Cultivating Stormwater Services with Soil Decompaction and Amendment

Stuart S. Schwartz, Ph.D.[1]; and Brennan Smith[2]

Abstract: Stormwater management has traditionally focused on increased runoff from impervious areas (IAs) accompanying urbanization. Far less consideration has been directed to significant changes in the hydrologic characteristics of urban soils that also accompany urban development. Mass grading and standard site development practices disturb and compact urban soil profiles, dramatically reducing infiltration capacity, rooting depths, and the stormwater services provided by urban green spaces. Stormwater services may be purposefully restored using soil decompaction and amendment to rebuild porous permeable organic-rich soil profiles in urban pervious landscapes. In this study, the use of suburban subsoiling (SS) (soil decompaction and compost amendment) for restoring stormwater services was evaluated on a decommissioned highway roadbed and construction staging area that had been designated for afforestation by the Maryland Department of Transportation State Highway Administration. Suburban subsoiling increased the mean infiltration capacity of the site's disturbed compacted soils by more than an order of magnitude, with dramatic improvements in the bulk density (−28%), organic matter (+82%), and potential rooting depth (+20 to +30 cm) of the restored soil profile. Integrating SS with standard mass grading and land development practices can transform the built environment by cultivating sustainable stormwater services in anthropogenic landscapes. **DOI: 10.1061/(ASCE)HE.1943-5584.0002031.** © *2020 American Society of Civil Engineers.*

Author keywords: Stormwater; Soil compaction; Infiltration; Subsoiling; Urban; Sustainability.

Introduction

Urban stormwater management has traditionally focused on increased runoff from impervious areas (IAs) accompanying urban land-use change. The emergence of IA as a primary indicator of urbanization and hydrologic alteration (Arnold and Gibbons 1996) engenders the widespread implicit assumption that urban *pervious* land uses retain the characteristics of undisturbed natural soils (Gregory et al. 2006; McGrane 2016; Pitt et al. 2008). In practice, the characteristics and stormwater services provided by urban soils are frequently decoupled from the undisturbed natural soils they replace (Jim 1998; McGrane 2016). For soils in the National Cooperative Soil Survey, the USDA Natural Resources Conservation Service (NRCS) defines the hydrologic soil group for a map unit component based on the soil infiltration rate and the depth to the shallowest confining layer in the soil profile. Yet NRCS cautions that no reliable hydrologic inferences can be made about the properties of disturbed soils without an onsite investigation (USDA 2009). Bonta (2013) compared the soil profile destruction and compaction from urbanization to that found in surface mine reclamation. Gregory et al. (2006) found compaction from construction activities resulted in a 70%–99% reduction in infiltration capacity in the sandy soils of a Florida residential development. Indeed, McGrane (2016) characterized the hydrologic behavior and infiltration dynamics usually encountered in urban green spaces as *mere artefacts of anthropogenic modifications*. Soil disturbance, mass grading, and both purposeful and inadvertent compaction commonly result in green *pervious* land uses with limited infiltration capacity, shallow rooting depths, and dramatically reduced stormwater services.

At the parcel scale, Voter and Loheide (2018) showed that compacted pervious areas could be a major source of stormwater runoff. They concluded that so-called impervious-centric low impact development (LID) practices (such as disconnecting downspouts and impervious surfaces) may be substantially less effective unless compacted soil conditions are simultaneously improved. Comparing two carefully monitored zero-order catchments near Seattle, Burges et al. (1998) determined that more of the observed runoff in their suburban developed watershed was being generated from pervious land uses with disturbed soil profiles than from impervious surfaces. At the watershed scale, Smith et al. (2015) identified significant changes in urban flood response owing to compacted urban soils in the Baltimore Ecosystem Study's well-studied Dead Run watershed. They found that the flood peak reduction expected from removing a single compacted soil layer in the watershed would be comparable to the cumulative flood peak reduction currently achieved by all of the detention ponds in the basin. Herrmann et al. (2018) found that urban soil profiles in 11 different US cities consistently showed significant alteration and loss of soil horizons compared to preurban reference profiles. The pervasive incidence of disturbed compacted urban soil profiles led Schwartz and Smith (2016) to suggest that most urban pervious landscapes produced using standard mass grading and construction practices might best be described as grass growing in a thin veneer of topsoil on compacted fill.

The significant hydrologic effects of urban soil compaction (Gregory et al. 2006; Pitt et al. 2008) have motivated revised methods and specifications for more sustainable land development practices (Balousek 2003; Bean and Dukes 2015; Chen et al. 2014; Jeldes et al. 2013; Marx et al. 1999; Sweigard et al. 2007).

[1]Senior Research Scientist, Center for Urban Environmental Research and Education, Univ. of Maryland Baltimore County, Baltimore, MD 21250 (corresponding author). ORCID: https://orcid.org/0000-0003-3636-575X. Email: stu_schwartz@umbc.edu

[2]Engineer-Model Analyst, Anne Arundel County, Maryland Bureau of Watershed Protection and Restoration, 2662 Riva Rd., Annapolis, MD 21401. Email: Pwsmit32@aacounty.org

Note. This manuscript was submitted on March 6, 2020; approved on August 21, 2020; published online on November 16, 2020. Discussion period open until April 16, 2021; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, © ASCE, ISSN 1084-0699.

Innovative grading practices that decompact and amend disturbed compacted soils can significantly reduce runoff and restore stormwater services in urban greenspaces (Mohammadshirazi et al. 2016; Olson et al. 2013; Sinnett et al. 2006, 2008). Schwartz and Smith (2016) demonstrated the dramatic restoration of stormwater services that accompanied soil decompaction and amendment following the removal of an impervious asphalt playground at a Baltimore city public school. They referred to this practice as *suburban subsoiling* (SS) (alluding to the adaptation of agricultural subsoiling practices to urban landscapes) and described how SS could be cost-effectively implemented with only modest changes to standard grading practices.

This paper evaluated the use of SS to restore stormwater services on a decommissioned highway roadbed (RB) and adjoining construction staging area (SA), following the demolition and removal of the highway pavement and subbase by the Maryland Department of Transportation State Highway Administration (MDOT SHA). The pavement removal was motivated by permit requirements to treat or remove IA called for in MDOT SHA's Municipal Separate Storm Sewer System (MS4) permit. Following pavement removal, contractors used standard construction practices to grade and permanently stabilize the site, establishing the *pretreatment* condition for this investigation. Replicate plots were established to compare soil properties and stormwater services of plots in the site's in situ soils and plots treated with SS. The site exemplified the acceptable norm and typical condition of pervious landscapes resulting from standard mass grading and site development practices and provided an ideal site for this study.

The following section describes the study site and methods used for plot preparation and analysis. Results from replicated plot treatments are presented and compared in the "Results" section. The "Discussion" section discusses the implications and transferability of the results, along with credits, incentives, and pragmatic considerations for institutionalizing SS to restore stormwater services. Conclusions are summarized in the "Summary and Conclusions" section.

Methods

Site Description

The study site consists of a former construction SA and highway RB in the Mesozoic lowland district of the Piedmont Plateau physiographic province in Taneytown, Maryland (39°40′30.1″N, 77°09′23.2″W). The soil survey for Carroll County, Maryland, maps the entire site as Bucks silt loam soils, described as prime farmland with good drainage and depth to restrictive feature (lithic bedrock) of approximately 100–150 cm. The RB is the former alignment of Maryland Route 853E and was decommissioned for IA removal credit under MDOT SHA's Federal MS4 permit. The decommissioned site had been graded, stabilized with permanent vegetative cover, and allowed to return to volunteer native vegetation without any additional mowing or long-term maintenance. The site's graded compacted condition following pavement removal typifies *pervious land uses* associated with mass grading and construction and defined the *pretreatment* condition for this study. The decommissioned stabilized site presented an ideal location to study stormwater services in disturbed compacted pervious landscapes.

Site Characterization

Both pretreatment and posttreatment soil properties were characterized by field sampling to estimate bulk density (BD), organic matter (OM), texture, infiltration, and soil strength. Soil strength was characterized by soil cone index (CI) profiles measured with a logging cone penetrometer. Field protocols and methods followed methods described in Schwartz and Smith (2016). The significance of differences in mean soil parameters 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).

Soil Core Analysis

Shallow 5-cm-diameter soil cores were collected and used to estimate BD, OM, and soil texture. Bulk density was calculated from oven-dried cores. Dried cores were then ground with a mortar and pestle and subsampled to estimate OM content determined by the loss on ignition method at 450°C and soil texture using the hydrometer method (Gee and Bauder 1986).

Infiltration Testing

Field infiltration capacity was estimated with the single-ring falling head method (Elrick et al. 1995; Touma et al. 2007; Zeleke and Si 2005). Falling head infiltration tests used 15-cm-diameter rings driven to an approximate depth of 7.5 cm. Following Schwartz and Smith (2016), field saturated hydraulic conductivity was estimated from the observed drawdown curve and field-estimated change in the pretest volumetric water content using Reynolds's (2008) solution for a falling head ring infiltrometer.

Cone Index/Soil Strength

The field-scale heterogeneity of soil strength was characterized using a Spectrum FieldScout SC-900 logging cone penetrometer (Aurora, Illinois). The CI is closely correlated with soil strength and BD and varies with soil moisture (Ayers and Perumpral 1982; Nguyen and Mohajerani 2015; Vaz et al. 2013). The CI also provides a useful indicator of soil impedance to root growth. At field capacity, common criteria for vegetative rooting consider CI values greater than 2.1 MPa (300 psi) as soil strength that impedes the growth of most fibrous plant roots. Soil profiles with CI values less than 1.4 MPa (200 psi) are generally considered to offer low physical impedance to root development (Gugino et al. 2009; Moebius-Clune et al. 2016). The effect of soil moisture on the field-measured CI was controlled for by conducting penetrometer surveys approximately 2 days following a soaking rain that sustains saturated conditions in the soil profile prior to the onset of drainage. This commonly suggested field criterion provides an operational means to collect penetrometer profiles under similar moisture conditions close to field capacity.

Pretreatment Site Assessment and Plot Plan

Infiltration tests and BD cores were used to characterize the pretreatment condition and heterogeneity of the site in the summer of 2012. The site assessment, combined with knowledge of the site history, led to a planting plan with replicated plots in both the compacted RB and the construction SA (previously used for parking and temporary construction offices), as shown in Fig. 1. Replicate plots were prepared using either (1) ST establishment methods on in situ soils following MDOT SHA specification 705 (MDOT 2008) or (2) SS consisting of deep ripping with compost amendment, followed by seeding and mulching consistent with standard MDOT SHA specifications for turf establishment. The plot plan shown in Fig. 1(b) delineated three sets of plots with (ST and SS) treatments in both the SA and the RB. Plot dimensions 3.7 m wide and 15.2 m long (12 × 55 ft) were selected to enable MDOT SHA contractors to use standard full-size tillage equipment with standard means and methods. The analysis of soil disturbance resulting from

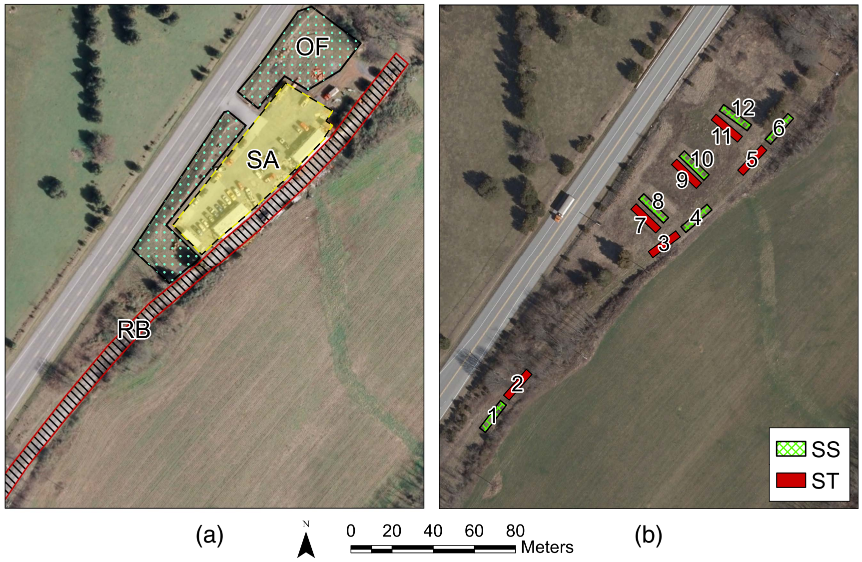

Fig. 1. Project site showing (a) RB, SA, and undisturbed open field (OF) subareas prior to decommissioning; and (b) plot design for decommissioned site prior to treatment showing location and number of plots designated for treatment with standard turf (ST) and suburban subsoiling (SS). (Base images courtesy of Maryland Statewide Imagery.)

authentic (rather than research-simulated approximations of) standard contractor practices is a unique contribution of this study. All test plot locations were GPS referenced and marked in the field to ensure that the plots were located within the footprint of historical construction activities.

The areas delineated in the initial site assessment as well as the locations of Plots 1–6 in the RB and plots 7–12 in the SA are shown in Fig. 1. This paper compares soil properties and stormwater services following SS and ST treatments in both RB and SA subareas.

Plot Preparation and Planting

The site was prepared for planting in September 2014, by spraying existing vegetation with glyphosate followed by mowing. MDOT SHA district maintenance personnel ripped all SS plots to a depth of approximately 50 cm using a Class II Worksaver R-130 single-shank ripping blade. Like many state transportation departments, MDOT SHA composts the carcasses of road-killed deer. Composting provides a safe, cost-effective method to dispose of road kill, yielding a beneficial organic soil amendment (Bonhotal et al. 2007). The lengthy static aerobic composting process results in a very mature compost, with nutrients overwhelmingly present in organic form. Following deep ripping of SS plots, MDOT SHA maintenance personnel surface-applied approximately 5 cm of mature deer carcass compost that was incorporated into the ripped soil profile using an Imants soil spader (Reusel, Netherlands).

All plots were planted by MDOT SHA contractors, using standard means and methods. ST plots were tilled, seeded, and mulched in October 2014, following standard MDOT SHA specifications for turf establishment (MDOT 2008). Owing to a miscommunication with contractors, SS plots were left mulched but unplanted over the winter, resulting in dense vigorous volunteer vegetation growth through early summer 2015. All SS plots were again sprayed and mowed in early August 2015 to clear weeds and volunteer vegetation. Mowed SS plots were planted and mulched using excelsior fiber mats in late August 2015. ST plots that had been planted in fall 2014 displayed highly uneven cover and were therefore overseeded in August 2015.

Sampling

The dense volunteer vegetation that developed through the spring and summer of 2015 limited summer data collection to BD soil cores from the ST and SS plots, before the plots were either sprayed, mowed, and planted (SS plots) or overseeded (ST plots). Soil cores collected in summer 2015 were analyzed for texture, BD, and OM. After planting (SS) or overseeding (ST) in August 2015, the turf plots were left to germinate and grow in through the fall of 2015. Fall 2015 sampling collected a dense set of cone penetrometer profiles from each plot as well as paired (SS-ST) infiltration tests from both the RB and SA plots. Cone penetrometer profiles were collected in October 2015, with infiltration tests performed on every plot in November 2015.

Results

Pretreatment Sampling

The initial (pretreatment) site assessment characterized soil conditions in the SA, RB, and an adjoining open field (OF) subarea (which had not been disturbed by prior MDOT SHA pavement removal activities) [Fig. 1(a)]. The initial site assessment provided estimates of the mean texture, BD, OM, and infiltration capacity of each of the three subareas. Pretreatment site conditions are summarized in Table 1.

Table 1. Pretreatment site conditions

Parameter	OF	SA	RB
Infiltration (cm/h)	2.30 ± 2.41	0.15 ± 0.11	0.07 ± 0.04
Bulk density (g/cc)	1.26 ± 0.09	1.44 ± 0.15	1.58 ± 0.11
Organic matter (%)	5.46 ± 1.70	3.09 ± 0.54	3.01 ± 0.37
Sand (%)	23.2 ± 6.6	38.6 ± 9.5	38.1 ± 2.8
Silt (%)	63.0 ± 5.7	47.1 ± 6.6	46.0 ± 2.1
Clay (%)	13.9 ± 2.3	14.3 ± 3.8	15.9 ± 1.3
Texture	Silt loam	Loam	Loam

Note: OF = open field; SA = staging area; and RB = roadbed.

Soil Core Analysis

The OF subarea was clearly outside the disturbance limits of the RB and SA and showed significantly higher OM (5.46% ± 1.7) and lower mean BD (1.26 ± 0.09), highlighting the compacted pretreatment state of the SA and RB subareas after decommissioning and stabilization. Texture, mean BD, and OM of the OF subarea were significantly different ($p < 0.05$) than both the RB and SA subareas. Both the RB and the SA consisted of loam soils with about 38% sand and 47% silt. Texture in the OF area was a silty loam with 23% sand and 63% silt, consistent with the silty loam texture mapped in the county soil map. The texture differences underscore the significant disturbance, earth moving, and soil *replacement* associated with historical grading and construction operations on the site that established the pretreatment conditions for this study. Bulk density data clearly showed residual compaction in both the RB and SA, with consistently higher compaction in the RB ($p < 0.05$). The RB had the highest mean BD (1.58 ± 0.11), consistent with legacy compaction for load-bearing strength from historical highway construction. Mean OM and texture in RB and SA subareas were not significantly different. Replicated SS and ST treatments in both the RB and SA subareas enabled the comparison of site preparation treatments (SS versus ST) as well as subarea compaction effects.

Infiltration Testing

Sixteen infiltration tests were initially performed over the three distinct subareas with results summarized in Table 1. Although the mean infiltration rates varied by more than an order of magnitude, infiltration differences between subareas were not statistically significant, reflecting the high variability of the OF infiltration rates. All infiltration tests were geolocated to validate their location with respect to the footprints of the original RB and SA.

Posttreatment Sampling

Soil Core Analysis

SS plots consistently showed significantly lower BD and higher OM than ST plots ($p \ll 0.001$). SS plots in the SA had significantly lower BD than SS plots in the RB ($p < 0.05$); SS significantly improved, but did not completely mitigate, the legacy compaction of the RB soils. Organic matter differences between SS plots in the RB and SA were not significant ($p = 0.325$), confirming that compost incorporation by soil spading was equally effective in both subareas.

Preparation of ST plots had no lasting effect on the BD of compacted soils in either the RB or the SA. Overall the SS treatment significantly reduced BD and increased OM compared to ST plots and pretreatment conditions, notwithstanding persistently higher BD in the RB compared with the SA. The BD of the ST plots was not significantly different than pretreatment BD in either the RB ($p > 0.25$) or SA ($p > 0.87$) subareas. Compared to pretreatment conditions, ST OM was moderately higher in the SA plots ($p < 0.05$) but was not significantly different ($p > 0.19$) in the RB subarea. Results for SS and ST plots are summarized in Table 2 for each subarea and pooled by treatment across (RB and SA) subareas. Box and whisker plots of BD and OM for each subarea both before and after treatment are presented in Fig. 2.

Table 2. Posttreatment soil core analysis for suburban subsoiled (SS) and standard turf (ST) treatments

	n	BD (g/cc)	OM (%)	Sand (%)	Silt (%)	Clay (%)
All SS	12	1.11 ± 0.21	6.40 ± 1.90	39.7 ± 1.7	44.4 ± 2.7	15.9 ± 1.2
Roadbed SS	6	1.24 ± 0.16	5.82 ± 0.84	40.1 ± 1.9	44.0 ± 2.9	15.9 ± 1.3
Staging area SS	6	0.98 ± 0.17	6.99 ± 2.54	39.3 ± 1.6	44.8 ± 2.6	15.9 ± 1.1
All ST	12	1.56 ± 0.11	3.50 ± 0.44	39.0 ± 4.0	44.2 ± 5.2	16.8 ± 2.5
Roadbed ST	6	1.63 ± 0.08	3.42 ± 0.42	40.2 ± 2.2	44.1 ± 1.2	15.7 ± 1.5
Staging area ST	6	1.49 ± 0.10	3.58 ± 0.48	37.9 ± 5.3	44.3 ± 7.7	17.9 ± 3.0

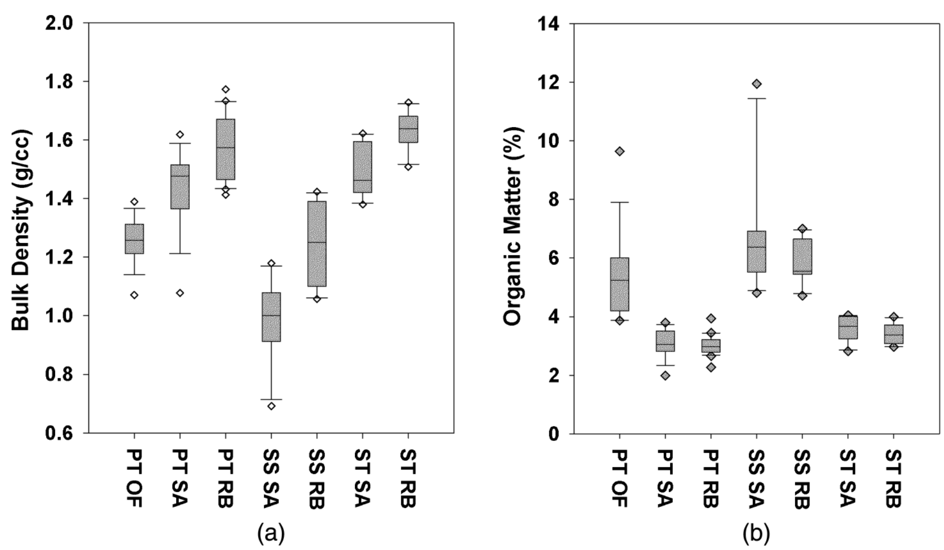

Fig. 2. (a) Bulk density; and (b) organic matter before and after treatment. Site areas correspond to OF SA and RB. Samples were taken pretreatment (PT) and following SS or ST treatment.

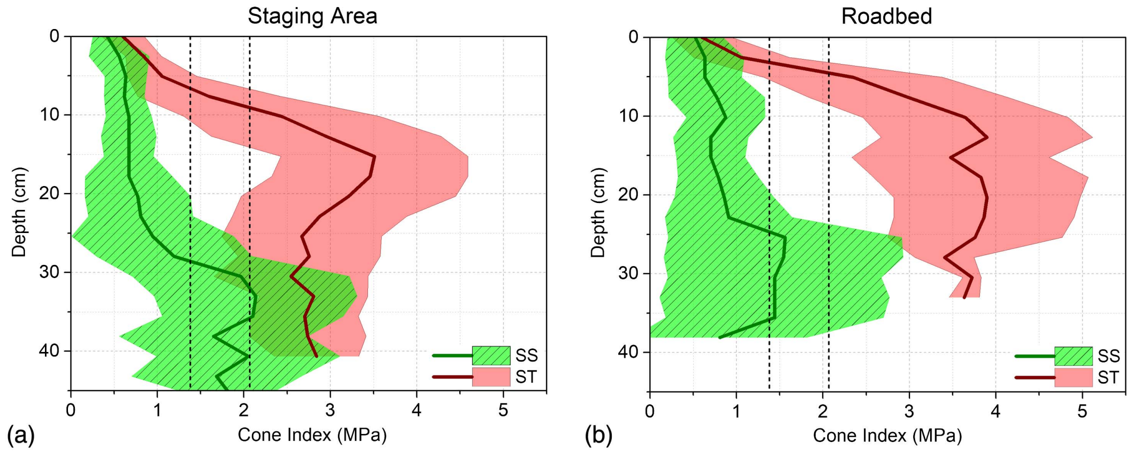

Fig. 3. Median cone index profiles ±1 standard deviation for SS or ST plots in (a) staging area; and (b) roadbed.

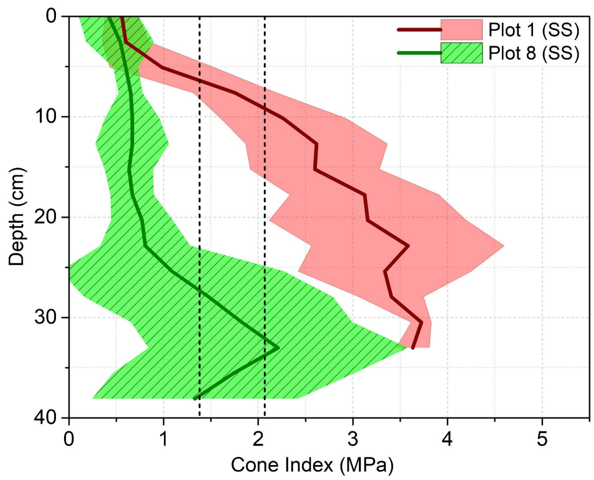

Fig. 4. Cone index profiles for SS RB Plots 1 and 8.

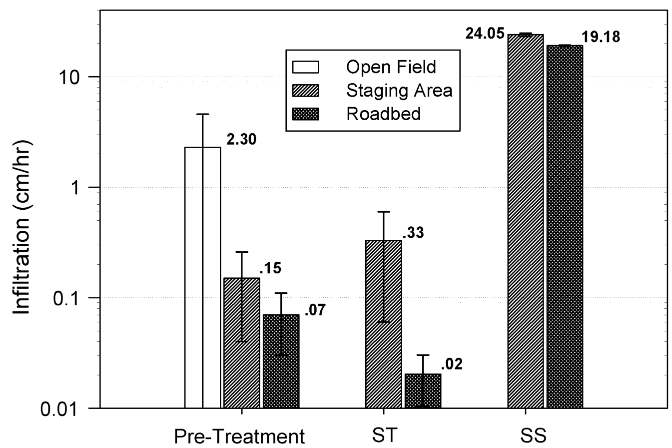

Fig. 5. Mean infiltration rates in OF, RB, and SA subareas. Results are shown prior to treatment and for plots prepared with ST establishment and with SS. Note logarithmic scale for infiltration.

Cone Index Profiles

Differences in the mean CI between ST and SS plots were statistically significant to depths of at least 30 cm in both SA and RB plots, and for all plots pooled across subareas. Median CI profiles ±1 standard deviation are shown for SS and ST plots in the SA and RB subareas in Fig. 3. The vertical dashed lines in Fig. 3 highlight critical root-limiting CI thresholds of 1.4 and 2.1 MPa. The median CI for the SS plots remained below the 1.4 MPa threshold to a depth of over 25 cm in both the SA and the RB plots, demonstrating the significantly greater potential rooting depth created by SS regardless of pretreatment compaction.

Infiltration Testing

By the fall of 2015 Plot 1 (closest to the site entrance) manifested significant recompaction effects with the highest BD and lowest infiltration rate of all the SS plots. Plot 1 clearly displayed rutting and parallel tire tracks, in which soil was too compacted to support vegetation. The median CI on SS Plot 1 reached the root-impeding value of 1.4 MPa at a depth of only 5 cm. For comparison, the median CI on SS Plot 8 (the last SS plot in the RB that received no traffic) remained below 1.4 MPa for depths up to 25–28 cm, as shown in Fig. 4.

When characterizing infiltration rates for RB SS plots, inclusion of Plot 1 infiltration data raised the standard deviation of the mean SS infiltration rate from 0.18 to 8.36 cm/h. The unusually low infiltration rate on Plot 1 was clearly attributable to recompaction and was therefore treated as an outlier that was not included in the infiltration results summarized in Fig. 5. The mean infiltration capacity of the remaining SS plots (22.10 cm/h ± 2.72) was significantly greater ($p \ll 0.001$) than the mean infiltration capacity of either the pooled ST plots (0.17 cm/h ± 0.24) or pooled (SA and RB) pretreatment (PT) data (0.11 cm/h ± 0.09). The dramatic difference between SS and ST mean infiltration rates followed the differences in CI profiles and BD, as expected.

The mean infiltration rate of the SS plots in the SA (24.05 cm/h ± 0.78) was significantly greater ($p < 0.01$) than the mean infiltration of the SS plots in the RB (19.18 cm/h ± 0.18). The mean infiltration of the ST plots was only moderately higher ($p < 0.05$) in the SA (0.33 cm/h ± 0.27) than in the RB (0.02 cm/h ± 0.01). Notwithstanding the acceptable (>95%) ST turf cover established in fall 2015, the mean infiltration capacity of the ST plots was not significantly different than pretreatment infiltration in the SA ($p > 0.39$) and was actually moderately *lower* ($p < 0.05$) than mean pretreatment infiltration in the RB.

Discussion

Recompaction on Plot 1

Vehicle traffic at the site entrance significantly recompacted Plot 1, highlighting the inherent vulnerability of decompacted soil to recompaction. Decompaction and amendment for stormwater services is best targeted to subareas where permanent traffic and usage patterns will not present significant recurring recompaction risks. Even modest levels of compaction can cause a disproportionate loss of infiltration capacity in an otherwise undisturbed soil profile. Compaction changes the pore size distribution of undisturbed soils; increasing the BD of a loamy soil by just 10% can reduce the saturated hydraulic conductivity by 45% to over 65% (Schwartz and Smith 2018). In an uncompacted soil, the initial increase in BD disproportionately eliminates larger macropores and preferential flow paths (dominated by gravity drainage) that predominantly support infiltration (McGrane 2016; Menon et al. 2015; Mooney 2002). The compacted pore size distribution becomes heavily skewed toward micropores, resulting in a disproportionate reduction in hydraulic conductivity.

Overflow parking areas and similar land uses that receive recurring vehicle traffic are particularly vulnerable to recompaction—especially under high soil moisture conditions. Suburban subsoiling and complementary sustainable landscape technologies should therefore be matched to a site's permanent traffic and usage patterns. For high traffic areas, alternate practices, such as engineered structural soils or suspended pavement systems, can deliver load-bearing green spaces that resist compaction, albeit at significantly greater cost (Grabosky and Bassuk 2016; Grabosky et al. 2008; Page et al. 2015; Smiley et al. 2006; Urban 1996).

Stormwater Credit

Consistent credits for runoff reduction and stormwater management with SS can be quantified based on the site-specific properties of the soil profile. Following the approach used by Holman-Dodds (2006), a one-dimensional soil physics model was used to quantify the difference in estimated stormwater services provided by ST and SS plots in the RB subarea of the site in this study. The hydrologic response of the RB plots was simulated for the mean texture, BD, OM, infiltration capacity, and depth of decompaction (for SS plots) observed in the field. Following Martin and Kaye (2014) and Schwartz and Smith (2016), the stormwater services of the RB plots were quantified by an *effective curve number* (ECN) estimated by fitting the NRCS curve number (CN) relationship to simulated rainfall-runoff depths from the 10 site-specific 24-h design storms that are available from the NOAA Precipitation Frequency Data Server for NOAA Atlas 14 (NOAA 2011).

As an additional reference point, the ECN for the roadbed soil texture was also estimated for an idealized uncompacted soil profile, assuming the entire soil column was decompacted to its native BD with 5% OM. The simulated rainfall-runoff events and weighted ECN fits are shown in Fig. 6. Table 3 summarizes these results with an example of ECN-based runoff reduction calculations that are easily performed using standard familiar CN computations. Compared to the ST plots (which showed no significant improvement from pretreatment conditions), the SS plots reduced ECN-estimated runoff from the 1-year and 2-year design storms by 92.9% and 87.7%, respectively. For designers and regulators, characterizing *site-specific* hydrologic services with an ECN based on the *site-specific* soil profile provides a consistent familiar computational framework to quantify runoff reduction and institutionalize stormwater credits for soil decompaction and amendment.

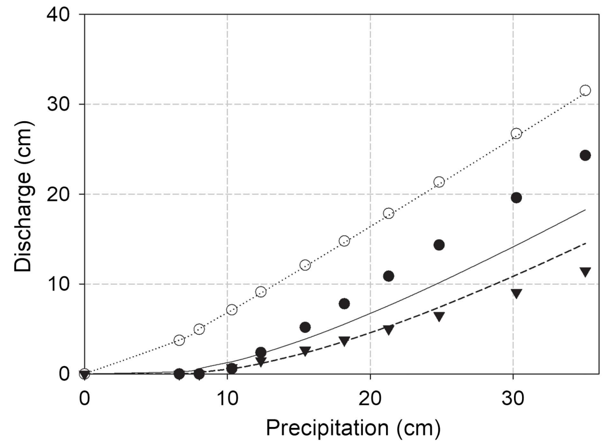

Fig. 6. ECN fit (lines) and simulated design storm runoff (symbols) for ST (empty circles) ECN = 88 (dotted line), SS (filled circles) ECN = 54.5 (solid line), and healthy (filled triangles) ECN = 46.3 (dashed line) soil profiles on RB soils.

Table 3. Effective curve number (ECN) runoff computations

	ECN	1-year storm	2-year storm
Storm depth (cm)	—	6.63	8.03
Simulated ECN runoff (cm)			
Healthy soil	46.3	0.03	0.18
Roadbed ST plots	88.0	3.94	5.18
Roadbed SS plots	54.5	0.28	0.64
Runoff reduction from ST	—	3.66	4.55

Incentivizing Suburban Subsoiling

Contractor practices that satisfy current MDOT SHA specifications for turf establishment reliably produced full vegetative cover on all of the study plots. For the ST plots, fully acceptable vegetative cover was achieved without any significant improvement in BD or infiltration compared to pretreatment conditions. In contrast, SS supported vigorous verdant turf in restored soil profiles that dramatically improved infiltration capacity, BD, OM, and potential rooting depths in both the RB and SA subareas. Even so, contractors have no direct incentive to adopt practices that deliver these superior stormwater outcomes unless specifications and acceptance criteria explicitly require more than just permanent vegetative cover. The results presented here underscore why acceptable vegetative cover alone is neither a dependable nor sufficient indicator of the stormwater or other environmental services that can be reliably credited to urban pervious land uses.

In the case of this study site, MDOT SHA's Federal (MS4) stormwater permit provides regulatory incentives for treating or removing IA—irrespective of the mean infiltration capacity of the resulting *pervious* land use. The ST roadbed plots with a mean infiltration rate of 0.02 cm/h earn the same IA removal credit as the SS roadbed plots that restored a mean infiltration rate of nearly 20 cm/h. Impervious area removal credits alone offer no direct incentive for restoring higher infiltration or stormwater services, beyond the absence of IA. They do, ironically, provide implicit incentives for practices that rapidly establish the vegetative cover that currently defines an acceptable pervious land use endpoint for construction acceptance and regulatory compliance—even on disturbed compacted soils with diminished hydrologic services.

Well-established contractor practices represent rational cost-effective responses to construction specifications and acceptance criteria. Sustainable stormwater services can be incentivized in construction specifications by requiring minimum infiltration rates and decompaction depths as explicit acceptance criteria for urban land development—beyond permanent vegetative cover.

Suburban subsoiling transforms urban green space into multifunctional green infrastructure. Schwartz and Smith (2016) suggested how the superior sustainable outcomes from SS could be *implemented* with only minor incremental changes to standard construction practices. The superior sustainable stormwater services from SS can similarly be *incentivized* by integrating consistent site-specific credits for restoring stormwater services into environmental site design and regulatory practice.

Summary and Conclusions

Stormwater management has traditionally focused on increased runoff from IAs accompanying urbanization, implicitly ignoring significant changes in soil characteristics that also accompany urban land development. Modern mass grading and construction practices disturb and compact urban soil profiles, increasing BD and dramatically reducing infiltration capacity and rooting depths. Disturbed compacted soil profiles produced by standard grading and construction practices systematically eliminate stormwater services from the urban pervious landscape. Lost stormwater services may be purposefully restored using soil decompaction and amendment to rebuild porous permeable organic-rich urban soil profiles.

In this study, the use of SS (soil decompaction and compost amendment) was evaluated to restore stormwater services on a decommissioned highway RB and construction SA that had been designated for afforestation by the Maryland Department of Transportation State Highway Administration. The pretreatment condition of the study site exemplified disturbed compacted soil profiles produced by modern mass grading and construction practices. In both RB and SA subareas, SS restored exceptional stormwater services and supported superior sustainable turf cover. SS plots consistently developed dense verdant turf cover in restored soil profiles with dramatically improved infiltration capacity, BD, OM, and potential rooting depth. In contrast, ST plots prepared using standard methods and specifications for turf establishment, reliably established 95% turf cover without any significant improvement in BD or infiltration capacity compared to pretreatment conditions. The results underscore why land cover alone, even with fully acceptable vegetative cover, is neither a sufficient nor dependable indicator of the stormwater services (or other environmental services) that can be reliably credited to urban pervious land uses.

Deriving a site-specific ECN from the properties of the restored soil profile allows restored stormwater services to be quantified using standard familiar curve number computations. Quantifying consistent credits for runoff reduction incentivizes the use of SS as a cost-effective alternative to gray infrastructure and traditional stormwater best management practices. The ECN enables runoff reduction from SS to be quantified for value-engineered design or commoditized and traded in stormwater programs that support market mechanisms and incentives to advance regional stormwater management goals.

Suburban subsoiling can be *implemented* with only minor incremental changes to standard site development practices. Suburban subsoiling can similarly be *incentivized* by integrating site-specific credits for stormwater runoff reduction in environmental site design and regulatory compliance. Institutionalizing SS can transform the built environment by cultivating sustainable stormwater services in anthropogenic landscapes.

Appendix I. Effective Curve Number

Soil profile ECNs were estimated by simulating water movement through an idealized 1-m soil column for 10 site-specific 24-h design storms from NOAA Atlas 14 (NOAA 2011). Design storms had recurrence intervals of 1, 2, 5, 10, 25, 50, 100, 200, 500, and 1,000 years. The simulated hydrologic response of the SS roadbed plots was quantified by an ECN estimated by fitting the SCS curve number relationship to simulated rainfall-runoff (P-Q) responses for the 10 design storms. The ECN was estimated with a weighted least-squares fit in which the influence of each design storm on the ECN fit is weighted by the long-term annual storm frequency (computed as the inverse of the storm recurrence interval) following methods described in Martin and Kaye (2014) and Schwartz and Smith (2016). The weighted least-squares fit ensures that more frequent design storm events have a greater influence in fitting the ECN, just as they would in a long continuous hydrometeorological data record.

The ECN is the CN value that minimizes the weighted sum of squared deviations between the simulated and CN-computed runoff depths of all $N = 10$ design storms [Eq. (1)]:

$$\underset{CN}{\text{Min}}\, Z = \sum_{i=1}^{N} w_i (Q_i^{CN} - Q_i^{\text{sim}})^2 \tag{1}$$

where P_i = depth of ith design storm with recurrence interval T_i that produces simulated runoff Q_i^{sim} and calculated curve number runoff Q_i^{CN}. The CN initial abstraction I_a and asymptotic storage S conform to conventional NRCS curve number methods: $S = (25{,}400/\text{CN} - 254)$ and $I_a = \lambda S$ for $\lambda = 0.2$, and $Q_i^{\text{CN}} = 0$ for $P_i < I_a$, and $Q_i^{\text{CN}} = (P_i - I_a)^2/(P_i + 0.8S)$ otherwise. The normalized weight for the ith storm is inversely proportional to the storm recurrence interval, $w_i = T_i^{-1}/\sum_{i=1}^{N} T_i^{-1}$.

Data Availability Statement

Data presented in the figures and tables are available from the corresponding author by request.

Acknowledgments

The authors gratefully acknowledge the expert contributions by George Leidig from Autrusa Enterprises in performing soil spading and the maintenance staff from MDOT SHA District 7, who performed soil ripping and compost application. Special thanks to Sharon Hawkins for her careful attention to detail and skillful navigation of MDOT SHA administrative procedures. This project would not have been possible without the efforts of Dan Uebersax and Margot Bartosh in the Office of Environmental Design, who championed this research, navigated the collaborative engagement of key colleagues across SHA, and graciously solved some of the most unexpected challenges encountered along the way. Their support of this project and commitment to improving the outcomes and long-term success of MDOT SHA projects are gratefully acknowledged. Special thanks are extended to Neil Haines, Dave Smith, Paul Haines, Jim Jones, Roberta Cowan, Dave Lubman, Rob Hill, and Rich Wilke for their contributions to the project. Thoughtful comments from T. Whitlow and three anonymous reviewers significantly improved the manuscript and are gratefully acknowledged.

The authors acknowledge the use of base images in Fig. 1 courtesy of Maryland Statewide Imagery. Work was supported by funding in compliance with 23 U.S.C. 505, "State Planning and Research" program, and is gratefully acknowledged.

References

Arnold, C. L., and C. J. Gibbons. 1996. "Impervious surface coverage—The emergence of a key environmental indicator." *J. Am. Plann. Assoc.* 62 (2): 243–258. https://doi.org/10.1080/01944369608975688.

Ayers, P. D., and J. V. Perumpral. 1982. "Moisture and density effect on cone index." *Trans. Am. Soc. Agric. Eng.* 25 (5): 1169–1172. https://doi.org/10.13031/2013.33691.

Balousek, J. 2003. "Quantifying decreases in stormwater runoff from deep tilling, chisel plowing, and compost-amendment." Accessed February 25, 2008. http://www.countyofdane.com/landconservation/papers/quantifyingdecreasesinswrunoff.pdf.

Bean, E. Z., and M. D. Dukes. 2015. "Effect of amendment type and incorporation depth on runoff from compacted sandy soils." *J. Irrig. Drain. Eng.* 141 (6): 04014074. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000840.

Bonhotal, J., E. Z. Harrison, and M. Schwarz. 2007. *Composting road kill*. Ithaca, NY: Cornell Waste Management Institute.

Bonta, J. V. 2013. "Managing landscape disturbances to increase watershed infiltration." *Trans. ASABE* 56 (4): 1349–1359.

Burges, S. J., M. S. Wigmosta, and J. M. Meena. 1998. "Hydrological effects of land-use change in a zero-order catchment." *J. Hydrol. Eng.* 3 (2): 86–97. https://doi.org/10.1061/(ASCE)1084-0699(1998)3:2(86).

Chen, Y. J., S. D. Day, A. F. Wick, and K. J. McGuire. 2014. "Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity." *Sci. Total Environ.* 494–495 (Oct): 329–336. https://doi.org/10.1016/j.scitotenv.2014.06.099.

Elrick, D. E., G. W. Parkin, W. D. Reynolds, and D. J. Fallow. 1995. "Analysis of early-time and steady-state single-ring infiltration under falling head conditions." *Water Resour. Res.* 31 (8): 1883–1893. https://doi.org/10.1029/95WR01139.

Gee, G. W., and J. W. Bauder. 1986. "Particle-size analysis." In *Methods of soil analysis. Part I: Physical and mineralogical methods*, 383–413. Madison, WI: American Society of Agronomy—Soil Science Society of America.

Grabosky, J., and N. Bassuk. 2016. "Seventeen years' growth of street trees in structural soil compared with a tree lawn in New York City." *Urban For. Urban Greening* 16: 103–109. https://doi.org/10.1016/j.ufug.2016.02.002.

Grabosky, J., N. Bassuk, and T. Haffner. 2008. "Plant available moisture in designed soils for pavement systems." *Hortscience* 43 (3): 597.

Gregory, J. H., M. D. Dukes, P. H. Jones, and G. L. Miller. 2006. "Effect of urban soil compaction on infiltration rate." *J. Soil Water Conserv.* 61 (3): 117–124.

Gugino, B. K., O. J. Idowu, R. R. Schindelbeck, H. M. van Es, D. W. Wolfe, B. N. Moebius-Clune, J. E. Thies, and G. S. Abawi. 2009. *Cornell soil health assessment training manual*. 2nd ed. Geneva: Cornell Univ.

Herrmann, D. L., L. A. Schifman, and W. D. Shuster. 2018. "Widespread loss of intermediate soil horizons in urban landscapes." *Proc. Natl. Acad. Sci. USA* 115 (26): 6751–6755. https://doi.org/10.1073/pnas.1800305115.

Holman-Dodds, J. K. 2006. "Assessing infiltration-based stormwater practices." Ph.D. dissertation, Dept. of Civil and Environmental Engineering, Univ. of Iowa.

Jeldes, I. A., E. C. Drumm, and J. S. Schwartz. 2013. "The low compaction grading technique on steep reclaimed slopes: Soil characterization and static slope stability." *Geotech. Geol. Eng.* 31 (4): 1261–1274. https://doi.org/10.1007/s10706-013-9648-0.

Jim, C. Y. 1998. "Urban soil characteristics and limitations for landscape planting in Hong Kong." *Landscape Urban Plann.* 40 (4): 235–249. https://doi.org/10.1016/S0169-2046(97)00117-5.

Martin, W. D., and N. B. Kaye. 2014. "Hydrologic characterization of undrained porous pavements." *J. Hydrol. Eng.* 19 (6): 1069–1079. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000873.

Marx, J., A. Bary, S. Jackson, D. McConald, and H. Wescott. 1999. *The relationship between soil and water: How soil amendments and compost can aid in salmon recovery*. Seattle: Kings County Dept. of Natural Resources.

McGrane, S. J. 2016. "Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: A review." *Hydrol. Sci. J.* 61 (13): 2295–2311. https://doi.org/10.1080/02626667.2015.1128084.

MDOT (Maryland Department of Transportation). 2008. *Maryland state highway administration standard specifications for construction and materials*. Baltimore: MDOT.

Menon, M., X. Jia, G. J. Lair, P. H. Faraj, and A. Blaud. 2015. "Analysing the impact of compaction of soil aggregates using X-ray microtomography and water flow simulations." *Soil Tillage Res.* 150 (Jul): 147–157. https://doi.org/10.1016/j.still.2015.02.004.

Moebius-Clune, B. N., et al. 2016. *Comprehensive assessment of soil health—The Cornell framework manual*. 3rd ed. Geneva: Cornell Univ.

Mohammadshirazi, F., V. K. Brown, J. L. Heitman, and R. A. McLaughlin. 2016. "Effects of tillage and compost amendment on infiltration in compacted soils." *J. Soil Water Conserv.* 71 (6): 443–449. https://doi.org/10.2489/jswc.71.6.443.

Mooney, S. J. 2002. "Three-dimensional visualization and quantification of soil macroporosity and water flow patterns using computed tomography." *Soil Use Manage.* 18 (2): 142–151. https://doi.org/10.1111/j.1475-2743.2002.tb00232.x.

Nguyen, B. T., and A. Mohajerani. 2015. "Determination of CBR for fine-grained soils using a dynamic lightweight cone penetrometer." *Int. J. Pavement Eng.* 16 (2): 180–189. https://doi.org/10.1080/10298436.2014.937807.

NOAA (National Oceanic and Atmospheric Administration). 2011. "NOAA precipitation frequency data server." Accessed August 22, 2018. https://hdsc.nws.noaa.gov/hdsc/pfds/index.html.

Olson, N. C., J. S. Gulliver, J. L. Nieber, and M. Kayhanian. 2013. "Remediation to improve infiltration into compact soils." *J. Environ. Manage.* 117 (Mar): 85–95. https://doi.org/10.1016/j.jenvman.2012.10.057.

Page, J. L., R. J. Winston, and W. F. Hunt. 2015. "Soils beneath suspended pavements: An opportunity for stormwater control and treatment." *Ecol. Eng.* 82 (Sep): 40–48. https://doi.org/10.1016/j.ecoleng.2015.04.060.

Pitt, R., S. E. Chen, S. E. Clark, J. Swenson, and C. K. Ong. 2008. "Compaction's impacts on urban storm-water infiltration." *J. Irrig. Drain. Eng.* 134 (5): 652–658. https://doi.org/10.1061/(ASCE)0733-9437(2008)134:5(652).

Reynolds, W. D. 2008. "Saturated hydraulic properties, ring infiltrometer." In *Soil sampling and methods of analysis*. 2nd ed., edited by M. R. Carter and E. G. Gregorich, 1043–1056. Boca Raton, FL: CRC Press.

Ruxton, G. D. 2006. "The unequal variance *t*-test is an underused alternative to Student's *t*-test and the Mann-Whitney *U* test." *Behav. Ecol.* 17 (4): 688–690. https://doi.org/10.1093/beheco/ark016.

Schwartz, S. S., and B. Smith. 2016. "Restoring hydrologic function in urban landscapes with suburban subsoiling." *J. Hydrol.* 543 (Part B): 770–781. https://doi.org/10.1016/j.jhydrol.2016.10.051.

Schwartz, S. S., and B. Smith. 2018. "The hydrologic legacy of soil disturbance and compaction in the urban pervious landscape." In *Proc., 2018 Fall Meeting*. Washington, DC: American Geophysical Union.

Sinnett, D., J. Poole, and T. R. Hutchings. 2006. "The efficacy of three techniques to alleviate soil compaction at a restored sand and gravel quarry." *Soil Use Manage.* 22 (4): 362–371. https://doi.org/10.1111/j.1475-2743.2006.00053.x.

Sinnett, D., J. Poole, and T. R. Hutchings. 2008. "A comparison of cultivation techniques for successful tree establishment on compacted soil." *Forestry* 81 (5): 663–679. https://doi.org/10.1093/forestry/cpn039.

Smiley, E., L. Calfee, B. Fraedrich, and E. Smiley. 2006. "Comparison of structural and noncompacted soils for trees surrounded by pavement." *Arboriculture Urban For.* 32 (4): 164.

Smith, B. K., J. A. Smith, M. L. Baeck, and A. J. Miller. 2015. "Exploring storage and runoff generation processes for urban flooding through

a physically based watershed model." *Water Resour. Res.* 51 (3): 1552–1569. https://doi.org/10.1002/2014WR016085.
Sweigard, R., J. Burger, C. Zipper, J. Skousen, C. Barton, and P. Angel. 2007. "Low compaction grading to enhance reforestation success on coal surface mines." Accessed December 4, 2018. https://arri.osmre.gov/FRA/Advisories/FRA_No.3.pdf.
Touma, J., M. Voltz, and J. Albergel. 2007. "Analysis of short-time single-ring infiltration under falling-head conditions with gravitational effects." *Eur. J. Soil Sci.* 58 (1): 229–238. https://doi.org/10.1111/j.1365-2389.2006.00830.x.
Urban, J. 1996. "Room to grow." *Landscape Archit.* 86 (3): 74–97.
USDA. 2009. "National engineering handbook title 210-VI. Part 630, chapter 7: Hydrologic soil groups." Accessed August 8, 2013. http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=22526.wba.
Vaz, C. M. P., J. M. Manieri, I. C. de Maria, and M. T. van Genuchten. 2013. "Scaling the dependency of soil penetration resistance on water content and bulk density of different soils." *Soil Sci. Soc. Am. J.* 77 (5): 1488–1495. https://doi.org/10.2136/sssaj2013.01.0016.
Voter, C. B., and S. P. Loheide. 2018. "Urban residential surface and subsurface hydrology: Synergistics effects of low-impact features at the parcel scale." *Water Resour. Res.* 54 (10): 8216–8233. https://doi.org/10.1029/2018WR022534.
Zeleke, T. B., and B. C. Si. 2005. "Parameter estimation using the falling head infiltration model: Simulation and field experiment." *Water Resour. Res.* 41 (2): W02027. https://doi.org/10.1029/2004WR003407.