included Mann, Plant Science and CCC. On the Fernow, Centennial and Plant Science sites, compost was incorporated with hand shovels to perform the S & D procedure. On the Roberts, Mann Library and CCC sites, a backhoe was used to incorporate compost.

Soil samples were collected from September 9, 2012 through November 20, 2012. Five soil samples were taken in a transect across the length of the landscape bed per study site. At each of the 5 sites, 3 undisturbed soil cores, each 248.5 cm<sup>3</sup> in volume, were extracted from the S & D soils with a mallet and wood block. Scoop & Dump samples were taken at the mulch soil interface layer where bark particles were no longer visible at an average depth of 6.16 cm (std dev = 3.60 cm). Undisturbed cores were removed and emptied into plastic bags. Soil pits were measured to determine the depth of bark mulch, S & D layer and the depth that the sub-soil layer began. Soil samples were not taken underneath trees that were present on sites prior to S & D restoration since these soils received no treatment.

Unamended control sites were selected for the locations at Plant Science, Mann and CCC. These locations were selected in turf areas in close proximity to study sites and samples were taken at approximately the same distance along the original transect. Turf was removed and three undisturbed soil cores were inserted into the soils with a mallet and wood block at an average depth of 7.43 cm (std dev = 3.66 cm). Unamended control soil samples were taken at approximately equal depths to analogous S & D sample sites.

Samples were taken to Cornell's Soil Health Lab and stored in refrigeration at 4 °C until ready to be processed. Soils were processed and analyzed from December 2012 through March 2013. Soil samples were analyzed using Cornell's Soil Health Test standard methods (Gugino et al., 2009; Schindelbeck et al., 2008). Samples were air dried for two days until they reached a friable state prior to processing in the lab. Once friable, soils were sieved through an 8 mm screen to remove stones and large organic debris.

### 2.2. Soil health tests

#### 2.2.1. Bulk density

Soil bulk density was calculated after drying soils at 105 °C by determining total dry weight divided by volume of combined soil cores and reported as g/cm<sup>-3</sup>.

#### 2.2.2. Soil resistance

Soil resistance was assessed on September 17, 2013 using the Investigator Soil Compaction Meter electronic penetrometer with a 1.27 cm tip. All penetrometer measurements were taken within the same day. The electronic penetrometer was used to measure resistance in 5.08 cm intervals and continued until no further penetration was possible or the end of the graduated measurement bar on the penetrometer was reached (Bengough and Mullins, 1990; Gugino et al., 2009; Lapen et al., 2004).

#### 2.2.3. Texture

236.5 cm<sup>3</sup> of 8 mm sieved soil was removed and weighed into a pre-weighed canister. Canisters were placed in an oven at 60 °C for 2 days until all moisture was removed. Soils were then passed through a 2 mm sieve. Fourteen grams of soil were placed into a Falcon centrifuge tube for rapid soil texture analysis. Soil sub-samples were mixed and centrifuged with 3% sodium hexametaphosphate to disperse soil into suspension. Sub-samples were screened through a 0.053 mm sieve. Particles remaining on top of the sieve screen represented the sand component of the soil and were washed off into a pre-weighed can, dried and weighed. Silt and clay particles that passed through the sieve were re-suspended in water in a 600 ml beaker and allowed to settle for 2 h. Particles remaining in suspension after 2 h were considered to be clay and were decanted leaving only silt at the bottom of the beaker. Silt on the bottom was washed into a second pre-weighed can. Both the sand and silt cans were dried at 105 °C. Dry weight was measured.

Percentage sand and silt were calculated by subtracting their dry weights from total dry weight of soil added to centrifuge. The remaining fraction was clay (Gugino et al., 2009; Kettler et al., 2001).

#### 2.2.4. Available water holding capacity

Sixty grams of soil were used to determine available water holding capacity (AWHC), defined as water held in the soil between permanent wilting point (1500 kPa) and field capacity (10 kPa).

The AWHC test was conducted with a standard pressure chamber with ceramic plates and was reported on a gravimetric basis (Gugino et al., 2009).

#### 2.2.5. Aggregate stability

To obtain aggregates, dried soil was shaken for 10 s on a 0.25 mm screen on a Coarse Sieve Shaker. Wet aggregate stability testing was conducted using a Cornell Rainfall Simulator (Ogden et al., 1997). The rainfall simulator delivered 12.5 mm of water dropped from a height of 500 mm simulating a heavy thunderstorm. Over the time period, 0.74 J of energy was dispensed per sieve of aggregates. This aggregate stability test measured soil particles that slake off of the aggregates during simulated rain fall, mimicking erosional forces at the soil's surface. The weight of aggregates on the sieve was determined before and after the simulated rainfall. The difference in weight was recorded and aggregate stability reported on a percentage basis (Gugino et al., 2009; Moebius et al., 2007).

#### 2.2.6. Active carbon

Twenty grams of soil, dried at 40 °C, were removed and passed through a 2 mm screen. Soil aggregates smaller than 2 mm were placed on a sheet and poured into a scintillation vial. Active carbon was assessed using the potassium permanganate (KMnO<sub>4</sub>) oxidizable carbon (Pox-C) method (Weil et al., 2003).

#### 2.2.7. Potentially mineralizable nitrogen

Two Falcon tubes were each filled with 8 g of fresh 2 mm sieved soil for testing potentially mineralizable nitrogen. One of the sub-samples was tested using potassium chloride (KCl) to determine ammonium (NH<sub>4</sub><sup>+</sup>) content. Sub-sample two was incubated in anaerobic conditions for seven days. After a week, the sub-sample was tested to determine ammonium concentrations. The difference between sub-sample one and sub-sample two was determined. PMN is reported as micrograms nitrogen mineralized per gram dry weight of soil per week (µgN/gdwtsoil/week) (Gugino et al., 2009).

#### 2.2.8. Organic matter

Organic matter was assessed by loss on ignition method (LOI). Percent loss on ignition was converted to percentage organic matter and multiplied by a correction factor. The equation utilized was: % Organic Matter = (% Loss on ignition \* 0.7) - 0.23 (Burt, 2014; Gugino et al., 2009).

#### 2.2.9. Soil nutrients

Dried soils were sent to The Cornell Nutrient Analysis Laboratory for analysis. Available soil nutrients were extracted with a Morgan's solution (pH 4.8) and analyzed on an ICP spectrometer for P, K, Fe, Mg, Mn and Zn.

### 2.3. Statistical analysis

Statistical analyses were conducted using JMP pro 10.0 (SAS Institute Inc., NC, USA). Comparison of treatments was calculated using an Oneway ANOVA to determine mean values and *F* statistic. Tukey HSD was used to compare mean values. Linear regression analysis was conducted to determine effects over time in the chronosequence. Survival analysis and a log-rank chi-square test were used to determine mean depth that root-limiting resistance was met using a soil

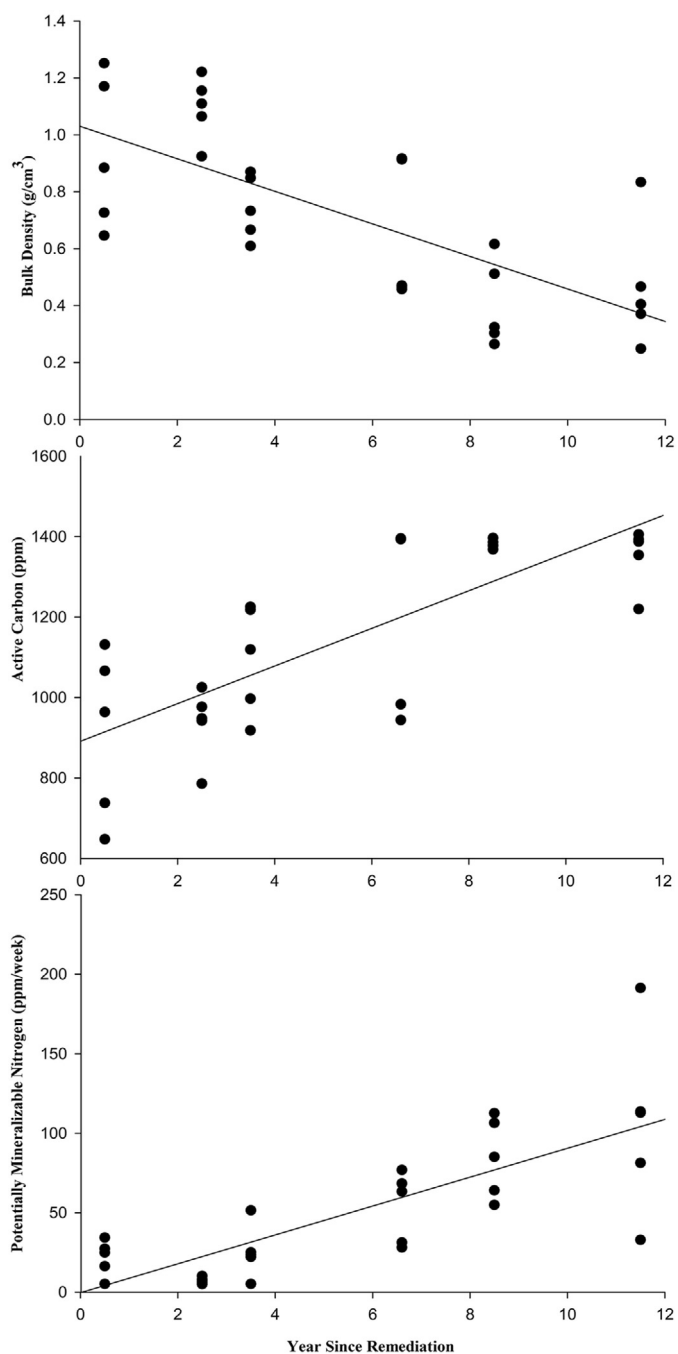


Fig. 1. Chronosequence showing decreased bulk density ( $R^2 = 0.50$ ) ( $p < .0001$ ) ( $n = 30$ ) increased active carbon ( $R^2 = 0.61$ ) ( $p < .0001$ ) ( $n = 30$ ) and increased potentially mineralizable nitrogen ( $R^2 = 0.61$ ) ( $p < .0001$ ) ( $n = 30$ ) from time since occurrence of Scoop & Dump remediation. Each grouping by year represents a different study location as follows; CCC (6 months), Mann (2 years, 6 months), Roberts (3 years, 6 months), Plant Science (6 years, 5 months), Centennial (8 years, 6 months) and Fernow (11 years, 6 months).

penetrometer. When normality or equal variance was not possible, alternatives to ANOVA tests were utilized including Welches ANOVA.

## 3. Results

### 3.1. Bulk density

Changes in soil quality could be detected within one year of soil amendment. Bulk density decreased below root limiting thresholds of  $< 1.4 \text{ g/cm}^3$  (Daddow and Warrington, 1983) within one year of

**Table 1**  
Soil quality indicators.<sup>b</sup>

Soil quality property	Scoop & Dump	Unamended	Std Err	P-value
Bulk density (g/cm <sup>3</sup> )	0.89	1.47	0.06	< .0001
Available water holding capacity (%)	0.22	0.15	0.01	< .0001
Aggregate stability (%)	72.41	34.90	4.88	< .0001
Active carbon (mg/kg <sup>-1</sup> )	1022.47	361.60	51.51	< .0001
Potentially mineralizable nitrogen (mg/kg <sup>-1</sup> )	27.53	3.11	4.41	.0005
Organic matter (%)	8.43	3.23	0.58	< .0001
Phosphorus (mg/kg <sup>-1</sup> )	180.133 <sup>a</sup>	14.32	46.182	.017
Potassium (mg/kg <sup>-1</sup> )	221.833	65.84	24.784	.0001
Magnesium (mg/kg <sup>-1</sup> )	400.607	120.747	34.996	< .0001
Iron (mg/kg <sup>-1</sup> )	3.56	2.073	0.31587	.0025
Manganese (mg/kg <sup>-1</sup> )	53.1 <sup>a</sup>	20.7933	4.3307	< .0001
Zinc (mg/kg <sup>-1</sup> )	5.12667 <sup>a</sup>	1.94 <sup>a</sup>	0.78061	.0074
pH (mg/kg <sup>-1</sup> )	7.32	7.53	0.1053	.1631

<sup>a</sup> Nutrients above the optimal range according to Cornell Soil Health Test.

<sup>b</sup> Samples included five replicates taken per soil treatment across three sites (CCC, Mann, Plant Science) ( $n = 30$ ).

remediation (Scoop & Dump = 0.94 g/cm<sup>3</sup>, Unamended = 1.54 g/cm<sup>3</sup>). Over a 12-year period and six sites S&D soils exhibited a decrease in bulk density by 51% ( $n = 30$ ) (Fig. 1). Comparing S&D to unamended (Unam) controls across three sites showed significant reduction in bulk density in S&D soils. (Table 1).

### 3.2. Soil resistance

Significant differences were observed using a survival analysis at a mean depth where root-limiting resistance (> 300 PSI) was encountered in the soil profile. Scoop&Dump soils showed approximately three times greater depth that roots could penetrate before reaching limiting pressures compared to unamended soils (Table 2).

### 3.3. Texture and mulch depth

Scoop & Dump soil observed across all of the sites showed a range of textural classes. Loam textured soils composed 60% of the total samples. An additional 33.3% of S&D soils fell within a loam related class (clay loam, sandy loam, silty loam, silty clay loam). The remaining 6.7% of S&D soil fell within the textural class clay. This clay grouping represented two samples taken from the Plant Science site. The texture of unamended soils across the three study sites used as control fell within the ranges of loam (46.67%) and sandy loam (53.33). S&D soils on average across all sites were 15.65 cm (6.16 in) thick with average mulch depths of 4.55 cm (1.79 in).

### 3.4. Available water holding capacity

In comparing S&D soils to unamended soils, available water holding capacity was significantly higher in S&D soils (Table 1).

### 3.5. Aggregate stability

In comparing S&D soils to unamended soils, aggregates found in

**Table 2**  
Comparative depth at which root limiting pressure occurred by treatment.<sup>a</sup>

Scoop & Dump (cm)	Std err	Unamended (cm)	Std err	Log-rank prob > chisq
24.74	0.26	8.74	0.36	< .0001

<sup>a</sup> Comparative depth at which root limiting psi (> 300) was reached using an electronic soil penetrometer. Depth units are in cm.

S&D soil resisted degradation, maintaining more than double their composition when challenged with simulated rainfall (Table 1).

### 3.6. Active carbon

Active carbon was improved by 228% compared to the unamended controls (Scoop & Dump = 909.60 ppm, Unamended = 277.40 ppm) within one year of remediation. Over a 12-year period and six sites, active carbon increased by 48% ( $n = 30$ ) (Fig. 1). In comparing S&D soils to unamended soils, active carbon was increased by 183% in S&D soils (Table 1).

### 3.7. Potentially mineralizable nitrogen

Potentially mineralizable nitrogen improved 665% within one year of remediation (Scoop & Dump = 21.60 ppm/wk, Unamended = 2.82 ppm/wk). Over a 12 year period and six sites potentially mineralizable nitrogen increased by 391% ( $n = 30$ ) (Fig. 1). In comparing S&D soils to unamended soils, potentially mineralizable nitrogen was nine times higher in S&D soils (Table 1).

### 3.8. Organic matter

Organic matter was significantly higher in S&D sites compared to unamended sites (Table 1). Across all S&D sites organic matter ranged from 2% to 48.6% with a median value of 9.15%.

### 3.9. Soil nutrients

Phosphorus, potassium, magnesium, iron, manganese, and zinc were higher in S&D soils compared to unamended soils. No statistically significant differences were observed for pH (Table 1).

## 4. Discussion

The study was designed as an observational exploration of changes in soil quality in remediated urban soils over the course of time and compared to unamended sites. Since these conditions are representative of what land care practitioners would experience in the field, they represent a chance to explore the impacts of soil remediation on an applied level. Although outside the scope of this current study the S&D soil remediation strategy has shown an increase in shoot and root dry weight and total leaf area compared to trees growing in unamended soils (Schwartz Sax, 2015). The increased tree growth performance was directly correlated with improvements in soil quality and demonstrated the benefit of the S&D technique on plant growth.

### 4.1. Bulk density

The S&D method of soil remediation was developed in an attempt to improve rooting environments for woody plants growing in impacted urban soils by physical fracturing and incorporation of organic matter.

Typical urban impacts such as building construction, foot traffic and heavy machinery compact soils above a threshold that plant roots are able to penetrate. Soil texture is the primary factor that determines root growth-limiting bulk density. Root limiting thresholds have ranged from 1.40 g/cm<sup>-3</sup> for clays and silts to 1.75 g/cm<sup>-3</sup> for sands (Daddow and Warrington, 1983). It has been demonstrated that the use of a backhoe and no soil amendments can loosen compacted soils and increase soil pore volume, decrease bulk density and decrease soil resistance (Rolf, 1991). Loosening soils with a pneumatic sub-soiler has also been shown to result in both increases and decreases in soil bulk density depending on soil texture. These changes have been partially explained by soil swelling. Soils that have swelled can increase bulk density over time as they re-settle, losing the benefit of the aeration (Rolf, 1992). From these studies it was determined that physical



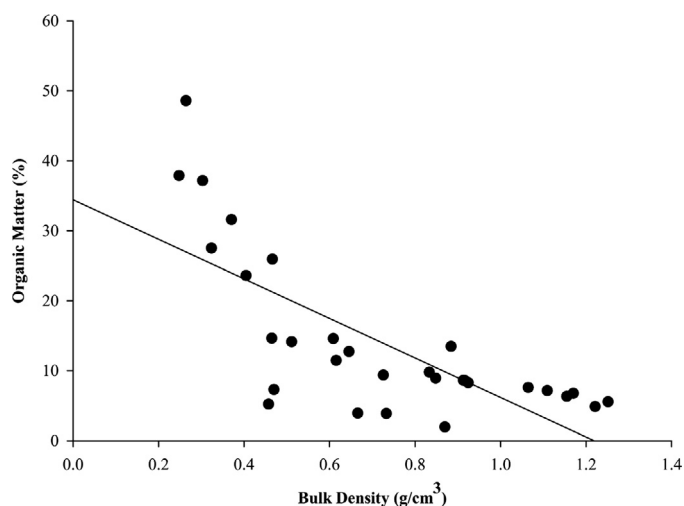


Fig. 2. Regression analysis showed that large increases in organic matter correlated with decreased bulk density across all Scoop & Dump sites ( $R^2 = 0.54$ ,  $p = < .0001$ ,  $n = 30$ ).

loosening of soils has short term benefits but does not maintain prolonged reductions in soil bulk density.

Our study demonstrates that the combined practice of organic matter incorporation (compost and mulch) and physical fracturing improves bulk density (Table 1) and that as organic matter increases, bulk density decreases (Fig. 2). This improvement in bulk density was observed within a year after compost amendment and continued to improve over a 12-year period (Fig. 1). The bulk density of S & D soils compared to unamended soils showed reductions below root-limiting thresholds regardless of texture.

Reduction of bulk density by incorporation of organic matter occurs as the result of multiple factors working together. Increases in aggregate stability and aggregate size create a soil structure that is resistant to compression. Reduction in bulk density potentially increases airspace between aggregates through the creation of a lattice structure.

The low density, highly porous nature of organic matter, when incorporated into heavier bulk soil, has a loosening effect. It has been shown that the incorporation of organic matter into mineral soils decreased bulk density between 1 and 6% with organic matter making up 5–25% of the total volume of the experimental soils (Hudson, 1994). A similar technique to S & D known as profile rebuilding has been investigated and shown to improve (decrease) soil bulk density and transplant success of trees within their first year (Layman et al., 2010). Additionally, plant growth performance has been directly linked with the S & D technique of soil remediation. *Ficus benjamina* ‘Evergreen’ growing in S & D soils showed an increase in leaf area and root/shoot dry weights compared to unamended soils. Increases in root/shoot dry weight and leaf area were directly correlated with decreases in bulk density using linear regression analysis and demonstrated plant performance benefiting from remediation (Schwartz Sax, 2015).

Organic matter incorporation and its positive effects on reducing bulk density, increasing aggregate stability and improving soil porosity have commonly been observed as improving synchronously with each other (Aggelides and Londra, 2000; Cogger et al., 2008; Layman et al., 2010; Rivenshield and Bassuk, 2007).

#### 4.2. Resistance

Soil resistance is measured by a penetrometer that assesses the amount of force required to push the device into the soil profile. Readings greater than 300 psi indicate pressures for which root penetration is limited. Soil resistance is considered a relative measurement because increased soil water content has been shown to decrease soil resistance (Aggelides and Londra, 2000). Due to this limitation,

penetrometer measurements for this study were taken shortly after soils had reached field capacity and all soils were assessed within a period of several hours. Penetrometers are easy to use instruments and measurements are a helpful indicator for quick field assessments of compaction making it an appropriate semi-quantitative tool for assessing resistance.

Significant differences were observed using a survival analysis in mean depth at which root-limiting resistance was encountered in the S & D soils compared to unamended controls. This shows that S & D soils have almost three times greater rooting depth available to plants before reaching a root limiting resistance (Table 2).

#### 4.3. Texture and mulch depth

At the Plant Science site, clay textured soils were only observed in S & D soils. This suggests that clay particles were present in the compost that was incorporated into the soil or transported in during the building construction process that had occurred on the site prior to restoration. Depth of mulch across sites did not show any relationship with time.

#### 4.4. Available water holding capacity

Available water holding capacity is mediated in soils by texture, organic matter, bulk density and aggregate stability. Texture is generally considered to be the primary factor that determines a soil's AWHC. Other factors that can play significant roles are gravel, organic matter and density. Presence of gravel (particles > 2.0 mm) decreases AWHC and can significantly increase bulk density. Bulk density, depending on the loosening or compaction of soils, can affect AWHC from –10% to 20%. Organic matter in a range of 0.5% to 8.0% has been shown to increase AWHC in silt loam soils (Saxton and Rawls, 2006).

A study looking at increasing organic matter in sand, silt loam and silty clay loam soils has found that as organic matter (OM) increased, the volume of water held at field capacity and permanent wilting point also increased. The increase at field capacity was larger than at wilting point, resulting in an overall AWHC increase (Alliaume et al., 2013). It has been shown that OM incorporated into different textural classes of soil can have significantly differing effects. Increasing OM in coarse textured soils significantly increased AWHC more than in fine textured soils. In low OM soils this was more pronounced but if OM was present at larger percentages (> 5%) AWHC increased regardless of textural class (Rawls et al., 2003). Scoop and Dump soils having significantly higher OM inputs than most agricultural soils, which could explain the increase in our study. High quantities of OM correlated with decreased bulk density (Fig. 2).

Across all S & D sites a positive correlation was observed between available water holding capacity and organic matter. This positive correlation between soil organic carbon and AWHC has also been observed by Alliaume et al. (2013).

Across all S & D sites a negative correlation was observed between available water holding capacity and bulk density. This increase in AWHC, correlated with decreased bulk density, could be partially explained by an increase in OM. The three indicators (OM, AWHC, BD) all have synergistic effects showing correlations between the factors. Rawls et al. (2003) suggested that in soils with large amounts of incorporated OM, bulk density is a strong indicator of AWHC because of overlapping effects of these indicators (Rawls et al., 2003).

#### 4.5. Aggregate stability

The Cornell Soil Health Lab uses a sprinkle infiltrometer that simulates a heavy rainstorm event. This instrument delivers a uniform amount of energy in the form of raindrops, providing a quantitatively determined impact on the soil aggregates. This method chiefly quantifies slaking, the fragmentation of particles off of aggregates (Gugino et al., 2009).

Increases in soil organic matter have been shown to increase aggregate stability through increased hydrophobicity. The hydrophobic properties of OM consequently have been shown to increase the amount of time it takes for water to absorb into the aggregates. Increases in soil carbon content have been correlated with aggregate stability and decreased slaking. Additionally, it has been observed that organic matter associated with clay increased soil hydrophobicity (Chenu et al., 2000).

An improvement was observed in aggregate stability in the S & D soils compared to unamended soils. The increase in aggregate stability was observable within a year of incorporation of compost and improvements remained over time. In chronosequence across a period of 12 years no correlation was observed over time. This finding suggests that improvements in aggregate stability occur rapidly after soil amendment and remain enhanced into the future.

Improvements in aggregate stability have commonly been observed as a benefit of compost amendment into soils (Aggelides and Londra, 2000; Cogger, 2005). All composts used in the S & D study had been stabilized and in a mature state before incorporation. Mature, finished compost is thought to stabilize soil aggregates through enhancing greater particle cohesion, increasing hydrophobicity of soils and resisting the degrading mechanical effects of raindrop impacts (Annabi et al., 2007). The increase in aggregate stability in S & D soils could be partially explained by the finished compost quality.

The increases in aggregate stability as a result of the S & D process are in contrast to a study by Cogger et al. (2008) that found no increase in stability five years after compost application into soils. In that study, incorporation of compost into fine sandy loam to silt loam soils found no increase in aggregate stability compared to controls. The authors of that study suggested that this could be due to low clay content of the original soil (Cogger et al., 2008). Cogger used four nested sieves to conduct wet aggregate stability testing, which differs from the method employed by the Cornell Soil Health Lab.

#### 4.6. Active carbon

Active carbon (AC) using the Pox-C method refers to testing the labile fraction of the total soil carbon. This fraction of soil carbon is a preferred indicator because it is sensitive on a shorter time scale to changes in management compared to total organic carbon or organic matter by LOI. Pox-C has been shown to correlate with the indicators: microbial biomass, basal respiration, substrate-induced respiration, and soluble carbohydrates. This method also has been shown to have stronger correlations with aggregate stability and crop biomass production compared to total carbon (Weil et al., 2003).

A comprehensive study of the Pox-C method across different geographic and land management practices determined that this method has no direct relationship with textural class or environmental effects across the United States. Pox-C correlated with other soil biological indicators such as particulate organic matter, microbial biomass carbon and total organic carbon. Positive correlations with biological indicators make the Pox-C method a good indicator for soil quality and represent a method that is sensitive to changes in soil management.

A comparison of S & D amended soils and unamended sites showed that active carbon significantly increased after treatment. Over a period of 12 years, a linear relationship was observed with active carbon increasing over time. The regression trend implies that continual mulching of sites provides significant inputs of organic matter that likely play a role in the large increase in AC that was observed over time.

A similar response over time was observed with the biological indicator potentially mineralizable nitrogen. This suggests that the S & D process followed by planting can increase the biological activity of the soil. Although an increase in OM in S & D soils compared to unamended soils was observed no linear relationship was established for increasing organic

matter over time. This indicates that the soil carbon fraction that is measurable by the Pox-C test has a finer sensitivity in detecting changes in labile soil carbon compared to organic matter assessed by LOI.

As early as one year after S & D remediation, active carbon increased as much as three fold in the CCC site. This indicates that the largest increase in active carbon is from the initial incorporation of organic matter. Mulch, dropped leaves, root turnover, and microbial biomass carbon likely contributed to improving AC over time, but the increase was not as large compared to initial incorporation during the remediation process.

#### 4.7. Potentially mineralizable nitrogen

The potentially mineralizable nitrogen (PMN) is a process mediated by microorganisms. The PMN process and the rate of mineralization has been shown to be dependent on temperature, soil texture, moisture, soil oxygen, carbon to nitrogen ratios and organic matter chemical composition (Cabrera et al., 2005).

PMN has been observed in the Cornell Soil Health Lab to typically increase in conjunction with the elevation of other biological indicators including active carbon, organic matter and aggregate stability (Gugino et al., 2009). This is consistent with the findings of our study.

Over a 12-year period, potentially mineralizable nitrogen demonstrated a linear relationship increasing over time in S & D soils (Fig. 1). Linear relationships of nitrogen mineralization and time have been observed by other researchers studying chronosequence of farm field to forest succession in the Midwestern United States. This has been attributed to an increase in microbial biomass, carbon and nitrogen pools (Zak et al., 1990). Potentially mineralizable nitrogen in S & D sites compared to unamended sites significantly increased in our study (Table 1).

In a 1980 study (Porter et al., 1980) on nitrogen accumulation in turfed landscapes ranging in landscape age from 1 to 125 years, it was found that total nitrogen accumulated in the first 10 years at higher rates and continued at lower rates until 30 years after establishment (Brown et al., 2012). S & D soils showed a significant increase over time and are in agreement with the initial findings of Porter et al. (1980).

This increase over time is of particular note because additions of organic matter after site establishment were made as either residue from established landscape plants or mulch. Mulch with high C:N ratio has been shown to cause nitrogen immobilization decreasing plant available nitrogen pools in soils (Homyak et al., 2008). In S & D soils the initial mixing of compost and the annual application of mulch do not result in a decrease of PMN suggesting that mulch additions do not result in nitrogen immobilization. No supplemental nitrogen was applied to the sites which indicates that incorporated compost and annual mulch additions contribute to the increase in PMN.

#### 4.8. Organic matter

Urban soils have the potential to sequester and store large amounts of soil organic carbon through incorporation of OM into soils. A study conducted in Washington State has found that incorporation of organic matter into soils increased carbon content on average by 24% after a period of 2–15 years (Brown et al., 2012). Compost incorporation deep into the profile has been shown to increase total organic carbon (TOC) and microbial biomass carbon in soil depths of 15–30 cm (Chen et al., 2013).

In this study looking at S & D soils, organic matter percent was significantly higher in S & D sites compared to unamended sites. Organic matter was assessed by the LOI method. This method is adequate for soil quality purposes but does not give accurate measurement of total organic carbon. LOI method is considered to be a standard because of the ease of conducting the test, but does not account for all forms of carbon found in the soil. Additional forms of carbon include inorganic forms such as carbonates, contaminants from human activities and volatile organic

carbon. The LOI method can also have some error due to combustion of water or hydroxyl groups in the structural clay matrix of soils leading to an overestimation of carbon in soils. As a result, a correction factor is generally used to convert organic matter to organic carbon. This correction factor can range from 1.724 to 2.5 depending on the depth of sample in the profile as well as differing soil types. This makes the LOI method semi-quantitative (Schumacher, 2002). Because of the use of the LOI method, total organic carbon (TOC) was not quantitatively assessed although it was considered in this discussion.

The S&D process showed a higher OM percentage compared to unamended sites. As suggested by Chen et al. (2013) one explanation could be that deep incorporation of large volumes of OM increases TOC deeper in the soil profile because the carbon is protected from oxidation and microbial degradation.

In the same study it was observed that undisturbed soil stored more TOC in the top 10 cm of the profile compared to compost-amended soils. These findings support the recommendation of prioritizing soil protection as the first choice for soils on construction sites rather than removal of topsoil. At deeper depths (15–30 cm) the TOC levels were elevated in soils that received deep incorporation of compost compared to other treatments (Chen et al., 2013). The Chen et al. (2013) observations are inconsistent with the results of our study, which found an increase of OM in S&D soils high in the profile. S&D soils received annual mulching and had landscape plants established in them. In the Chen et al. (2013) study, sites did not receive mulch and were maintained as bare soil. These differences in landscape management could explain the differences between the findings of the two studies. Brown et al. (2012) also found that soil carbon increased in soils after compost application and incorporation on sites ranging from 2 to 15 years after establishment (Brown et al., 2012).

Increased organic matter has been shown to improve plant growth performance (leaf area, shoot/root dry weight) of *Ficus benjamina* 'Evergreen' growing in S&D soils compared to unamended controls (Schwartz Sax, 2015). This suggests that improvements in organic matter as a result of using S&D technique provide the dual benefit of improving soil quality and increasing tree growth.

#### 4.9. Soil nutrients

Soil nutrients phosphorus, potassium, magnesium, iron, manganese, and zinc were all significantly elevated in S&D soils compared to unamended soils. For S&D soils phosphorus, potassium, magnesium and zinc all showed increases in available nutrients as a result of treatment (Table 1).

Increases in plant available potassium, magnesium and zinc as a result of compost application have been documented to regularly occur (Gallardo-Lara and Nogales, 1987). Composts used as additions to horticultural substrates have been shown to have variable effects on soil macronutrients and plant uptake. This has been attributed to differences in initial feed stocks, pH and stabilization treatments (He et al., 2001).

Phosphorus levels in the S&D soils were above the optimal level but within normal ranges for the unamended site. Manganese in S&D soils was slightly above the recommended levels. Zinc in S&D and the unamended soils was above the optimal range (Gugino et al., 2009). pH levels between S&D and unamended soils were within the optimal range and no significant differences were observed between treatments (Table 1). These findings suggest that compost amendments can significantly impact soil nutrient status in conjunction with S&D remediation.

Excessive phosphorus (P) levels are a concern as an environmental pollutant due to leaching, causing eutrophication in freshwater systems. In agricultural systems manure is often applied to meet nitrogen demands of a given crop. Phosphorus is taken up by plants at different rates compared to nitrogen and as a result of applied manure, P can accumulate in soils becoming a source of pollution (Sharpley and

Withers, 1994). Elevated P levels in S&D soils could be a concern in runoff becoming a point source of pollution. This could potentially be avoided by using composts that do not include manures. Since the S&D method is used to create relatively small planting beds compared to agricultural fields, the concerns for runoff could be minimal in terms of environmental impacts. Further study will need to be conducted to better understand phosphorus availability and potential leaching after compost incorporation using the S&D method.

## 5. Conclusion

The Scoop & Dump method of soil remediation shows improvement in soil quality indicators – bulk density, resistance, aggregate stability, potentially mineralizable nitrogen, active carbon and organic matter content compared to unamended sites. Over a period of 12 years, soil quality indicators – bulk density, active carbon and potentially mineralizable nitrogen – improved over time showing long-term beneficial effects of using the Scoop & Dump Technique.

The application of the Scoop & Dump soil remediation strategy is an appropriate method for restoring soils damaged by heavy equipment, building construction and urbanization impacts. With minimal annual maintenance including the addition of shredded bark mulch, these improvements in soil quality are maintained or enhanced over time. This technique offers a practical, research-based tool for green industry professionals, arborists and landscape contractors and has a strong potential for improving soil quality using locally sourced materials and sustainable methods.

## Acknowledgment

The authors would like to acknowledge the Toward Sustainability Foundation for funding support through the Organic & Sustainability Systems Research, Teaching & Outreach program. Thanks are extended to Robert Schindelbeck and the Cornell Soil Health Lab for their expertise, advice and tireless efforts that were instrumental in carrying out this research.

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