RESEARCH SECTION

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Decompaction and organic amendments provide short-term improvements in soil health during urban, residential development

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Abstract: Urban land use, characterized by intense soil disturbance for site development, is rapidly expanding across the globe. This disturbance can have long-lasting effects on urban soil ecosystem service performance (e.g., water infiltration, turfgrass growth, and carbon [C] sequestration). We established a unique, multistakeholder collaboration with a private land-development company, environmental advisory nonprofit organization, and research university to study residential development effects on soil health and the effectiveness of rehabilitation practices. More specifically, we tested the impact of five current, locally recommended soil rehabilitation practices implemented at early stages of urban, residential development. In a controlled, real-world setting, we tested five treatments—a combination of decompaction and organic amendment additions—after major soil disturbances of mass and fine grading (part of subdivision development). Specific treatments included (1) a business-as-usual (or control) with compacted subsoil and 10 cm loosened topsoil, (2) mechanically decompacted subsoil and 10 cm loosened topsoil, (3) biologically decompacted subsoil using a green manure (with tillage radish [*Raphanus sativus*]) and 10 cm loosened topsoil, (4) mechanically decompacted subsoil with 2.5 cm of loosened topsoil mixed with 2.5 cm compost, and (5) mechanically decompacted subsoil mixed with 2.5 cm compost and 2.5 cm loosened topsoil. After turfgrass was established in all plots, per typical practice for erosion control, we measured physical, chemical, and biological soil health properties at 0 to 15 and 15 to 30 cm depths. The tillage radish had little-to-no effect on any soil properties, likely due to poor establishment. Compost amendments increased soil organic matter (+43%), soil test phosphorus (+79%), and soil test potassium (+60%) mostly in the top 0 to 15 cm. Compost amendments had little effect on soil microbial biomass and activity (measured as decomposition); however, they did increase salt-extractable organic C in the top 0 to 15 cm (+220%). We found even stronger effects of mechanical subsoil decompaction, which increased infiltration rate by over 2,000% and time-to-runoff by 463%, on average, providing evidence that deep ripping subsoils improves water influx and reduces runoff from residential lawns. Decompacting subsoil and adding compost had clear benefits to physical and chemical soil health early in urban, residential development. We would recommend land developers use both practices for improving soil ecosystem services in the short term, and there may be longer-term benefits too.

Key words: construction—ecosystem services—lawn—restoration—soil quality—turfgrass

In the last half century, *Homo sapiens* have become an increasingly urban species, causing rapid expansion of residential land use in the United States and worldwide (Seto et al. 2012; Ritchie et al. 2018). To accommodate this expansion, urban areas are expanding into adjacent land uses such as agriculture, forests, grasslands, and other unmanaged landscapes (Thompson et al. 2023). Compared to other nonurban landscapes, residential land use has three features that affect its ability to provide ecosystem services: (1) variable but potentially large and frequent inputs (pesticides, fertilizers, and irrigation) (Groffman et al. 2023); (2) uniform, shallow-rooted, vegetative groundcover, typically a monoculture of *Poa* or *Gramineae* spp. (Thompson and Kao-Kniffin 2017); and lastly (3) a protracted, intensive, and high-disturbance initial site preparation called "site grading" (figure 1) (Chen et al. 2014).

When nonurban lands are being developed for the first time, or if prior urban spaces are being redeveloped, site grading—shaping the land for structures, utilities, or to maintain drainage—is a key part of the development process (Sharky 2014). Site grading involves repeated sequences of earth (i.e., soil) moving activities with increasingly finer degrees of precision as the site is developed, from mass grading to fine grading (figure 1, Steps 1 and 5). Mass grading in residential landscapes begins with the removal of preexisting, undesired vegetation (e.g., grubbing) and the removal and stockpiling of topsoil (e.g., stripping) to be respread later (figure 1, Step 1). Grubbing removes coarse woody debris and other large particulate organic matter, that when decomposed, would result in undesirable soil settling. Stockpiled topsoil is placed onsite, or in some cases off-site, so as not to impede other mass grading activities.

The construction of residential subdivisions, a specific case of urban land development, usually involves civil engineers and landscape architects working with developers to subdivide a larger land unit into individual lots that will be sold to homebuilders or future homeowners (figure 1). During the initial mass grading step, the landscape is shaped for major infrastructure like roads, sewers, and utilities. Mass grading ensures desirable drainage, or in other words, the landscape is shaped so that water flows away from individual lots. Later, as individual lots are sold and houses built, lot-level fine grading occurs for the building foundation, pavement, site amenities, and landscaping.

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Figure 1

The process of site grading from mass grading to final landscaping. Grading is the process of reshaping the landscape in order to accommodate residential infrastructure. There are seven steps with three mobilization phases with mass-grading being the largest soil disturbance. Regarding the treatments in this study (table 1 and figure 2), the tillage radishes were planted prior to Step 5, all other treatments were implemented between Step 5 and Step 6.

The potential time lag between mass grading and fine grading of individual lots can be months, or even years, and differentiates residential subdivision development from other urban development patterns that typically occur as quickly as possible. Soil rehabilitation practices during the interim may have immediate impacts on soil erosion and water quality but also long-lasting impacts on urban, residential ecosystem services.

Without soil rehabilitation practices, these site grading activities can result in two major undesirable consequences for soils—compaction and loss in soil organic matter (SOM). Some subsoil compaction is necessary for structural stability but less desirable for lawns. Subsoil overcompaction via heavy equipment is becoming increasingly important as equipment is getting larger (Lamandé et al. 2018; Keller and Or 2022). The removal and stockpiling of topsoil expose it to erosion and enhanced decomposition (Luo et al. 2019). The reapplication process is also not precise, and thus topsoil is often mixed with subsoil. These now highly disturbed soils are permanently altered and functionally different than the previous, undisturbed soil. All of this results in a compacted landscape with lower topsoil SOM relative to the initial conditions before the mixing and respreading (Kaye et al. 2005; Pouyat et al. 2006; Chen et al. 2013a). This all is a major disruption to normal soil functioning, i.e., soil health, and there are few equivalent anthropogenic disturbances in magnitude and extent.

Growing interest in maintaining or even improving healthy soil function has expanded beyond agriculture (Karlen et al. 2021), and developers are increasingly looking to find ways to improve all aspects of healthy urban soil functioning, and not just as a structural support. The brief but highly disturbed initial stages of urban land-use development are also vulnerable to losses of soil and nutrients—especially without proper precautions on the developer's part. Furthermore, what happens at these initial stages likely set soil on a trajectory that either exacerbates or mitigates these environmental consequences. For example, severe subsoil compaction could decrease soil infiltration rates for years, leading to excess stormwater runoff and erosion, not to mention the long-term nutrient losses even after turfgrass has been well established (IDNR 2006; Pease et al. 2022).

To alleviate these short-term (and potentially long-term) postconstruction negative outcomes of site grading, many experts suggest soil rehabilitation practices that include a combination of "decompaction" and/or adding organic amendments, such as compost (Pease et al. 2022; IDNR 2023). By decompaction we are referring to the loosening (lowering the bulk density) of residential soil that may have either been unintentionally or intentionally compacted in the development process, but now the land developer would prefer less compacted soils to grow a turfgrass lawn or use for garden landscaping. Such mechanical decompaction techniques include deep-ripping or tillage prior to turfgrass establishment to temporarily reduce compaction, increase infiltration, and improve plant root growth.

In addition to mechanical decompaction, adding organic amendments like compost and green manure such as tillage radishes (*Raphanus sativus*) during residential development could also help to improve some of these physical soil health outcomes like decreasing bulk density and increasing infiltration (Meek et al. 1982; Celik et al. 2010; Baldwin-Kordick et al. 2022). This could especially be the case with using "tillage" radish, which simultaneously provides physical decompaction, increases infiltration, and is adding organic material to the urban soil as cover crop dies and decomposes (Chen and Weil 2010; White and Weil 2011; Burr-Hersey et al. 2017). The use of tillage radish after mass grading and before fine grading (figure 1, Step 5) has not previously been evaluated. Furthermore, adding organic amendments can also enhance the chemical and biological aspects of soil health. For example, adding compost can increase microbial biomass, total soil organic carbon (C), and even improve soil physical properties in urban residential soils (Loper et al. 2010; Chen et al. 2013b, 2014; Sax et al. 2017).

In the United States, regulations related to national, municipal storm sewer system permitting may recommend that land developers use some of these soil rehabilitation approaches to create a more functional soil profile for stormwater management (IDNR 2009, 2018, 2023). For example, the Soil Quality Management and Restoration Methods, listed in the *Iowa Stormwater Management Manual* (ISWMM), suggests the use of mechanical decompaction and recommends adding composted yard waste (IDNR 2023). However, few, if any, of these practices have been evaluated in a scientifically rigorous manner.

Given the rapid expansion of residential land use and need to alleviate short- and long-term environmental issues related to site preparation, we tested potential remediation practices during site grading that can build healthy, resilient soils and set the course for a sustainable urban development. Our overarching goal was to test the effectiveness of ISWMM soil restoration practices, plus some modifications (figure 2 and table 1), in improving soil health after the fine grading step of residential development (figure 1, Step 5). More specifically we focus on response of three physical (bulk density, infiltration rate, and penetration resistance), two biological (microbial biomass and decomposition), and three chemical (SOM, cation exchange capacity [CEC], and pH) measurements of soil health in response to these treatments. We hypothesized that mechanical "decompaction" would help improve physical aspects of soil health, but only by using compost or green manure in addition would we gain soil health benefits in all three categories.

Materials and Methods

Site Description and Experimental Design. The study took place near Iowa City, Iowa, in a mixed-use commercial, residential, and farming area (41.689558, –91.489640). Due to the lack of evidence of a soil gradient, and practicalities of working with large-scale construction equipment, we designed the trial as a systematic (nonrandomized), blocked design experiment in a 0.76 ha field (supplemental material figure S1). Prior to establishing the experiment, the field was left fallow for several decades and in Conservation Reserve Program (Skold 1989) with vegetation mostly bromegrass (*Bromus* spp.). Fill material was also brought in over several years and placed in the vicinity. The three dominant soil series in the field are ~73% Colo-Ely complex (Cumulic Endoaquolls or Aquic Cumulic Hapludolls), ~22% Fayette silt loam (Typic Hapludalfs), and Downs silt loam (Mollic Hapludalfs)

Figure 2

The five experimental treatments compared in this study adapted from the *Iowa Storm Water Management Manual* (ISWMM) (IDNR 2023). See table 1 for further treatment information.

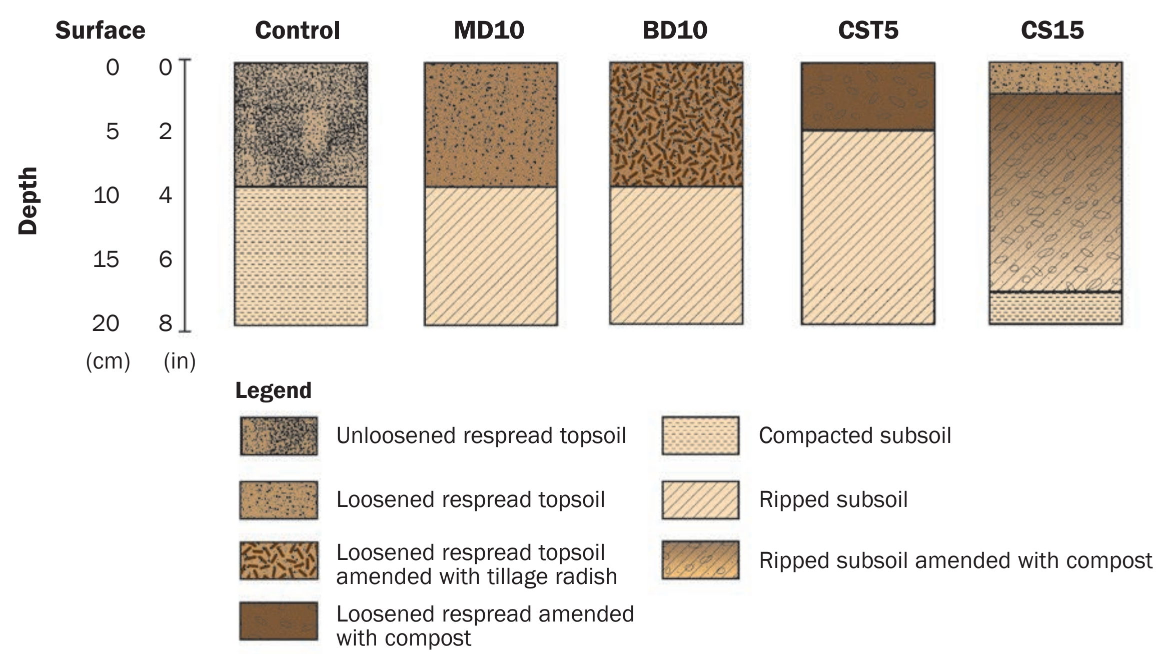

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Table 1
Treatment (or practice) information—paired with figure 2.

Name or ID	Origin	Subsoil decompaction/topsoil	Organic soil amendment
Control	Typical or conventional practice for Iowa, United States	None/add 10 cm topsoil	None
MD10	ISWMM Method 5	Rip 10 cm subsoil/add 10 cm loosened topsoil	None
BD10	Modified ISWMM Method 5	Rip 10 cm subsoil, tillage radish in topsoil/add 10 cm loosened topsoil	Yes, decomposing tillage radish in subsoil. Radish planted at 102,000 to 136,000 seeds ha^{-1} (3.4 kg ha^{-1}).
CST5	ISWMM Method 6	Rip 15 cm subsoil, add mix of loosened 2.5 cm topsoil + 2.5 cm compost	Yes, 109 Mg ha^{-1} compost* mixed with loosened topsoil.
CS15	Modified ISWMM Method 6	Rip 15 cm subsoil add 2.5 cm compost, then add 2.5 cm loosened topsoil	Yes, 109 Mg ha^{-1} compost tilled into subsoil.

Note: ISWMM = *Iowa Storm Water Management Manual*.

*Compost characteristics in table S1.

formed in footslopes of alluvial fans with low slope ~5% (USDA NRCS 2022). The 30-year mean annual temperature and precipitation (± standard error) are 10.6°C ± 1.1°C and 968 ± 218 mm, respectively (IEM 2020).

We simulated typical protocols for the mass grading step at the site on September 12, 2019 (figure 1, Step 1). The topsoil was stripped and stockpiled onsite using a John Deere 750k bulldozer with an operating weight of 14,677 kg. A six-wheel 140H AWD Grader (Caterpillar Inc., Irving, Texas) with total operating weight of 20,828 kg was used to simulate soil compaction during the mass grading and utility installation (figure 1, Steps 1 and 2). Ten centimeters of topsoil was placed on top of these soils using the same bulldozer. Then the five treatments were replicated sequentially in three blocks with 61 m × 6 m plots (table 1, figure 2, and figure S1). Development Steps 2, 3, and 4 (figure 1) were not simulated in this experiment because they deal with infrastructure installation (which we did not do at the plot scale for obvious reasons).

The application of the straw and/or a stabilizing cover crop would typically be required for soil erosion control practices following Step 3 (figure 1), when the site would be undisturbed for a substantial period (IDNR 2023). Simulating this, all plots were seeded with cereal rye (*Secale cereale*) and mulched with straw. The BD10 plots were also initially seeded with tillage radish on September 12, 2019, at a rate of 3.4 kg ha^{-1} (or 102,000 to 136,000 seeds ha^{-1}) in addition to the cereal rye and straw. Plots were mowed in summer of 2020. Poor germination of tillage radish occurred the following spring of 2020, so we reseeded all BD10 with tillage radishes on September 2, 2020, at the same rate and added annual ryegrass (*Lolium Multiflorum*) at a rate of 10.2 kg ha^{-1} (standard best management practice from ISWMM) (IDNR 2023). There was successful germination of tillage radish in the spring of 2021 (figures S2 and S3).

On May 11, 2021, simulating the fine grading activities (figure 1, Step 5), the subsoil in all plots were equally compacted to the best of our ability with typical grading equipment in the region. The earth moving during this fine grading was conducted with a 750K Martin Bulldozer (John Deere Inc., Moline, Illinois), which weighs 16,000 to 17,000 kg and has a 3.9 m^2 track base. Also, we used a six-wheel 140M3 AWD Grader (Caterpillar Inc., Irving, Texas) with total operating weight of 20,828 kg for grading. For soil decompaction, we used a T590 Compact Track Loader (Bobcat Company, West Fargo, North Dakota) with 3,664 kg operating weight and 0.7 m^2 track base equipped with a 1.9 m wide XR Ripper with 0.5 m depth capability (CL Fab, Clarinda, Iowa). For the decompacted treatments, which included all but the control treatment, a first pass was ripped to 10 cm followed by a second and third pass to 15 cm.

On May 12, 2021, finishing fine grading (figure 1, Step 5), we added the same amount of composted yard waste at the recommended rate of 2.5 cm, which is approximately 109 Mg ha^{-1} of dry material, to the CST5 and CS15 treatments. The bulk density and moisture content of the compost was 0.46 g cm^{-3} and 58.1% moisture (table S1). The primary difference between the two compost treatments was how it was mixed and applied to the soil. With the CST5 treatment, the compost was mixed with 5 cm of topsoil and added on top of decompacted subsoil. Whereas with the CS15 treatment, the compost was mixed with the subsoil and then 2.5 cm loosened topsoil was added per local recommendations. Steps 6 and 7 (figure 1) were not simulated in this experiment and all soil testing occurred after this time.

Field and Laboratory Soil Health Analyses. Bulk density, pore space, and water-filled pore space (WFPS) were measured by using the "core method" on November 16, 2021 (Grossman and Reinsch 2002). Briefly, in each plot, surface vegetation was removed. A 30 cm deep soil core (3.2 cm diameter) was collected using a slide hammer soil corer with stainless steel segments at 5 cm depths (AMS Inc., American Falls, Idaho). Field-collected cores were individually bagged, labeled, and returned to the lab for processing. Fresh samples were weighed, then dried at 100°C for 72 hours and reweighed to determine soil moisture content and bulk density. Three 5 cm soil core segment bulk densities were averaged for 0 to 15 and 15 to 30 cm bulk density. Infiltration rates and time-to-runoff were measured on the plots using Cornell sprinkle infiltrometers four times between July 1 and November 16, 2021 (Ogden et al. 1997).

Soil samples were collected on November 16, 2021, and analyzed fresh for microbial biomass and salt-extractable organic C and nitrogen (N). Microbial biomass C and N (MBC and MBN) and salt-extractable C and N (SEOC and SEON) were analyzed using a modified version of the chloroform-fumigation method (Vance et al. 1987; Potter et al. 2023). The C and N measured in nonfumigated samples reflects a pool of potentially labile, extractable substrates for microbial decomposition. All extracts were analyzed for nonpurgeable organic C and total N (TN) via combustion on a Shimadzu TOC-L analyzer with TN capabilities (Shimadzu Corp., Kyoto, Japan). MBC and MBN were calculated by the differences between fumigated and nonfumigated samples and corrected by the extraction efficiency factors of 0.45 (MBC) and 0.54 (MBN) (Brookes et al. 1985; Joergensen 1996).

The same soils used for MBC, MBN, SEOC, and SEON were air-dried at 22°C to 24°C for one month and analyzed for plant-available nutrients. Soil test phosphorus (STP) and potassium (STK) was extracted with 2 g soil per 20 mL of Mehlich III extract and analyzed on an ICP-OES 7300 Machine (Perkin Elmer, Waltham, Massachusetts). SOM was measured on 5 to 10 g of soil using loss on ignition for 6 hours at 400°C. Soil pH and buffer pH were measured on a Lignin probe (Lignin, Albuquerque, New Mexico). Soil pH was measured using a 1:1 soil/water slurry.

Biological activity was measured as decomposition of green (*Camellia sinensis*) and rooibos (*Aspalathus linearis*) teas via previous methods (Keuskamp et al. 2013, Middleton et al. 2021). Briefly, reinforced and labeled tea bags were buried at 4 cm in all plots on July 1, 2021, and retrieved on August 30, 2021 (60 days later). Upon retrieval, soil was gently removed from tea bags. Tea was dried at 50°C for 3 days and weighed, then placed in a muffle furnace at 550°C overnight to get ash remaining. Ash-free dry mass loss was calculated as final minus initial divided by the initial weight.

Data Handling and Statistical Analyses. All statistical analyses were done in R (V. 4.3.1) and data visualization in SigmaPlot v.15 (Inpixon Inc., Palo Alto, California). We used a two-pronged approach to analyzing differences among treatments. At each stage we would proceed further if main effects or interactions were significant at $\alpha = 0.1$. First, we used one-, two-, or three-way ANOVAs depending on if there were multiple depths (e.g., soil analyses at 0 to 15 cm and 15 to 30 cm), or multiple dates (bulk density on spring, summer, and autumn) using *lm* function in R. We were only interested in main effect of treatment or interaction with these other moderating variables. If only a main treatment effect, we used maximum-minimum normalization (value minus minimum divided by maximum minus minimum) for each depth and/or date so we could analyze across depths and dates to get main effect of treatment only. When there were significant interactions with treatment, we analyzed each depth/date separately. We used *TukeyHSD* function for posthoc means comparison among treatments with significant differences at $\alpha = 0.1$. Second, we ran orthogonal contrasts where comparing all treatments. We ran two versions of orthogonal contrasts—one evaluating decompaction and addition of manure treatment. For example, to evaluate decompaction, we compared all treatments that had subsoil decompaction (MD10, BD10, CST5, and CS15) versus no subsoil decompaction (Control). To evaluate the effect of an organic amendment, whether green or composted yard waste (table 1), we compared all treatments that had some form of manure (BD10, CST5, and CS15) versus those with none (Control and MD10).

Results and Discussion

Effects of Decompaction on Soil Health. Our soil bulk densities ranged from 0.8 to 1.9 g cm^{-3} (figure 3). Our infiltration rates were highly variable but there were more consistent differences among treatments (figure 4). Compared to other studies on urban soils, our bulk density, pore space, and infiltration measurements are within the norm

Figure 3

Physical soil properties: bulk density (BD), total pore space (TPS), and water-filled pore space (WFPS). Data points are means with standard errors (*n* = 3). See table 1 for treatment details.

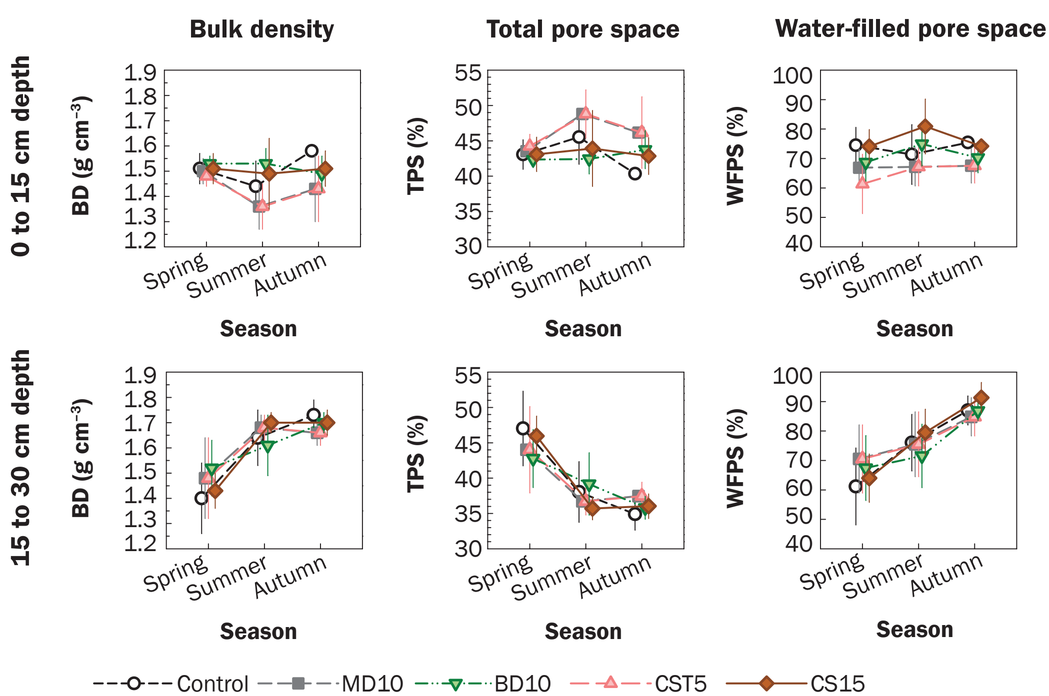
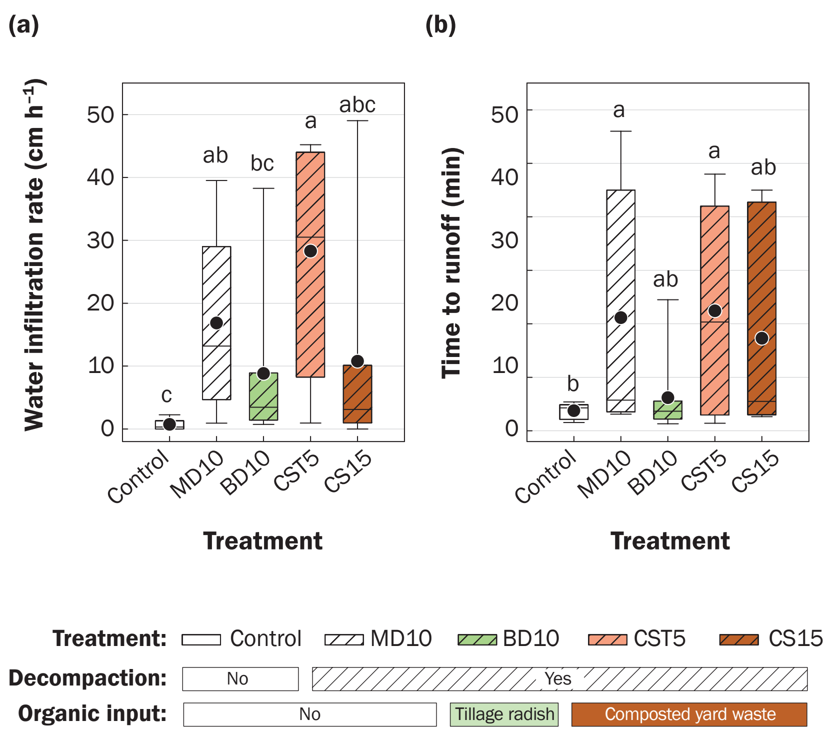


Figure 4

(a) Infiltration rate and (b) time-to-runoff. Boxplots (n = 12) show total variation with 10th percentile (lower whisker), 25th percentile (lower box shoulder), median (horizontal line in box), mean (large black dot), 75th percentile (upper box shoulder), and 90th percentile (upper whisker). Significant treatment differences are indicated by lowercase letters. See table 1 for further treatment details.



(Hamilton and Waddington 1999; Olson et al. 2013). A study of three urban sites in Minnesota showed range in soil bulk density from 1.3 up to 1.7 g cm^{-3} (Olson et al. 2013), and both the 0 to 15 and 15 to 30 cm depths are within this range. With regard to infiltration rates, a study of 15 residential lawns in Pennsylvania showed a range from <1 up to 40 cm h^{-1} (Hamilton and Waddington 1999), and this is quite comparable to the range in our values (figure 4).

In our experiment, we used a track loader–mounted ripper head to break up compacted subsoil (figure 2). This mechanical decompaction had mixed effects on physical soil properties (figures 3 and 4; table 2). For example, mechanical decompaction had little effect on bulk density and pore space (figure 3 and table 2). This could be due to the dynamic nature of soil bulk density and a rapid settling of decompacted soils. Also, contributing to measurement noise is the imprecise method for measuring soil bulk density. There was a slight decrease in soil bulk density, ~ 0.4 g cm^{-3}, but only in CST5 treatment at 0 to 15 cm depth compared to other Control, MD10, and BD10 (p-value < 0.042) (figure 3). However, there were much stronger effects on water intake, as decompaction increased infiltration rate by over 2,000% and time-to-runoff by 463% on average compared to the control (figure 4 and table 2). Yet, despite only marginal bulk density changes, the substantial improvements in water intake from the physical soil rehabilitation aligns with the goals of the *Iowa Stormwater Management Manual* (IDNR 2023).

A similar study in the nearby state of Minnesota showed that decompaction tillage alone was ineffective at increasing infiltration rates; however, when combined with yard waste compost, the two practices increased infiltration from 50% to over 200% (Olson et al. 2013). These varied responses to tillage as decompaction strategy likely depend on many factors including (but not limited to) how compacted the soil is to start, depth and intensity of tillage (depending largely on equipment access), soil texture, soil moisture at time of tillage, time since infiltration or hydraulic conductivity measurements are taken, and a variety of other factors.

Although on average greater than the control, using the tillage radish for biological decompaction did not have as strong of an effect on infiltration. This contrasts with other studies, exclusively in agricultural soils, that show tillage radish can decrease bulk density and improve infiltration rates (Chen and Weil 2010; Blanco-Canqui and Ruis 2020). The lack of a tillage-radish decompaction effect could be for a variety of reasons but the primary reason was lack of tillage radish biomass (figures S2 and S3). Tillage radish growth may have been limited by 2021's cold winter, but also allelopathy with cereal rye or high soil bulk densities may have played a role (discussed more in the next section).

It may also be unreasonable to expect significant improvement in infiltration from tillage radish from only one year. Most agriculture studies monitor cumulative soil changes from cover crops, like tillage radish, over multiple years and still find more gradual changes (Moore et al. 2014; Wood and Bowman 2021). However, that is not possible with a "one-and-done" approach to biological decompaction used during initial stages of urban, residential development. There are other techniques to ameliorate compaction and increase infiltration in urban landscapes that we did not test here, such as planting trees that create deeper root channels for macropore water flow (Bartens et al. 2008), or even postdevelopment rehabilitation with tillage and mixing compost (Chen et al. 2014).

Some land managers and researchers are looking beyond the site preparation steps and at rehabilitating urban soils many years after the third mobilization phase, so called postdevelopment rehabilitation (Chen et al. 2014). Chen et al. (2014) found that mixing compost and partial tillage increased soil C in macroaggregates. While our mechanical decompaction treatments during predevelopment had strong positive impacts on infiltration rate and time-to-runoff, decompaction treatments had little effect on soil chemical or biological properties at either depth (figures 5 and 6). Adding compost and green manure as organic amendments, however, did have positive impacts on these soil properties—especially adding yard waste compost.

Effects of Compost and Green Manure on Soil Health. Our soils were slightly alkaline ranging from pH of 7.6 to 7.8 (figure

Table 2
Overall treatment contrast means (standard errors) and *p*-values* from orthogonal contrasts.

		Decompaction			Organic input		
Soil property	**Units**	**Control (none)**	**Subsoil decompaction**	***p*-value**	**Control and MD10 (none)**	**Compost or green manure added**	***p*-value**
Physical							
Bulk density	g cm^{-3}	1.52 (0.02)	1.49 (0.02)	ns	1.52 (0.01)	1.48 (0.08)	ns
Pore space	cm^3 cm^{-3} × 100	42.6 (0.7)	43.8 (2.8)	ns	42.6 (2.4)	44.2 (3.0)	ns
Infiltration rate	cm h^{-1}	0.70 (0.85)	17.1 (17.20)	<0.001	8.77 (3.37)	17.23 (5.30)	ns
Time-to-runoff	min	3.76 (0.42)	16.54 (5.40)	0.017	12.46 (5.17)	14.91 (4.94)	ns
Chemical							
pH	unitless	7.7 (0.0)	7.8 (0.1)	ns	7.7 (0.1)	7.8 (0.1)	ns
CEC	meq 100 g^{-1}	16.4 (1.3)	17.5 (0.5)	ns	16.2 (0.6)	17.9 (0.6)	ns
SOM	%	2.33 (0.12)	3.08 (0.89)	0.053	2.2 (0.17)	3.42 (0.75)	0.003
STP	mg P kg^{-1}	34.7 (2.7)	57.6 (6.5)	<0.001	34.7 (1.2)	65.2 (7.0)	<0.001
STK	mg K kg^{-1}	115 (9)	181 (20)	0.013	113 (4)	205 (21)	0.002
Biological							
SEOC	mg C kg^{-1}	67 (16)	90 (14)	ns	55 (9)	105 (16)	0.020
SEON	mg N kg^{-1}	5.5 (0.3)	7.5 (1.6)	ns	4.5 (0.6)	8.8 (2.0)	ns
MBC	mg C kg^{-1}	332 (47)	404 (26)	ns	351 (25)	415 (33)	ns
MBN	mg N kg^{-1}	36 (4)	45 (3)	ns	38 (4)	46 (4)	ns
MBC:MBN	unitless	9.2 (0.6)	9.2 (0.5)	ns	9.4 (0.5)	9.1 (0.6)	ns
Green tea mass loss at 60 d	g loss g $initial^{-1}$	0.48 (0.02)	0.49 (0.01)	ns	0.50 (0.03)	0.49 (0.01)	ns
Red tea mass loss at 60 d	g loss g $initial^{-1}$	0.29 (0.01)	0.30 (0.02)	ns	0.29 (0.18)	0.31 (0.02)	ns

Notes: CEC = cation exchange capacity. SOM = soil organic matter. STP = soil test phosphorus. STK = soil test potassium. SEOC = salt-extractable organic C. SEON = salt-extractable organic N. MBC = microbial biomass C. MBN = microbial biomass N.

*ns = not significant

5). Like many soils, urban or not, SOM is greater in the upper 0 to 15 cm (2% to 7%) compared to 15 to 30 cm (1.5% to 2.5%). Soil pH, SOM, and CEC will be largely dependent on inherent soil properties—such as texture, mineralogy and parent material—in combination with past vegetation and long-term management. Few studies have looked at the impact of a single organic matter amendment added predevelopment in urban, residential soils. This organic input is critical for both immediate prevention of soil erosion, as in the case of the tillage radish cover crop, but also may have longer-term positive effects on soil functions like nutrient-suppling power (i.e., reduction of fertilizer inputs), soil water holding capacity, and soil biota habitat in residential lawns. Our study, to our knowledge, is the only residential soil study to trial tillage radish as an organic amendment, whereas other studies typically use only composed yard waste (composted leaves, grass, and stems).

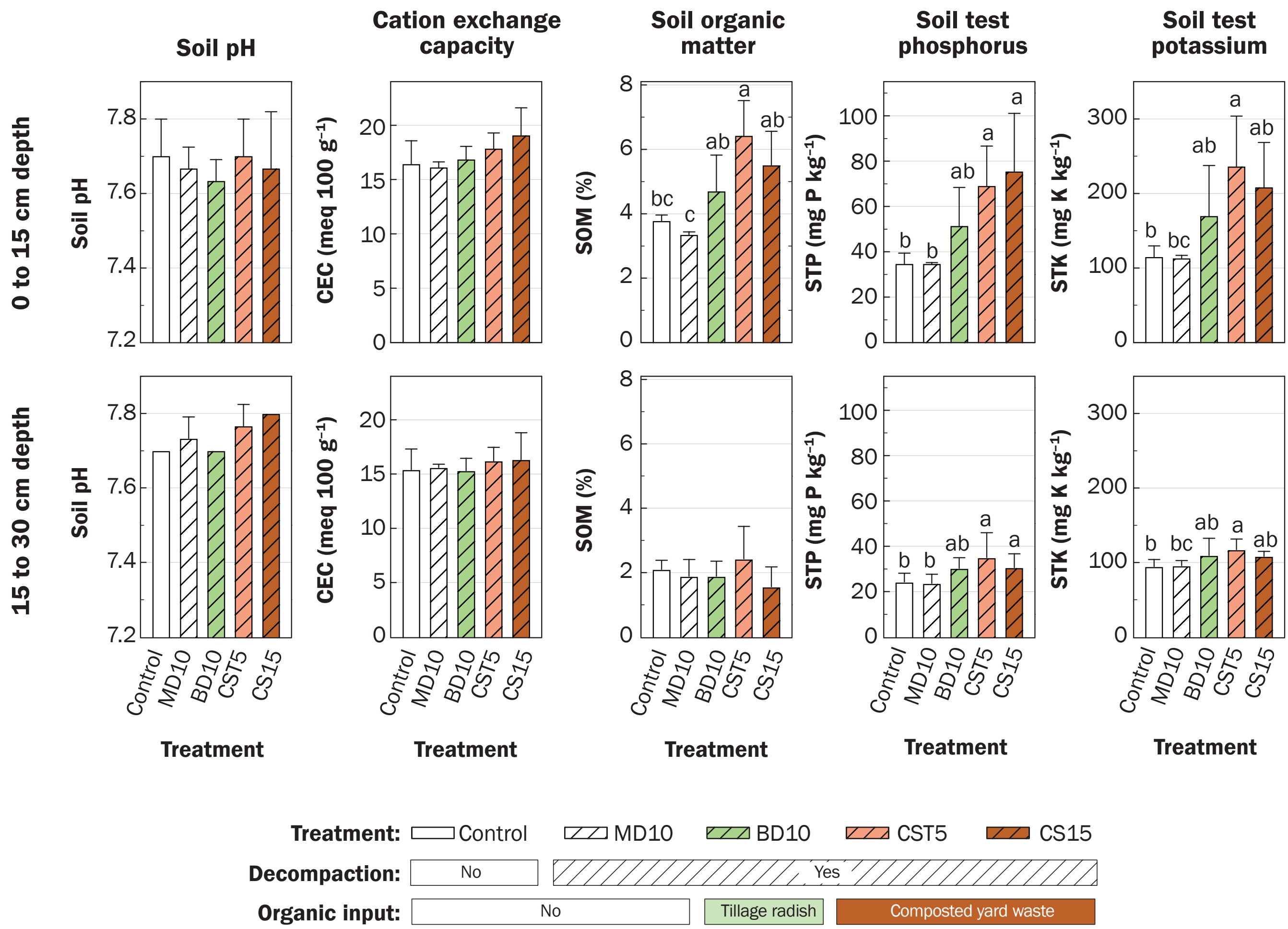
Adding organic amendments tended to increase indicators of chemical and biological soil health but had little effect on soil physical parameters (figures 4 and 5; table 2). Where we observed significant organic amendment effects, the compost had stronger effects than adding tillage radish, especially for top 0 to 15 cm of soil. This is due to two factors. First, tillage radish biomass input rates into soils were most likely much less than compost rates, mostly because of lack of robust growth (although we did not measure the tillage radish biomass). The tillage radish was planted on September 12, 2021, and at 102,000 to 136,000 seeds ha^{-1} and resulted in modest growth (figures S2 and S3). Second, the compost was added and mixed with topsoil (figure 2), thus the positive effects are mostly concentrated in 0 to 15 cm soil depth increment (figure 5). It is possible that the tillage radish may have been limited by soil compaction, even if planting conditions had been ideal. Generally, soil bulk densities greater than 1.6 g cm^3 can be root limiting, even for tillage radishes (Jansen 2021). Thus, this is the paradox. We want to use tillage radish's substantial tap root (White and Weil 2011) to decompact residential soils, but the high bulk densities in urban soils may be a barrier to success.

On average, adding compost increased SOM by 43%, but only in the top 15 cm of the soil profile (figure 5). Adding organic amendments, in general, tends to have positive effects on SOM and soil organic C. For instance, a meta-analysis across 49 sites showed that about 10% to 14% of total C inputs from manures persists in soil, the rest likely converted to and lost as carbon dioxide (CO_2) (Maillard and Angers 2014). A more relevant study on rehabilitation of Virginia urban soils showed that adding composted leaves postdevelopment had little effect on total C at 0 to 5, 5 to 15, and 15 to 30 cm, but did increase MBC by 142% on average, with the greatest effect being at the lowest depth (Chen et al. 2013b). This contrasts with our finding that organic amendments had little effect on MBC, nor most other biological soil health measures.

Just as composted yard waste is a source of C, it is also a source of plant macro- and

Figure 5

Chemical soil health measurements: CEC = cation exchange capacity, SOM = soil organic matter, STP = soil test phosphorus (Melich-III), and STK = soil test potassium (Melich-III). Data are means with standard errors (n = 3) and significant treatment differences are indicated by lowercase letters. See table 1 for further treatment details.



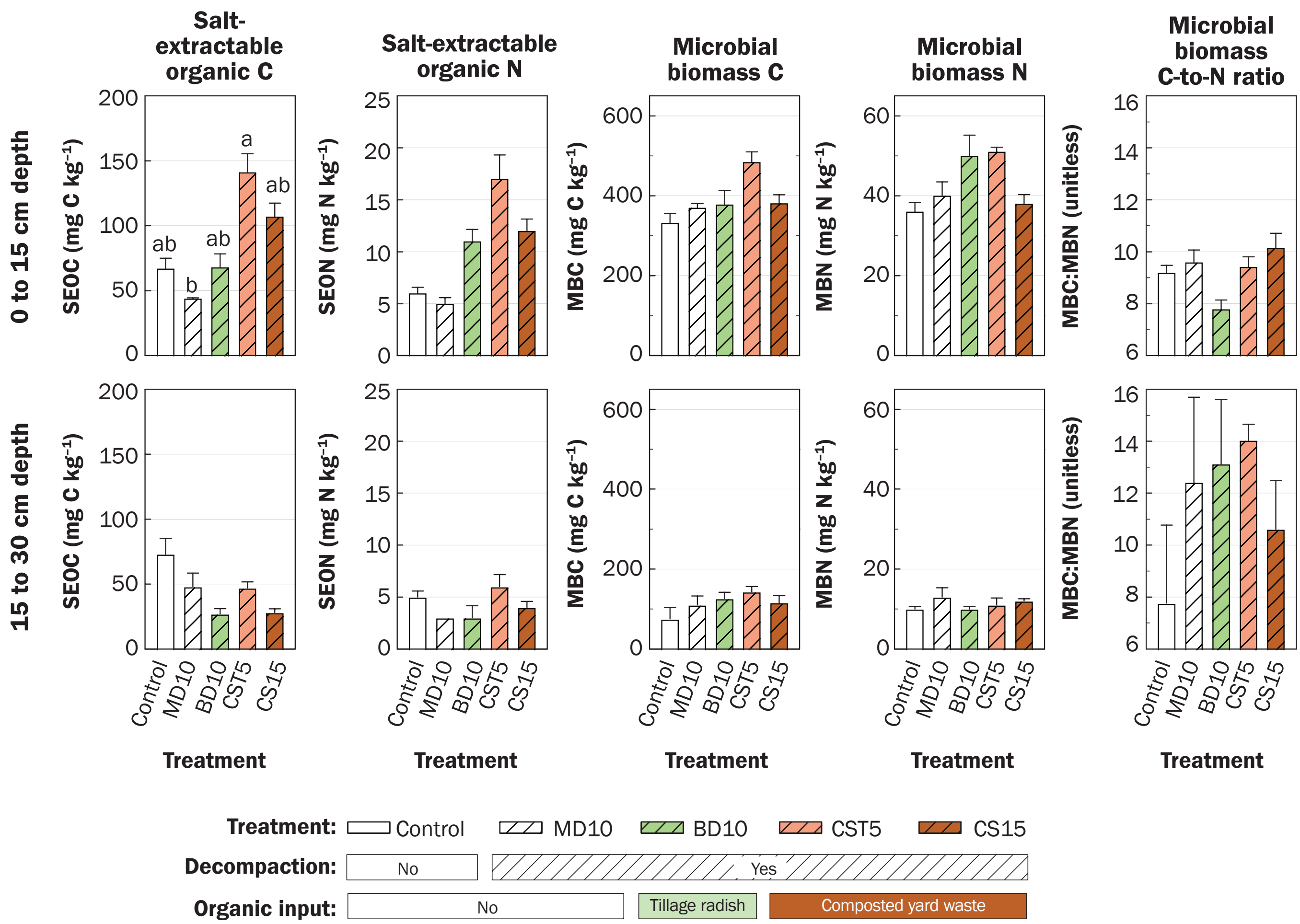
micronutrients. Adding compost significantly increased STP by 79% and STK by 60% compared to no compost treatment (MD10). Unlike SOM, however, the effect on these macronutrients persisted to 15 to 30 cm depth, albeit of a lesser magnitude (figure 4). This addition of STP and STK could help prolong turfgrass growth and delay need for later P and K applications (Frank and Guertal 2013), and the mobility of these two nutrients is not as much a concern as nitrate (NO_3^-). Soil NO_3^--N and ammonium (NH_4^+)-N remained low in our soils (<1.05 ppm).

While the compost tended to increase soil microbial biomass, activity via tea decomposition, and substrates available to microbes (e.g., SEOC and SEON), only a few of these soil properties were significantly different compared to the no amendment treatments (table 2 and figure 6). Compost increased SEOC by 220% compared to no amendment at all (i.e., Control and MD10) (figure 6 and table 2). SEOC is easily extractable, i.e., low molecular weight, organic compounds that are likely easily mineralized by microorganisms (Said-Pullicino et al. 2007; Strosser 2010). It is generally thought that greater soil SEOC concentrations is better for soil health because of this connection to microbial activity, and it may even help contribute to lower nutrient (especially N) loss (Potter et al. 2023). A similar measurement to SEOC is used as part of the "Haney Test" for soil health (Haney et al. 2008, 2010, 2012), which is a series of measurements designed to assess general biological soil health and has been used as predictor of crop N needs (Yost et al. 2018). Although the Haney Test uses water-extractable C, and not salt-extractable C as in our study, the measurements should be very comparable.

Other studies show organic amendments can significantly increase microbial biomass and activity (Kallenbach and Grandy 2011; Baldwin-Kordick et al. 2022), even in the few studies on urban soils (Wiseman et al. 2012; Chen et al. 2013b). However, in our study only SEOC was significantly different from unamended treatments. We attribute this to inherent variation in these measurements and perhaps because the composted yard waste had a wide C-to-N ratio (C:N = 33.6) (table S1).

Figure 6

Biological soil health measurements: SEOC = salt-extractable organic carbon (C), SEON = salt-extractable organic nitrogen (N), MBC = microbial biomass C, MBN = microbial biomass N, and MBC:MBN = microbial biomass C-to-N ratio. Data are means with standard errors (n = 3) and significant treatment differences are indicated by lowercase letters. See table 1 for further treatment details.



Summary and Conclusions

Residential developments will continue to increase in parallel with human population growth. It is contingent upon land developers, driven by other stakeholders, to find ways to rehabilitate these highly disturbed soils both pre- and postdevelopment. Here we show that both decompaction with subsoil tillage and addition of organic amendments can improve multiple metrics of soil health in the short term. Mechanical tillage reliably enhanced infiltration compared to compacted soil under traditional management. Compost, added as an organic amendment, increased SOM and some chemical and biological soil properties. Each strategy, decompaction or organic amendments, fulfils separate goals (table 2) but should be considered together for maximum benefit to soil ecosystem services. These improvements in urban, residential soil health likely translate to longer-term reduction in stormwater runoff and improved turfgrass growth, requiring less irrigation and fertilizer inputs; however, this remains untested as long-term studies in urban settings are extremely rare.

The rapid pace of land development, combined with the economic need to quickly construct housing, means there is a limited window of time for implementing soil health enhancing practices like those trialed in this study. This is an entirely different model than the continual approach to soil health management found in agroecosystems. The limited treatment interventions and short-term measurements included in this study reflect the reality of research in urban ecosystems. The majority of the world's population, however, interact more with urban, residential soils than they do with agricultural soils; therefore, these increasingly important soils are deserving greater attention.

Residential, urban development should create multifunctional landscapes that fulfil human needs while also minimizing environmental impact. To achieve this goal, developers will need evidence-based guidance. An important part of this is collaborative research that includes multiple stakeholders (e.g., academia, private developers, and nonprofit organizations). These multistakeholder partnerships—while challenging and possibly resulting in compromises between scientific rigor versus practical feasibility—

allow for vital research under real-world conditions that cannot be easily simulated in typical, academic research settings.

Supplementary Material

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2024.00111.

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References

Baldwin-Kordick, R., M. De, M.D. Lopez, M. Liebman, N. Lauter, J. Marino, and M.D. McDaniel. 2022. Comprehensive impacts of diversified cropping on soil health and sustainability. Agroecology and Sustainable Food Systems 46(3):331–363.

Bartens, J., S.D. Day, J.R. Harris, J.E. Dove, and T.M. Wynn. 2008. Can urban tree roots improve infiltration through compacted subsoils for stormwater management? Journal of Environmental Quality 37(6):2048–2057.

Blanco-Canqui, H., and S.J. Ruis. 2020. Cover crop impacts on soil physical properties: A review. Soil Science Society of America Journal 84(5):1527–1576.

Brookes, P.C., A. Landman, G. Pruden, and D.S. Jenkinson. 1985. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biology and Biochemistry 17(6):837–842.

Burr-Hersey, J.E., S.J. Mooney, A.G. Bengough, S. Mairhofer, and K. Ritz. 2017. Developmental morphology of cover crop species exhibit contrasting behaviour to changes in soil bulk density, revealed by X-ray computed tomography. PLoS One 12(7):e0181872.

Celik, I., H. Gunal, M. Budak, and C. Akpinar. 2010. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. Geoderma 160(2):236–243.

Chen, Y., 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. Science of the Total Environment 494(2014):329–336.

Chen, Y., S.D. Day, A.F. Wick, B.D. Strahm, P.E. Wiseman, and W.L. Daniels. 2013a. Changes in soil carbon pools and microbial biomass from urban land development and subsequent post-development soil rehabilitation. Soil Biology and Biochemistry 66(2013):38–44.

Chen, Y., S.D. Day, A.F. Wick, B.D. Strahm, P.E. Wiseman, and W.L. Daniels. 2013b. Changes in soil carbon pools and microbial biomass from urban land development and subsequent post-development soil rehabilitation. Soil Biology and Biochemistry 66(2013):38–44.

Chen, G., and R.R. Weil. 2010. Penetration of cover crop roots through compacted soils. Plant and Soil 331(2010):31–43.

Frank, K.W., and E.A. Guertal. 2013. Potassium and phosphorus research in turfgrass. Turfgrass: Biology, Use, and Management 56(2013):493–519.

Groffman, P.M., A.K. Suchy, D.H. Locke, R.J. Johnston, D.A. Newburn, A.J. Gold, L.E. Band, J. Duncan, J.M. Grove, and J. Kao-Kniffin. 2023. Hydro-bio-geo-socio-chemical interactions and the sustainability of residential landscapes. PNAS nexus 2(10):pgad316.

Grossman, R.B., and T.G. Reinsch. 2002. Core Method. *In* Methods of Soil Analysis, Part 4: Physical Methods, ed. W. Al. Dick, L. Al-Almoodi, J.H. Dane, and C.G. Topp, 207. Madison, WI: Soil Science Society of America.

Hamilton, G.W., and D.V. Waddington. 1999. Infiltration rates on residential lawns in central Pennsylvania. Journal of Soil and Water Conservation 54(3):564–568.

Haney, R.L., W.F. Brinton, and E. Evans. 2008. Soil CO_2 respiration: Comparison of chemical titration, CO_2 IRGA analysis and the Solvita gel system. Renewable Agriculture and Food Systems 23(2):171–176.

Haney, R.L., A.J. Franzluebbers, V.L. Jin, M.-V. Johnson, E.B. Haney, M.J. White, and R.D. Harmel. 2012. Soil organic C:N vs. water-extractable organic C:N. Open Journal of Soil Science 2(3).

Haney, R.L., E.B. Haney, L.R. Hossner, and J.G. Arnold. 2010. Modifications to the new soil extractant H3A-1: A multinutrient extractant. Communications in Soil Science and Plant Analysis 41(12):1513–1523.

IDNR (Iowa Department of Natural Resources). 2023. Iowa Stormwater Management Manual. Des Moines, IA: IDNR.

IDNR. 2006. Chapter 2: Vegetation and Soil Stabilization Control Measures. *In* Iowa Construction Site Erosion Control Manual. Des Moines, IA: IDNR. http://publications.iowa.gov/8127/1/const_erosion.pdf.

IDNR. 2009. Chapter 5: Infiltration Practices. *In* Iowa Stormwater Management Manual. Des Moines, IA: IDNR. https://www.iowadnr.gov/Environmental-Protection/Water-Quality/NPDES-Storm-Water/Storm-Water-Manual.

IDNR. 2018. National pollution discharge elimination system (General permit No. 2). Des Moines, IA: IDNR. https://www.iowadnr.gov/Portals/idnr/uploads/water/npdes/gp2.pdf.

Jansen, M. 2021. An evaluation of tillage radish (*Raphanus sativus* L.) to alleviate post-construction soil compaction and germination potential under varying environmental conditions. Ames, IA: Iowa State University. https://dr.lib.iastate.edu/handle/20.500.12876/Nr1Vk1az.

Joergensen, R.G. 1996. The fumigation-extraction method to estimate soil microbial biomass: Calibration of the K_{ec} value. Soil and Tillage Research 28(1):25–31.

Kallenbach, C., and A.S. Grandy. 2011. Controls over soil microbial biomass responses to carbon amendments in agricultural systems: A meta-analysis. Agriculture, Ecosystems & Environment 144(1):241–252.

Karlen, D.L., M. De, M.D. McDaniel, and D.E. Stott. 2021. Evolution of the Soil Health Movement. *In* Soil Health Series: Volume 1, Approaches to Soil Health Analysis, 21-48. Hoboken, NJ: John Wiley & Sons, Inc.

Kaye, J.P., R.L. McCulley, and I.C. Burke. 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Global Change Biology 11(4):575–587.

Keller, T., and D. Or. 2022. Farm vehicles approaching weights of sauropods exceed safe mechanical limits for soil functioning. Proceedings of the National Academy of Sciences 119(21):e2117699119.

Keuskamp, J.A., B.J.J. Dingemans, T. Lehtinen, J.M. Sarneel, and M.M. Hefting. 2013. Tea Bag Index: A novel approach to collect uniform decomposition data across ecosystems. Methods in Ecology and Evolution 4(11):1070–1075.

Lamandé, M., M.H. Greve, and P. Schjønning. 2018. Risk assessment of soil compaction in Europe–Rubber tracks or wheels on machinery. Catena 167(2018):353–362.

Loper, S., A.L. Shober, C. Wiese, G.C. Denny, C.D. Stanley, and E.F. Gilman. 2010. Organic soil amendment and tillage affect soil quality and plant performance in simulated residential landscapes. HortScience 45(10):1522–1528.

Luo, H., Y. Rong, J. Lv, and Y. Xie. 2019. Runoff erosion processes on artificially constructed conically-shaped overburdened stockpiles with different gravel contents: Laboratory experiments with simulated rainfall. Catena 175(2019):93–100.

Maillard, É., and D.A. Angers. 2014. Animal manure application and soil organic carbon stocks: A meta-analysis. Global Change Biology 20(2):666–679.

Meek, B., L. Graham, and T. Donovan. 1982. Long-term effects of manure on soil nitrogen, phosphorus, potassium, sodium, organic matter, and water infiltration rate. Soil Science Society of America Journal 46(5):1014–1019.

Mesonet, I. 2020. ISU Mesonet - Iowa State University Iowa Environmental Mesonet Climate Data. Ames, IA: Iowa State University. https://mesonet.agron.iastate.edu/.

Middleton, T.E., A.L. McCombs, S.R. Gailans, S. Carlson, D.L. Karlen, K.J. Moore, M.Z. Liebman, T.C. Kaspar, M.M. Al-Kaisi, and D.A. Laird. 2021. Assessing biological soil health through decomposition of inexpensive household items. Applied Soil Ecology 168(2021):104099.

Moore, E.B., M.H. Wiedenhoeft, T.C. Kaspar, and C.A. Cambardella. 2014. Rye cover crop effects on soil quality in no-till corn silage–soybean cropping systems. Soil Science Society of America Journal 78(3):968–976.

Ogden, C.B., H.M. Van Es, and R.R. Schindelbeck. 1997. Miniature rain simulator for field measurement of soil infiltration. Soil Science Society of America Journal 61(4):1041–1043.

Olson, N.C., J.S. Gulliver, J.L. Nieber, and M. Kayhanian. 2013. Remediation to improve infiltration into compact soils. Journal of Environmental Management 117(2013):85–95.

Pease, B., G.L. Thompson, and A.W. Thoms. 2022. Evaluation of compost and soil mix ratios for perennial ryegrass establishment on topsoil and subsoil. Hort Technology 32(2):191–198.

Pouyat, R.V., I.D. Yesilonis, and D.J. Nowak. 2006. Carbon storage by urban soils in the United States. Journal of Environmental Quality 35(4):1566–1575.

Ritchie, H., V. Samborska, and M. Roser. 2018. Urbanization. Oxford, England: Global Change Data Lab. https://ourworldindata.org/urbanization.

Said-Pullicino, D., K. Kaiser, G. Guggenberger, and G. Gigliotti. 2007. Changes in the chemical composition of water-extractable organic matter during composting: Distribution between stable and labile organic matter pools. Chemosphere 66(11):2166–2176.

Sax, M.S., N. Bassuk, H. van Es, and D. Rakow. 2017. Long-term remediation of compacted urban soils by physical fracturing and incorporation of compost. Urban Forestry & Urban Greening 24(2017):149–156.

Seto, K.C., B. Güneralp, and L.R. Hutyra. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences 109(40):16083–16088.

Sharky, B.G. 2014. Landscape Site Grading Principles: Grading with Design in Mind. Hoboken, NJ: John Wiley & Sons.

Skold, M.D. 1989. Cropland retirement policies and their effects on land use in the Great Plains. Journal of Production Agriculture 2(3):197–201.

Strosser, E. 2010. Methods for determination of labile soil organic matter: An overview. Journal of Agrobiology 27(2):49.

Thompson, G.L., N. Bray, P.M. Groffman, and J. Kao-Kniffin. 2023. Soil microbiomes in lawns reveal land-use legacy impacts on urban landscapes. Oecologia (2023):1–15.

Thompson, G.L., and J. Kao-Kniffin. 2017. Applying biodiversity and ecosystem function theory to turfgrass management. Crop Science 57(S1):S-238.

USDA NRCS (Natural Resources Conservation Service). 2022. Web Soil Survey. Washington, DC: Soil Survey Staff, USDA NRCS. https://websoilsurvey.nrcs.usda.gov/app/.

White, C.M., and R.R. Weil. 2011. Forage radish cover crops increase soil test phosphorus surrounding radish taproot holes. Soil Science Society of America Journal 75(1):121–130.

Wiseman, P.E., S.D. Day, and J.R. Harris. 2012. Organic amendment effects on soil carbon and microbial biomass in the root zone of three landscape tree species. Arboriculture & Urban Forestry 38(6):262–276.

Wood, S.A., and M. Bowman. 2021. Large-scale farmer-led experiment demonstrates positive impact of cover crops on multiple soil health indicators. Nature Food 2(2):97–103.

Yost, M.A., K.S. Veum, N.R. Kitchen, J.E. Sawyer, J.J. Camberato, P.R. Carter, R.B. Ferguson, F.G. Fernández, D.W. Franzen, and C.A. Laboski. 2018. Evaluation of the Haney Soil Health Tool for corn nitrogen recommendations across eight Midwest states. Journal of Soil and Water Conservation 73(5):587–592. https://doi.org/10.2489/jswc.73.5.587.