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Research papers

Restoring hydrologic function in urban landscapes with suburban subsoiling

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A B S T R A C T

Dramatic persistent hydrologic changes accompany urban land development, most commonly attributed to increased impervious area and drainage infrastructure. Modern land development and mass grading practices also result in the routine development of urban landscapes with highly disturbed compacted soil profiles. The common predictable result is an urban pervious landscape with greatly diminished infiltration capacity in greenspace that might best be described as grass growing in a thin veneer of topsoil on compacted fill. This paper describes the use of soil decompaction and amendment to restore hydrologic function following the removal of an impervious asphalt playground at a public school in Baltimore, MD, USA. The combination of soil decompaction with deep ripping and compost amendment is referred to as *suburban subsoiling*, alluding to the adaptation of agricultural subsoiling practices to restore hydrologic function in disturbed compacted urban soils. In this field-scale comparison with standard grading and landscaping practices, suburban subsoiling supported the highest infiltration rates, with the densest turf cover, highest soil organic matter and root zone soil moisture, and the lowest soil bulk density. As a sustainable alternative to traditional grading and topsoiling practices, suburban subsoiling offers a proverbial win-win solution, providing superior landscaping and restored hydrologic services with lower life-cycle costs. Though significantly different than current grading and landscaping practices, suburban subsoiling can be readily integrated in modern land development with only minor incremental changes in standard practices. Suburban subsoiling can transform the built environment through superior sustainable landscaping that restores the hydrologic function of urban pervious landscapes.

1. Introduction

Dramatic persistent hydrologic changes accompany urban land development. Urban hydrologic response is most commonly characterized by flashy storm hydrographs with increased runoff volumes and higher peak discharge rates attributed to increased impervious surface runoff and efficient drainage infrastructure. The breadth of environmental impacts associated with impervious area has led to its suggested use as a primary control for managing a wide range of planning, regulatory, and ecological goals in developed landscapes (Arnold and Gibbons, 1996). Simple heuristic planning criteria have been extended to include the institutionalization of impervious area caps in landuse planning and zoning; impervious area trading - to empower market-based approaches for innovative stormwater regulatory compliance; and even Total Maximum Daily Loads (TMDL) on impervious area, as a regulatory prescription to achieve designated uses in impaired water bodies (Arnold et al., 2010; Haase and Dornisch, 2009; Moglen and Kim, 2007; Raffensperger and Cochrane, 2010; Thurston et al., 2003). In developed watersheds across diverse physiographic and climatic regions, the recurring association of impervious area with intensified urban runoff and stream degradation has been described as the "urban stream syndrome" (Walsh et al., 2005). The seductive appeal of treating impervious area as a sufficient management criterion for mitigating urban stormwater development impacts is not, however, unequivocal (Beck et al., 2016; Brabec et al., 2002; Brabec, 2009; Jones et al., 2005; Moglen and Kim, 2007; Schwartz and Smith, 2014).

More critical investigations of human effects on urban hydrologic response recognize the heterogeneity in both the form (Beck et al., 2016; Mejia and Moglen, 2009, 2010; Moglen, 2000; Zhang and Shuster, 2014) and the hydrologic response of urban landscapes (Boyd et al., 1993; Burges et al., 1998; Meierdiercks et al., 2010; Polsky et al., 2014; Schwartz and Smith, 2014; Shuster et al., 2005). Leopold's (1991) characterization of expected lag time changes in developed watersheds in the San Francisco Bay

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region referred to the "discovery" of unexpectedly high runoff coefficients from pervious landuses ("golf courses and mowed lawns") in the constructed landscape. Wigmosta and Burgess (1997) compared detailed water budgets for a forested watershed and a physiographically similar suburban-developed watershed near Seattle, Washington. Contrary to their expectations, their thorough analysis showed that more runoff in the developed watershed was being generated from the *pervious* landscape than the impervious landscape. This counterintuitive result was largely attributed to clearing and grading practices that altered and disrupted the ~1 m pre-development forested soil profile, resulting in a pervious suburban landscape with an average post-development soil profile depth of only 10 cm (Burges et al., 1998). Indeed, Bonta (2013) compared the hydrologic effects of urbanization to the "drastic soil profile disturbances" associated with mine reclamation. The common association of mass grading and the wholesale disruption of native soil profiles in urban land transformation, underscores the importance of the pervious landscape in understanding urban hydrologic response. The deep-rooted conceptual model of flashy intensified urban water budgets dominated by runoff from impervious areas, so clearly framed by Leopold (1968), is incomplete and must admit a more complex and nuanced understanding of the hydrologic function of the urban pervious landscape.

Modern land development practices routinely produce pervious landscapes with highly disturbed compacted soil profiles from mass grading and incidental compaction from construction vehicles and heavy equipment operation (Gregory et al., 2006; Haynes et al., 2013; Pitt et al., 2008; Randrup and Dralle, 1997). Following mass grading and compaction, standard sediment and erosion control practices require prompt vegetative stabilization of compacted final finish grades, commonly specifying "topsoiling" (USDA, 2009a)- i.e. rapidly establishing turf cover in 5–10 cm of placed "topsoil". The most common predictable result is an urban landscape with severely limited infiltration capacity from greenspace that might best be described as grass growing in a thin veneer of topsoil on compacted fill. Burges et al. (1998) offer a notable example, observing that most residential lawns in the subdivision of their developed watershed consisted of "a thin layer of imported topsoil overlain by sod".

In the United States, Natural Resource Conservation Service (NRCS) curve number hydrology – based on landuse and hydrologic soil group (HSG) – remains a dominant tool for urban stormwater design. Yet the HSG which, in practice, is routinely taken at face-value from county soil maps, rarely accounts for the inherent disruption and compaction of urban soil profiles that accompanies mass grading and site preparation. As a consequence, curve number design hydrology based on landuse landcover and pre-development soils information, is not sufficient to reliably predict the hydrologic response of disturbed compacted urban landscapes without additional on-site investigation. The far-reaching implications for stormwater planning and hydrologic design prompted the explicit caution found in the NRCS National Engineering Handbook (USDA, 2009b):

> "As a result of construction and other disturbances, the soil profile can be altered from its natural state and the listed group assignments generally no longer apply, nor can any supposition based on the natural soil be made that will accurately describe the hydrologic properties of the disturbed soil. In these circumstances, an onsite investigation should be made to determine the hydrologic soil group."

The prevalence and consequences of urban soil compaction have led to significantly modified grading alternatives intended to restore hydrologic function and environmental services in the pervious landscape (Balousek, 2003; Chaplin et al., 2008; Lacey, 2008; Olson et al., 2013; PADEP, 2006; Sinnett et al., 2006, 2008). In Kings County, WA, the "Soils for Salmon" initiative (Marx et al., 1999) institutionalized urban soil husbandry for onsite management of stormwater runoff from new construction and infill development, with site-specific requirements far beyond simple limits on impervious area. From agricultural subsoiling and reforestation to land reclamation on abandoned surface mines, soil husbandry practices are increasingly recognized as essential tools to restore sustainable environmental services in human altered landscapes (Basta et al., 2016; Callaham et al., 2008; Cogger, 2005; EPA, 2011; Evanylo et al., 2016; Kumar and Hundal, 2016; Moffat and Bending, 2000; PADEP, 2006; Sloan et al., 2012; USDA, 2015).

A growing number of studies report results from experimental test plots that have been compacted to simulate standard urban land grading practices (Balousek, 2003; Chen et al., 2014; Glab and Szewczyk, 2014; Loper et al., 2010). This paper describes the field-scale implementation of soil decompaction and amendment in renovations at a Baltimore, MD public school that included the conversion of an asphalt playground to a stabilized turf field for impervious area reduction credit under the City's Federal stormwater permit. We refer to the combination of soil decompaction and amendment as *suburban subsoiling*, alluding to the adaptation of agricultural subsoiling practices to the sustainable restoration of hydrologic function in the built environment. The side-by-side use of suburban subsoiling and standard topsoiling in typical field-scale urban land transformation provided a rich opportunity to compare standard and alternative grading and landscaping practices. The following section describes the study site, and methods used to characterize the soil profile and hydrologic performance for fields established using both suburban subsoiling and standard grading and topsoiling. Section 3 summarizes the results from more than three years of post-treatment performance monitoring. The challenges opportunities and implications of advancing suburban subsoiling to restore urban hydrologic function and promote more sustainable urban landscapes are discussed in Section 4, with conclusions summarized in Section 5.

2. Methods

2.1. Site description and preparation

The study site is located at the Yorkwood Elementary School in the Piedmont physiographic province in northeast Baltimore, Maryland, USA. The Baltimore City soil map shows the school property located on soils of the Joppa-Urban land complex. The gently rolling local topography is dissected by stream valleys of the West Branch of the Herring Run tributary of Back River, with adjoining upland soils of the Sassafras-Joppa complex and hillslopes mapped as 8–15% slopes in the Sassafras gravelly loam. Site topography showed clear evidence of mass grading and cut-and-fill features from the original construction of a now-idle baseball field, an active asphalt parking lot, and the asphalt playground targeted for impervious area removal and conversion to turf.

Like many municipalities subject to US EPA Phase I stormwater requirements, Baltimore's National Pollution Discharge Elimination System (NPDES) stormwater permit includes prescribed goals for impervious area reduction. In collaboration with the Board of Education, the Baltimore Department of Public Works has undertaken a program to convert older asphalt school playgrounds to green space, to reduce stormwater runoff (Buckley et al., 2016; MDE, 2014). The study site is an example of one such project, in which City staff championed the use of suburban subsoiling (deep ripping and compost amendment) in place of standard topsoiling that was originally specified for site preparation.

Following asphalt removal, the compacted fill beneath the pavement was found to contain bulk trash and construction debris, including tree stumps, that made deep ripping impractical. The top 30 cm of this underlying fill were replaced with a select borrow as the subgrade for subsequent topsoil addition and amendment. Project scheduling constraints and the unanticipated expense of removing construction debris led to the decision to limit the suburban subsoiling (SS) treatment and debris removal to only half of the pavement removal footprint, implementing standard topsoiling (TS) practices with surface scarification and approximately 5–7.5 cm of topsoil spread on the other half. The change enabled a side-by-side comparison of the two treatments on an active public school playground.

Topsoil meeting Baltimore City specifications was spread over the entire site. On the field prepared with the SS treatment, the reconstructed profile of topsoil and select borrow over *in situ* material was ripped to an approximate depth of 50 cm with multiple passes of a 5-shank parabolic ripper. The ripped SS soil profile was amended with Leafgro (Maryland Environmental Services) vegetative compost, surface-applied to the SS field at an average depth of 7.5 cm. The actual compost thickness varied over the site due to significant irregularities on the soil surface left by tractor tracks and soil ripping. Spot checks of observed compost depths averaged 7.5 cm, but ranged from 2.5 to 12.5 cm over the irregular underlying surface of the SS field. Applied compost was tested at the Penn State Agricultural Analytical Services Lab (University Park, PA) using US Compost Council (USCC) testing methods.

Compost was incorporated with a chisel plow followed by a rotary tiller, striving for uniform incorporation to achieve a 2:1 soil-to-compost ratio throughout the amended profile (Balousek, 2003; Cogger, 2005). The effective depth of incorporation was significantly less than targeted due to inherent limitations of the tillage equipment. The final treated profile combines ripping to a maximum depth of 50 cm with the incorporation of compost into topsoil to a typical depth no greater than 12.5 cm. In August 2010, the SS and TS fields were hydroseeded with a mixture of 44.75% Rebel Exeda Tall Fescue, 44.64% Rebel IV Tall Fescue, 4.93% Wild Horse Kentucky Bluegrass, and 4.84% Soprano Perennial Ryegrass. After hydroseeding, the site received no additional irrigation or fertilizer. The ripped and amended SS profile was allowed to settle naturally after hydroseeding, without any surface rolling to enhance soil strength or accelerate soil consolidation. The only routine grounds management on the site was periodic mowing, with clippings returned to the field.

2.2. Soil sampling

Two distinct areas within the new grass playfield delineated fields prepared with standard topsoiling (TS) and suburban subsoiling (SS) as shown in Fig. 1. An adjoining field that had once been used as a baseball diamond, but subsequently allowed to return to volunteer turf and meadow cover received no treatment, but was also sampled for comparison as an untreated reference site (RS). Routine random sampling for infiltration, bulk density, soil texture and organic matter was conducted seasonally from 2011 to 2013, with supplemental sampling continuing in subsequent years. In addition, the overall field-scale root zone soil nitrogen, soil moisture, and soil strength of the three fields were characterized by soil composite samples and dense GPS referenced synoptic sampling of root zone soil moisture and cone penetrometer profiles. The mean and standard deviation of field-scale soil properties are reported along with the number of samples used to estimate each parameter, as (mean ± s.d., n = #). The significance of differences in mean soil parameters between fields was evaluated using two-sample unequal sample size unequal variance t-tests, also known as Welch's *t*-test, evaluated with the Welch approximate degrees of freedom, as described in detail in (Ruxton, 2006). Sample statistics for each soil parameter from the three fields are summarized in Table 1.

2.2.1. Infiltration

Infiltration was measured using the single ring falling head method (Elrick et al., 1995; Touma et al., 2007; Zeleke and Si, 2005) using 15 cm diameter rings driven to an approximate depth of 7.5 cm. A small section of a 0.178 mm (7-mil) thick plastic drop cloth was gently hand placed to conform to the inner ring wall and the soil surface before a pre-measured volume of water was applied to achieve an average initial head of either 2.5 cm or 3.75 cm at the start of each test. The plastic was then smoothly removed to rapidly establish a nearly instantaneous uniform initial ponded head on the soil with minimal soil disturbance, marking the start of the drawdown test.

Measured head and cumulative test time were recorded until the soil surface was no longer fully submerged (marking the end of uniformly ponded conditions). The initial volumetric soil moisture content θ_0 was estimated as the average of four time domain reflectometry (TDR) soil moisture measurements made around the perimeter of the ring using a spectrum Field Scout TDR-100 soil moisture meter with 7.5 cm TDR rods. Soil moisture at the end of the test was similarly recorded inside the ring, as an estimate of the field saturated moisture content θ_{fs}. The change in volumetric soil moisture during the test was estimated as $\Delta\theta = \theta_{fs} - \theta_0$. Field saturated hydraulic conductivity K_{fs} was estimated from the drawdown curve and field estimated $\Delta\theta$, using Reynolds's (2008) solution for a falling head ring infiltrometer.

2.2.2. Soil characteristics

Associated with each infiltration test, at least two 5 cm diameter cores were collected and used to estimate bulk density, organic matter, and soil texture in the upper 10–12 cm of the soil. These cores were augmented with additional bulk density cores, that were collected to help resolve the high spatial variability of bulk density on the SS field. Cores were taken with an AMS (American Falls, ID) split core sampling cup driven with a slide hammer. Approximately 1–3 cm of the top of the recovered core (containing surface vegetation, roots and thatch) was gently extruded in the field and removed before capping the 10 cm core for laboratory analysis. Each core was extruded and weighed in the lab before being oven dried overnight at 105 °C, with bulk density computed from the oven dried weight. Following bulk density estimation, each soil core was gently ground in a mortar with a rubber tipped pestle and screened through a 2 mm sieve. A subsample of approximately 25 g of the ground core was used to estimate organic matter content, determined by the loss on ignition method at 450 °C. A second 50 g subsample of the ground sieved core was used for texture analysis using the hydrometer method. (Gee and Bauder, 1986).

2.2.3. Soil nitrogen

Periodically, composite soil samples were randomly collected from the root zone of each of the fields with a 1.75 cm diameter soil probe. Samples were air dried, composited, and analyzed for standard lawn recommendations and soil nitrogen at the University of Delaware Soil Testing Laboratory (Newark, DE).

2.2.4. Synoptic sampling

Field-scale mean soil moisture and the spatial heterogeneity of soil strength were characterized for each field from synoptic samples of root zone soil moisture and cone penetrometer profiles. GPS-referenced field measurements of volumetric soil moisture were used to estimate and compare root zone soil moisture from

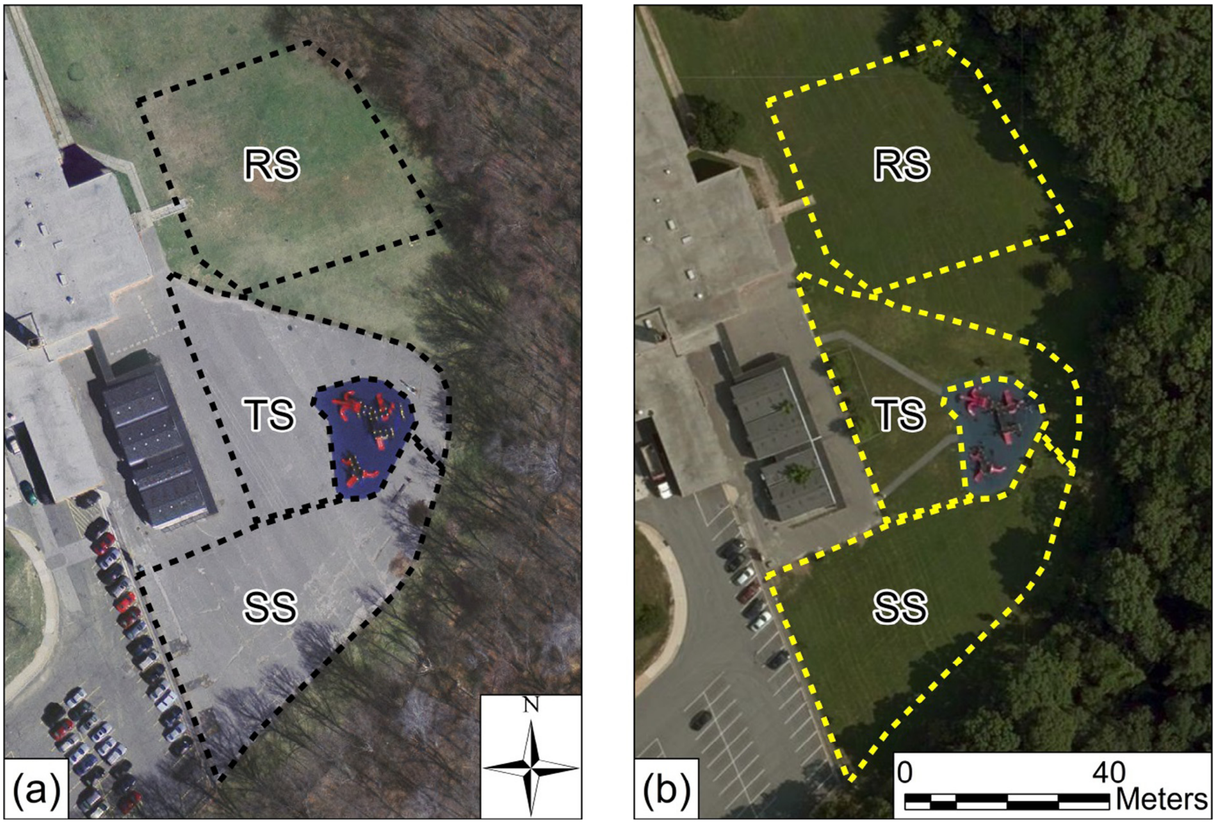

Fig. 1. Study site before (a) and after (b) impervious area removal and treatment showing areas treated with suburban subsoiling (SS), standard topsoiling (TS), and the area designated as an untreated reference site (RS).

Table 1
Sample soil property mean ($\bar{x}$), standard deviation (s), and sample size (n) from fields prepared with suburban subsoiling (SS), standard topsoiling (TS) and the reference site (RS).

Parameter	Field	$\bar{x}$	s	n
Biomass (g/m^2)				
	SS^{c1c2}	614.8	52.1	3
	TS^{ac1}	303.3	42.1	3
	RS^{ac2}	353.4	19.4	3
Infiltration (cm/h)				
	SS^{a}	8.33	7.09	33
	TS^{c}	0.59	0.78	21
	RS^{ac}	5.06	4.89	11
Bulk density (g/cc)				
	SS	1.25	0.16	95
	TS	1.71	0.12	65
	RS	1.40	0.08	33
Organic matter (%)				
	SS	9.39	3.40	98
	TS	3.05	0.94	67
	RS	4.00	0.85	36
Total nitrogen (g/kg)				
	SS^{c}	3825	493	5
	TS^{b}	1136	365	5
	RS^{bc}	2326	725	4
Soil moisture (%)				
	SS	35.3	6.87	102
	TS^{b}	25.6	6.83	77
	RS^{b}	23.4	6.25	130

Superscripts indicate pair-wise comparisons for which the difference between mean values are (a) not significantly different: $p > 0.05$; (b) marginally significant: $0.01 < p \leqslant 0.05$; or (c) significant $0.001 < p \leqslant 0.01$. Pairwise differences without superscripts (e.g. bulk density) are all highly significant: $p < 0.001$.

each field. Volumetric soil moisture was measured in the field with a Spectrum Field Scout TDR-300 soil moisture meter using 7.5 cm TDR rods.

In-situ soil strength was measured using a Spectrum Field Scout SC-900 logging cone penetrometer geo-referenced using a Trimble Geo XH GPS. The cone penetrometer profiles offer a detailed surrogate characterization of the spatial heterogeneity of compaction across the three study areas, with soil strength recorded as soil cone index in units of MPa. Cone index is closely correlated with bulk density and varies with soil moisture (Ayers and Perumpral, 1982; Bennie and Burger, 1988; Busscher et al., 1997; Hernanz et al., 2000; Vaz et al., 2011). To control for the effect of soil moisture on cone index measurements, synoptic penetrometer surveys were conducted approximately 2 days after a soaking rain as an operational means to collect penetrometer profiles under similar moisture conditions close to field capacity. At field capacity, common criteria for vegetative rooting considers cone index values greater than 2.1 MPa (300 psi) as soil strength that impedes the growth of most plant roots. Soil profiles with cone index values less than 1.4 MPa (200 psi) are generally considered to offer low physical impedance to root development (Gugino et al., 2009). In addition to the cone index values recorded within each profile, the maximum profile depths across the fields also help characterize the intensity and depth of compaction.

2.3. Turf biomass

Standing biomass on each of the fields was quantified in the summer of 2015 by hand clipping and collecting all above-ground vegetation from three randomly placed sampling frames. Clippings were air dried, oven dried at 60 °C, and weighed to give an estimate of mean above ground dry biomass in g/m^2.

3. Results

3.1. Compost analysis

On a dry weight basis the compost consisted of 65% organic matter and 1.9% total nitrogen, dominated by organic nitrogen (>99.98%) with a C:N ratio of 20.4. Compost bioassay using Marketmore 76 Cucumber seed achieved 100% germination and 100% vigor relative to the control, consistent with very mature compost. USCC respiration testing yielded 4.5 mg $CO_{2\text{-}C/g\ \text{organic matter/day}}$ indicating stable compost.

3.2. Germination, turf cover, and standing biomass

Within 9 months, striking differences in germination success, turf density, and species composition were clearly visible between the TS and SS fields. Initial vegetative cover on the TS field was relatively thin and irregular, dominated by clover and broad bladed rhizomatous crab grass. In sharp contrast, the SS field developed a dense verdant turf cover with virtually no visible clover or weed species in the first year following treatment.

Initial differences in turf appearance persisted throughout the sampling period. Clear differences in standing biomass were quantified five years after treatment, in the summer of 2015. The mean dry biomass on the SS field (614.8 g/m^2 ± 52.1), was more than twice that on the TS field (303.3 g/m^2 ± 42.1), consistent with visual assessment of the dense vigorous SS turf. The RS field showed extremely uniform cover with intermediate mean biomass of 353.4 g/m^2 ± 19.4 and the lowest sample variability among the fields. The lower mean biomass and higher variability of the TS field was consistent with the striking visual contrast between dense uniform cover on the SS field and the thin irregular cover on the TS field. Higher mean biomass with lower variance on the RS field reflected the more uniform cover and better developed thatch layer observed in the field. The clear difference between the SS field and both the TS and RS fields was highly significant ($p < 0.001$). Despite the clear difference in the appearance of the turf cover, there was no significant difference ($p = 0.101$) between the mean turf biomass on the TS and RS fields.

3.3. Infiltration

Infiltration tests demonstrated dramatic persistent differences between the mean field saturated hydraulic conductivity, K_{fs}, of the TS (0.59 cm/h ± 0.78, n = 21) and SS (8.33 cm/h ± 7.09, n = 33) fields, with mean RS infiltration (5.06 cm/h ± 4.89, n = 11) intermediate between the two (Fig. 2a). The significant differences understate the remarkably low infiltration of the "pervious" TS field that was prepared with standard topsoiling practices. Suburban subsoiling established dramatically higher infiltration, with median infiltration rates (6.60 cm/h) 50 times greater than the median infiltration rate on the TS field (0.13 cm/h). The reported results reflect only infiltration tests for which the observed drawdown was sufficient to allow the estimation of field saturated conductivity. A number of infiltration tests on the TS field showed such low rates of water entry that no significant drawdown could be recorded after several hours under ponded head conditions. These tests were halted and are not reflected in the TS infiltration rates reported here. We therefore interpret the low K_{fs} value reported for the TS field as an *overestimate* of the mean field infiltration capacity.

3.4. Bulk density

Bulk density showed significant persistent differences ($p < 0.001$) among all fields. Mean bulk density was consistently highest on the TS field (1.71 g/cc ± 0.12, n = 65) and lowest on the SS field (1.25 ± 0.16, n = 95). The mean RS bulk density was intermediate between the two (1.40 ± 0.08, n = 33), with the lowest variability among the three fields (Fig. 2b). The SS field had the lowest mean but the highest variance in bulk density, with some outlier bulk densities less than 1 g/cc from samples we interpret as isolated pockets of largely unincorporated compost. Maximum TS bulk density values exceed 1.8 g/cc and represent compaction levels that can substantially impede root growth.

3.5. Organic matter

Differences in mean soil organic matter among the three fields were all highly significant ($p \ll 0.001$) with SS (9.39% ± 3.40, n = 98) > RS (4.00% ± 0.85, n = 36) > TS (3.05% ± 0.94, n = 67), reflecting the significant addition of mature compost to the SS soil profile (Fig. 2c). Organic matter on the SS field was highly variable, reflecting heterogeneity in the effective depth of compost application and incorporation. Despite this variability, the significantly higher organic matter levels on the SS field showed no evidence of decline (e.g. due to net soil respiration) over more than three years of post-treatment sampling. Compared to the TS field, the significantly higher organic matter on the RS field is consistent with the slow steady accumulation of organic matter generated from decomposing leaf, stem, and root tissues, as described by Landschoot and McNitt (1994).

3.6. Texture

The average texture of samples from all three fields was a sandy loam. However, all fields had individual samples with loamy textures. Small differences in the mean particle size distributions (Table 2) from all three fields showed the highest clay and lowest silt content on the SS field, and the lowest clay and highest silt content on the RS field. A variety of methods may be used to estimate the water characteristics curves for each field from texture and

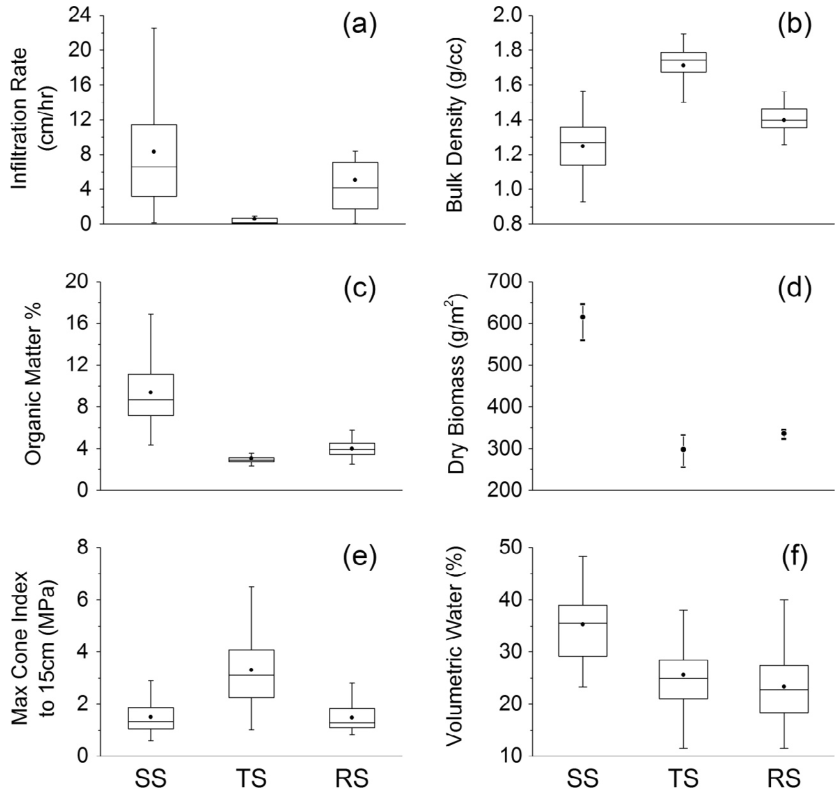

Fig. 2. Box-and-whisker plots of (a) infiltration; (b) bulk density; (c) organic matter; (d) high-low-mean plot of dry biomass; (e) maximum 0–15 cm cone index; and (f) 0–7.5 cm volumetric soil moisture. Biomass whiskers are high and low values around the mean. Field-scale results are summarized for suburban subsoiling (SS), topsoiled (SS), and reference site (RS) fields.

Table 2
Mean Particle Size Distribution.

	% Sand	% Silt	% Clay
Suburban Subsoiling (SS)	56 ± 3.8^{a}	30 ± 2.7^{a}	14 ± 2.2^{a}
Topsoiling (TS)	54 ± 2.0^{b}	34 ± 1.5^{b}	12 ± 1.5^{b}
Reference Site (RS)	54 ± 6.4^{ab}	36 ± 5.9^{c}	10 ± 2.1^{c}

Similarly superscripted letters indicate values that are not significantly different between sites at the 5% significance level.

bulk density (Arya et al., 1999; Barbu and Ballestero, 2015; Fredlund et al., 2002; Saxton et al., 1986). The small differences in the mean field textures were not sufficient to drive significant differences in the expected water holding capacity of the three fields.

3.7. Soil nitrogen

Nutrient analysis of composite soil samples found mean total nitrogen levels followed the familiar ranking SS (3825 mg/kg ± 493, n = 5) > RS (2326 mg/kg ± 725, n = 4) > TS (1136 mg/kg ± 365, n = 5), reflecting the significant reservoir of soil organic nitrogen established in the SS field by compost amendment. Soil nitrogen from all three fields was overwhelmingly present in organic form, with SS total nitrogen on the order of 3400–4400 mg/kg, compared to inorganic nitrogen (ammonium + nitrate) concentrations on the order of 7–15 mg/kg (reflecting transient availability of presumably mobile, plant available, inorganic nitrogen). Despite high total nitrogen, inorganic nitrogen levels were comparable to levels for urban soils reported elsewhere (Sloan et al., 2012).

3.8. Field scale cone penetrometer profiles

GPS referenced cone penetrometer profiles were used to characterize the spatial variability of soil strength in each field. The median cone index profiles from the July 2012 penetrometer survey are shown in Fig. 3. Despite the variability in cone index values, the median profiles underscore the dramatic differences between the fields. Median cone index of the TS profile increased rapidly with depth. TS median cone index values greater than 2.1 MPa below 10 cm suggested significant shallow impedance for rooting. In sharp contrast, the median SS and RS profiles remained less than 2.1 MPa to a depth of at least 30 cm on both fields.

The spatial heterogeneity of compaction represented by the distribution of the maximum cone index in the top 15 cm of the soil profile is shown in Fig. 4a. The maximum 15 cm cone index surface highlighted the dramatic differences between the fields. The SS and RS maximum 15 cm cone index values were not significantly different, but both were significantly less ($p < 0.001$) than the TS maximum cone index (Fig. 2e). Both median cone index profiles and maximum cone index values showed the similarity of the SS and RS fields.

Significantly higher cone index values reflected the greater extent and intensity of compaction throughout the TS soil profile. Even so, the significantly higher cone index values understated the compaction on the TS field. Many TS points at which cone index profiles were attempted were so densely compacted that the minimum 10 cm depth of penetration needed to be recorded by the logging penetrometer could not be reached. The unsuccessful TS profiles were not recorded and are not reflected in cone penetrometer data reported here or shown in Figs. 2–4. The inability to collect penetrometer profiles on the most compacted soil, introduced a sampling bias in the TS data that tends to *underestimate* the mean

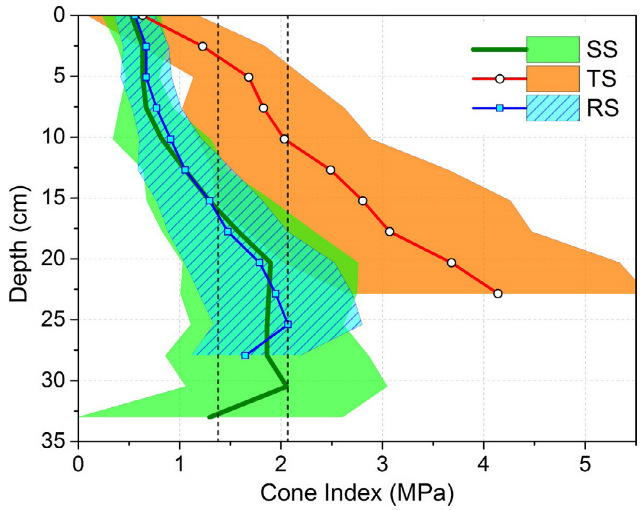

Fig. 3. Median Cone index profiles ±1 standard deviation for suburban subsoiling (SS); topsoiled (TS); and reference site (RS) fields. Profiles are truncated below depths supported by fewer than 4 profiles. Dashed vertical lines show rooting thresholds of 1.4 and 2.1 MPa.

cone index and, by inference, the intensity and extent of TS field compaction. Even with this inherent bias, the median cone index of the TS field (at points where it was possible to penetrate the soil to at least 10 cm) was significantly higher than the SS field and rapidly increased to higher root-limiting values at shallow depths compared to the SS and RS fields.

3.9. Soil moisture

In August 2012 (two years after treatment) root zone soil moisture on each field was characterized by a dense synoptic survey of GPS referenced volumetric soil moisture measurements in the top 7.5 cm of the soil profile (Fig. 4b). Like the cone index profiles, the TS soil moisture measurements were limited to points at which the TDR rods could be smoothly inserted into the top 7.5 cm of the soil making full uninterrupted soil contact along their entire length. Many potential sampling points in the TS field were so dense and dry that the TDR rods could not be inserted, introducing a sampling bias that overestimated the mean field-scale soil moisture. Despite this overestimation bias, the overall mean soil moisture on the TS field (25.6% ± 6.83, n = 77) was significantly lower than that on the SS field (35.3 ± 6.87, n = 102) (Figs. 2f and 4b) highlighting the lower water holding capacity of the root zone established with standard grading and topsoiling. The RS field had the lowest mean soil moisture (23.4 ± 6.25, n = 130) despite infiltration rates and cone index profiles similar to the SS field. Soil moisture on the RS field was consistently the lowest among the three fields. The difference in mean soil moisture between the RS and TS fields was marginally significant (p = 0.0111); differences in mean soil moisture between the SS field and both the TS and RS fields were highly significantly ($p \ll 0.001$).

4. Discussion

4.1. Superior sustainable landscaping

Results showcase the exceptional environmental services produced by suburban subsoiling. The SS field supports dense verdant turf without irrigation or chemical fertilizer inputs. Compared to standard grading and topsoiling, suburban subsoiling established a porous permeable soil profile with dramatically higher infiltration and water holding capacity, and low mechanical impedance to deep root growth.

Persistently high levels of organic matter in the SS field suggest the large one-time compost amendment may have surpassed a threshold of sustainability that restored a self-sustaining soil system (Larney and Angers, 2012). Healthy dynamic soil profiles may be renewed by new roots each spring as old senescent roots stems and grass clippings are recycled by dynamic soil ecosystem processes that maintain organic matter soil structure and permeability in the restored soil profile. Suburban subsoiling resulted in superior sustainable landscaping with exceptional environmental and hydrologic services that are not commonly realized in

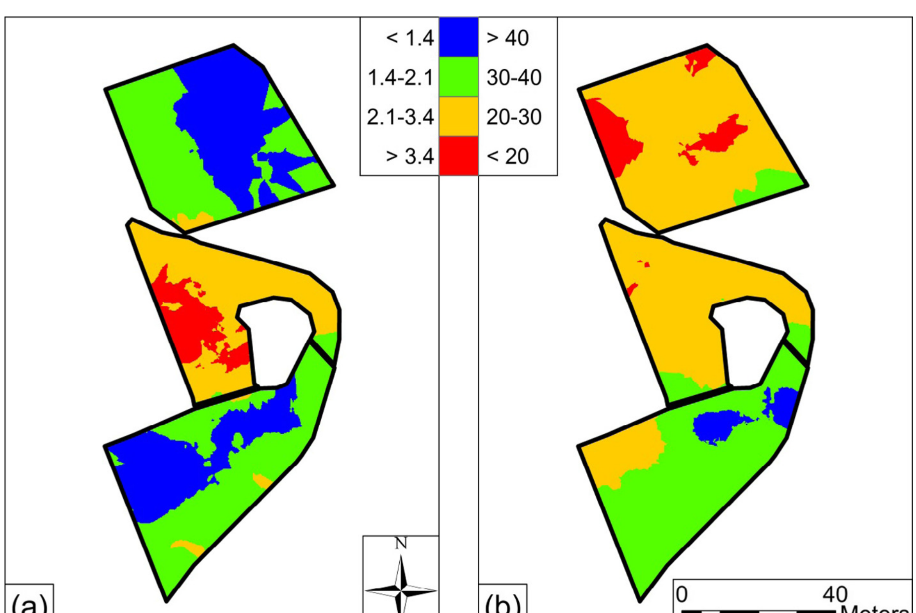

Fig. 4. Spatial distribution of (a) maximum cone index (MPa) in the top 15 cm of the soil profile; and (b) volumetric soil moisture (%) in the top 7.5 cm of the soil for the 2012 synoptic survey.

pervious landuses developed with standard grading and topsoiling practices.

4.2. Root zone soil moisture

Significantly higher soil moisture on the SS field supported vigorous, dense, drought-resistant turf. The RS field also had lower bulk density and higher infiltration rates than the TS field, with a median cone penetrometer profile similar to the SS field. It is therefore particularly striking that the lowest soil moisture was consistently found on the RS field. The low cone index values of the RS profiles suggested the rooting depth of the uniform turf cover on the field was largely unimpeded by soil compaction. Deeper rooted turf should be able to draw soil moisture from the entire rooting depth to satisfy transpiration demands, which could explain the lower soil moisture in the top 7.5 cm of the TS field. If, however, the low soil moisture was simply explained by transpiration from deeper rooted turf, we would have expected the much denser turf on the SS field to generate even greater transpiration, resulting in even lower soil moisture. The comparable infiltration rates on both SS and RS fields make the significantly higher soil moisture in the root zone of the denser turf on the SS field all the more remarkable. The SS turf not only infiltrated more rainfall, but retained more of that reduced runoff as shallow soil water.

The high mean soil moisture of the SS field was associated with significantly higher sustained levels of soil organic matter. Organic matter has been widely shown to increase soil water holding capacity, especially in coarser textured soils (Carter, 2007; Pandey and Shukla, 2006; Rawls et al., 2003). The effect of organic amendments on soil water holding capacity is, however, more complex (Cogger, 2005; Curtis and Claassen, 2009; Landschoot and Mcnitt, 1994; Nguyen et al., 2012; Thompson et al., 2008) and varies with soil texture, the rate and method of application, and type of organic soil amendment used (Khaleel et al., 1983). The similarity of bulk density, texture, infiltration rate, and cone penetrometer profiles on the SS and RS fields strongly support the hypothesis that the remarkable combination of consistently high levels of soil moisture and dense vigorous turf on the SS field is most likely attributable to the high organic matter content of the compost-amended profile. Although this hypothesis remains the subject of ongoing research, the observed results underscore the portfolio of superior sustainable environmental services that can be restored to the urban pervious landscape by suburban subsoiling.

4.3. Zero input turf

All the fields have been effectively managed as "zero-input" turf without supplemental irrigation or chemical fertilizer inputs. Routine ongoing grounds management was limited to periodic mowing with clippings returned to the turf. Among the zero-input fields, the environmental services from the SS field were clearly superior to the TS field. Turf on the SS field was more than twice as dense as the TS turf and provided superior cover, minimizing soil erosion risks. The dramatically higher SS infiltration rates yield far less runoff and drive consistently higher soil moisture. The SS field supports vigorous drought resistant turf while delivering superior stormwater services compared to the TS field that received standard grading and topsoiling.

Dramatic differences between the TS and SS fields highlight the range of contrasting expectations from so-called Freedom Lawns - i.e. turf maintained with no supplemental inputs (e.g. fertilizer, herbicides) beyond mowing, with clippings returned to the turf. Though commonly advocated as a preferred practice to minimize the environmental impacts from lawns, the prescriptive elimination of all supplemental turf inputs regardless of soil conditions can result in inferior turf cover and greater environmental risks from soil erosion and increased runoff. In contrast, Ervin's (2011) analysis concluded that the environmental impacts from lawns are more reliably minimized by minimizing the supplemental inputs needed to consistently establish vigorous dense permeable lawns that minimize runoff and soil erosion. The zero-input SS field exemplifies the superior environmental services of dense turf in a permeable soil profile. The thinner irregular cover of the zero-input turf on the TS field presents higher risks of soil erosion and nutrient losses from the higher runoff accompanying very low soil infiltration rates.

The abundant reservoir of organic nutrients established by compost amendment has thus far obviated the need for supplemental fertilizer inputs. Suburban subsoiling produced the superior turf endpoint envisioned by Ervin (2011) in soils that happen to need no additional irrigation or chemical fertilizer inputs, and have *therefore* been sustainable as low impact zero-input turf. Vigorous drought resistant turf requiring minimal supplemental inputs reduces life-cycle costs (Morris and Bagby, 2008), delivering superior sustainable landscaping that also reduces stormwater runoff, soil erosion, and nutrient loads to receiving waters.

4.4. Decoupling form and function

Data collected from infiltration tests, soil moisture measurements, and cone index profiles were all affected by densely compacted soil on the TS field. As a consequence, the striking results reported here actually underestimate the compaction and diminished hydrologic function resulting from standard grading and topsoiling practices on the TS field. More broadly, the compacted condition and greatly diminished hydrologic function of the TS field represents impaired conditions that may be commonly found throughout much of the urban pervious landscape (Hamilton and Waddington, 1999; Yang and Zhang, 2011, 2015). Moreover, the loss of hydrologic services resulting from mass grading, compaction, and topsoiling, cannot be reliably predicted from landuse, vegetation, or other conventionally observed landscape characteristics. This decoupling of form and function has significant implications for stormwater management (Woltemade, 2010) and the design of sustainable landscapes. For example, planning, and zoning instruments that focus primarily on limiting impervious area neglect a potentially significant – sometimes dominant – source of stormwater runoff that contributes to the degradation of urban stream ecosystems. Similarly, design hydrology that overestimates the infiltration capacity of pervious landuses may underestimate urban runoff (resulting in ineffective design), misidentify stormwater source areas, and erroneously prioritize and credit ineffective stormwater best management practices (e.g. disconnecting downspouts to redirect roof runoff to "pervious" landuses).

4.5. Estimated hydrologic services

The hydrologic benefits from suburban subsoiling were estimated by simulating design storm runoff and water movement through a simplified one-dimensional soil profile representing each of the three fields, using HYDRUS 1-D (Šimůnek et al., 2013). Design storm computations are familiar and well-accepted by practitioners and were performed using precipitation depths at the Baltimore Washington International Airport for ten 24-h storms with recurrence intervals between one and one thousand years (Bonnin et al., 2006). Storm event precipitation and simulated runoff were used to estimate an effective curve number (ECN) (Martin and Kaye, 2014; Schwartz, 2010) and an expected runoff coefficient, Rv (the ratio of runoff to precipitation) for each soil profile, as described in Appendix A.

Table 3
Estimated effective curve number (ECN) and runoff coefficient (Rv).

	ECN	Rv
SS	43.7	0.016
TS	87.4	0.520
RS	54.2	0.050

The expected Rv values reported in Table 3 indicate that suburban subsoiling could reduce the runoff from the TS field (prepared with standard grading and topsoiling) by more than a factor of 30. Similarly, despite a relatively low Rv, annual runoff from the RS field could be more than three times greater than the estimated annual runoff from the SS field. The design storm simulations were also used to estimate an ECN for each field, by finding the curve number that best fit the simulated rainfall-runoff response from all ten design storm events (Fig. 5). For practitioners, quantifying the hydrologic impact of soil decompaction and amendment with a site-specific ECN or Rv provides a hydrologically consistent means to integrate suburban subsoiling with current practice in environmental site design. The consistent estimation of a site-specific ECN or Rv also provides a hydrologically rational basis to consider runoff reduction credits, stormwater trading, and efforts to establish performance criteria for the design of sustainable landscapes – such as the Sustainable Sites Initiative (SITES, 2014).

4.6. Institutional implications

As a superior sustainable landscaping practice, suburban subsoiling can repay its higher initial implementation costs from savings in reduced irrigation and fertilizer inputs (Chollak and Rosenfeld, 1998; Morris and Bagby, 2008). When properly staged and integrated into the construction schedule, suburban subsoiling can be performed when suitable heavy equipment is already onsite, eliminating equipment mobilization costs. The implementation costs would then be limited to just compost costs and the marginal equipment and machine operator time for soil ripping and compost incorporation, prior to establishing final vegetation. For long-term land owners managing ongoing irrigation and fertilizer inputs, suburban subsoiling can have superior life-cycle costs with a short payback period. Considering similar soil improvement practices for stormwater runoff reduction in the City of Redlands, WA, Chollak and Rosenfeld (1998) found payback periods between nine months to three years, depending on the avoided costs of lawn care and irrigation water, and the initial water requirements to establish turf from either seed or sod.

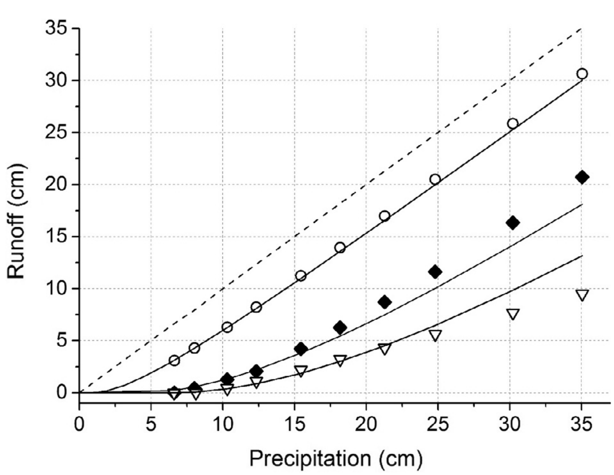

Fig. 5. Simulated (symbols) and best-fit frequency-weighted effective curve number (ECN) (lines) for design storm runoff from the SS (▽) ECN = 43.7; RS (◆) ECN = 54.2; and TS (○) ECN = 87.4; fields. Dashed 1:1 line corresponds to a curve number of 100.

For current practitioners, the multifunctional benefits of suburban subsoiling offer superior sustainable landscaping with slightly higher initial costs and lower life-cycle costs. Adopting consistent criteria to reliably credit the stormwater benefits from suburban subsoiling will advance the use of this practice as a cost-effective stormwater management best management practice (BMP), that can be readily incorporated into constructed landscapes through modest incremental modifications to standard grading and landscaping practices. Before suburban subsoiling can be reliably credited for regulatory compliance as a stormwater BMP, standard protocols will also need to be institutionalized for routine inspection and reliable maintenance of the restored hydrologic function of the pervious landscape, just as we must routinely inspect and maintain any other stormwater BMP.

5. Conclusions

Suburban subsoiling can restore urban hydrologic function by integrating urban soil husbandry into urban land development. We compared field-scale implementation of suburban subsoiling to standard topsoiling at a Baltimore City public school. The field prepared with suburban subsoiling consistently exhibited the highest infiltration rates, with the densest turf cover, highest soil organic matter and root zone soil moisture, and the lowest soil bulk density. Suburban subsoiling restored dramatically higher infiltration capacity compared to standard grading and topsoiling.

High soil moisture on the suburban subsoiling field was particularly striking compared to the untreated reference site, given the similarity in soil bulk density, soil penetrometer profiles, and mean infiltration rates between the two fields. The substantial one-time amendment with mature vegetative compost appears to have significantly increased water holding capacity and, by inference, plant available water. The SS field consistently manifested the highest soil moisture among the three fields, even with the higher transpiration demand inferred from the field's dense vigorous turf cover. More than three years of post-treatment performance monitoring data showed no evidence of organic matter decline, consistent with long-lasting effects of mature vegetative compost reported elsewhere (Cannavo et al., 2014). The results were also consistent with the establishment of a dynamic self-sustaining soil profile (Larney and Angers, 2012) in which soil ecosystem processes maintain the permeable porous organic soil profile, supporting new dense root growth each spring as grass clippings and older senescent roots and stems are assimilated by the soil ecosystem.

All of the fields were effectively managed as "zero-input" turf, receiving no irrigation or fertilizer inputs other than periodic mowing, with clippings returned to the turf. The thin uneven cover that developed from zero-input top-soiled turf has a higher risk of soil erosion, nutrient loss, and higher runoff accompanying very low soil infiltration rates. The dense verdant zero-input turf established with suburban subsoiling underscores the superior portfolio of environmental services realized from cultivating dense turf in a sustainable organic self-renewing soil profile. As a sustainable alternative to traditional grading and topsoiling practices, suburban subsoiling offers a proverbial win-win solution, providing superior sustainable landscaping and restored hydrologic services with lower life-cycle costs.

The hydrologic response of each of the fields was simulated with a simplified one-dimensional soil profile model. Hydrologic simulation of standard design event storms provided a consistent quantitative estimate of the hydrologic services supplied by suburban subsoiling. Compared to standard grading and topsoiling on the TS field, suburban subsoiling reduced the estimated mean annual runoff by more than a factor of 30. Quantifying the hydrologic impact of soil decompaction and amendment with familiar hydrologically consistent performance measures advances the integration of suburban subsoiling with current practice in environmental site design, and provides a hydrologically rational basis to consider runoff reduction credits, stormwater trading, and the design of sustainable landscapes

Though significantly different from current development practices, suburban subsoiling can be readily integrated in modern land development by coordinating minor incremental changes to standard grading and landscaping techniques. Slightly higher initial costs can be offset by reduced life cycle costs, while delivering cost-effective stormwater services from sustainable multifunctional landscapes. Consistent criteria to properly credit these stormwater services will provide compelling incentives to integrate suburban subsoiling into modern construction and land development practices. Suburban subsoiling can transform the built environment through superior sustainable landscaping that restores the hydrologic function of urban pervious landscapes.

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Appendix A

HYDRUS 1-D (Šimůnek et al., 2013) was used to simulate runoff and water movement through a simplified one-dimensional representation of a 100 cm soil profile for each of the fields. Soil hydraulic parameters were derived using field estimated values from Tables 1 and 2, and median field saturated hydraulic conductivity. Water characteristics curves were defined by Van Genuchten parameters estimated with the ROSETTA pedotransfer function, using field estimated texture and bulk density from Tables 1 and 2. (Schaap et al., 2001; Vangenuchten, 1980). Water movement through the simplified soil profiles was simulated without accounting for plant roots, using 24-h design storm depths from NOAA Atlas 14 (Bonnin et al., 2006). Design storm depths at the Baltimore Washington International Airport with recurrence intervals of 1, 2, 5, 10, 25, 50, 100, 200, and 1000 years were retrieved from the U.S. National Weather Service Precipitation Frequency Data server (http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=md) and distributed using the SCS Type-II hyetograph. Curve numbers and runoff coefficients are commonly estimated from historical records (Bonta, 2013; Hawkins, 1993), implicitly weighting smaller more frequent events more heavily than extreme events – by definition. To mimic this inherent frequency weighting, the ECN and Rv estimates weighted each simulated design storm result by its exceedance probability, explicitly placing proportionately higher weights on the more frequent storm events.

The event runoff coefficient for each design storm, Rv_i was weighted by its normalized exceedance probability, $w_i = p_i / \sum_{k=1}^{10} p_k$ where the exceedance probability, p_i is taken as the inverse of the design event recurrence interval. The probability weighted runoff coefficient for each field is calculated as the weighted sum of the event runoff coefficients: $Rv = \sum_i w_i Rv_i$. The expected runoff coefficient, Rv, gives a consistent estimate of the expected fraction of mean annual precipitation converted to runoff.

Following the approach in Martin and Kaye (2014) the ECN for each field was similarly optimized to minimize $Min_{CN} Z = \sum_{i=1}^{10} w_i \left(Q_i^{sim} - Q_i^{CN}\right)^2$ where Q_i^{sim} is the simulated runoff from the i-th design storm, and Q_i^{CN} is the event runoff calculated with curve number hydrology, using a unique curve number for each soil profile. The results are summarized in Table 3, with simulation results and the best ECN fit for each field shown in Fig. 5. Note how the ECN runoff more closely fits the smaller more frequent events. The use of a one-dimensional soil physics model to consistently characterize hydrologic effects of soil decompaction and amendment builds on Holman-Dodds's (2006) work to quantify the stormwater benefits of compost amendment.

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