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Tillage and Cover Crop Mix Effects on Urban Soil Performance

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Core Ideas

As part of the submission process, we ask authors to prepare highlights of their article. The highlights will consist of 3 to 5 bullet points that convey the core findings of the article and emphasize the novel aspects and impacts of the research on scientific progress and environmental problem solving.

The purpose of these highlights is to give a concise summary that will be helpful in assessing the suitability of the manuscript for publication in the journal and for selecting appropriate reviewers. If the article is accepted the highlights may also be used for promoting and publicizing the research.

Core Idea 1: Tillage reduced urban soil compaction

Core Idea 2: Rototill improved soil infiltration

Core Idea 3: Buckwheat, cowpea, sorghum-sudangrass mix reduced weed density and diversity

Core Idea 4: Radish growth was most vigorous in no-till plots

Core Idea 5: CUST_CORE_IDEA_5 :No data available.

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3. Buckwheat, cowpea, sorghum-sudangrass mix reduced weed density and diversity
4. Radish growth was most vigorous in no-till plots

Tillage and Cover Crop Mix Effects on Urban Soil Performance

Author list and affiliations: Blind for submission.

Abbreviations: DPFLI, Detroit Partnership for Food Learning and Innovation; MSU, Michigan State University

ABSTRACT

Urban soils are highly disturbed, resulting in the loss of vegetation, organic matter, and increased compaction. Urban farmers invest heavily in compost amendments, but a diversified strategy may better target specific soil issues. This study examined how various tillage methods and cover crop mixes affected common agricultural variables of interest, including soil compaction, water infiltration, herbaceous weedy plant emergence, and yield of a common root crop. We observed that high disturbance tillage with tractor implements revealed substantial debris below the surface due to past human activity. Tractor tilled plots also relieved compaction to significantly greater depths compared to no-till (minimal disturbance) and rototilled (moderate disturbance) plots. Rototilled plots showed the highest infiltration rate even compared to tractor tilled soils, challenging assumed benefits that might follow from extensive tillage. Furthermore, forage radish root mass tended to be greater in no-till plots, despite that tillage group having lower infiltration and higher compaction. The weed suppression cover crop mix of sorghum-sudangrass, buckwheat, and cowpea suppressed both warm and cool season weeds significantly better than the other two cover crop mixes. We posit that integrated approaches to soil management can improve soil function better than simply adding compost.

INTRODUCTION

Urban areas are the fastest growing regions of the world, and soils within cities are often highly degraded due to human activity (Oldeman, 1991). Soils play a significant role in ecosystem health, and urban soil restoration has implications for carbon sequestration, stormwater management, forestry, and agriculture (Pavao-Zuckerman, 2008). As cities reactivate vacant land with degraded soils, improving soil quality proves to be an obstacle to agriculture and landscaping projects. Urban farmers in particular invest large amounts of money and time into amending soil for vegetable production, yet strategies to improve urban soil quality for production has scarcely been studied. Thus, it is critical to study methods that can be applied within cities to improve the health of soils.

Urban soils are often compacted, low in organic matter, high pH, and contaminated from pollution and debris (Beniston & Lal 2011). These characteristics render them impractical for agricultural and landscaping projects because they are difficult to manage and support vigorous plants. Nonetheless, urban farming in Detroit continues to expand and utilize vacant lots, providing local communities with fresh produce as well as a cleaner and safer environment (Heckler, 2012). It is critical to study management practices that can improve the quality of urban soils to support the viability of soil-based projects.

Compost application is common and can improve physical, chemical, and biological soil properties, like soil aggregate structure and organic matter, which includes macronutrients like carbon, nitrogen, and phosphorus, along with other micronutrients. However, persistent focus on compost use leads to excessive phosphorus in garden soils (Small et al. 2019), making this management strategy less efficient for many crops. Instead, compost application should be combined with additional sustainable agricultural techniques that directly address challenges facing urban soils.

Tilling is widely used to combat soil compaction (Badalíková, 2009), especially rototilling on smaller operations (personal observation). Benefits of tilling include creating larger soil pores which enhance infiltration and drainage (Hill et. al, 1985). However, tilling applications can weaken soil structure (Catania et. al, 2018) and increase dependence on tillage technology for management.

In response to these long-term detriments, no-till farming has been promoted as a more sustainable alternative (Xiao-Bin, 2006; Roger-Estrade et al. 2010). However, in transitioning severely compacted soil to productive use, the short-term benefits of tilling may likely outweigh the long-term costs. Quantifying the short-term (1-2-year) benefits can support small-scale (e.g 232 m^2 or 2,5000 ft^2) farmers in developing effective and informed strategies to enhance soil performance.

Cover cropping can also be combined with tilling to build soil organic matter, lower pH, suppress weedy plants and insect pests, and/or alleviate compaction. Based on species characteristics, plant mixes can be tailored to specific agricultural functions such as building soil, scavenging nutrients, fixing nitrogen and loosening soil. Cover cropping is also recommended for reducing soil erosion and water runoff, which are issues for rural agricultural landscapes in the US Midwest as well as soils affected by sealed surfaces in urban settings (National Science and Technology Council, 2017).

In this study, we investigated how different tillage techniques and cover crop mixes affected soil quality over the course of one growing season, with longer term effects anticipated. The tillage methods ranged from high disturbance using a tractor and implements to minimal disturbance with a broadfork. Cover crop mixes were selected based on target functions including reducing compaction, suppressing weeds, and accumulating organic matter. We expected rototilling, a moderate soil disturbance, to be the most effective method for decreasing compaction and weed pressure. We also expected the compaction cover crop mix to have higher water infiltration rates than the other mixes due to the roots of those species facilitating infiltration into the soil. Finally, we documented how cover crop species and mixes performed in general regarding plant vigor.

MATERIALS AND METHODS

Study site

The study site was located at the Michigan State University (MSU) - Detroit Partnership for Food, Learning, and Innovation (DPFLI) (42.4119979˚N, -83.2627370˚W), an urban agriculture center in Detroit, MI, USA. Mean annual temperature is 9.5˚C and precipitation is 787 mm. The site was formerly a school property where the building was demolished in 2016. The site's history is similar to that of many parcels across Detroit and other cities where urban decline has led to increased vacant land with degraded soil.

The DPFLI is characterized by upland wetland properties with a relatively shallow A horizon (Fig. 1a) and metal artifacts from previous human construction. There is a nearby river, and soils have mostly clay texture (~37%), with some areas higher in silt and sand. Soil organic matter within the research plots is relatively low, the pH is high (alkaline), and water-stable aggregates is low (Table 1). Soil samples revealed concentrations of common contaminants and heavy metals below government direct contact standards. Various metals including Pb, Zn, Cu were found in the soil but at levels below the Environmental Protection Agency direct contact standards (Angelone, 2002).

Table 1. Baseline soil properties in study plot (Cornell Soil Health Lab, NY, USA).

Type	Soil Indicator	Value	Comparison	Issues
Biological	Organic matter (%)	2.8	Very low	Ion exchange
				Water retention
				C storage
	Respiration (mg CO_2 d^{-1})	0.2	Excellent	
Physical	Aggregate Stability (%)	16.9	Very low	Compaction
				Infiltration
				Runoff/Erosion
Chemical	pH		Very high	Plant toxicity
				Nutrient availability
	Extractable P (ppm)	2.2	Optimal	
	Extractable K (ppm)	107.8	Optimal	
	Minor elements		Optimal	
	Magnesium (Mg, mg kg^{-1})	468.8		
	Iron (Fe, mg kg^{-1})	6.5		
	Sodium (Na, mg kg^{-1})	47.8		
	Zinc (Zn, mg kg^{-1})	2.6		
	Heavy metals		Safe	
	Arsenic (As, mg kg^{-1})	6.9		
	Aluminum (Al, mg kg^{-1})	9283		
	Calcium (Ca, mg kg^{-1})	45970		
	Copper (Cu, mg kg^{-1})	0.7		
	Nickel (Ni, mg kg^{-1})	18.2		
	Lead (Pb, mg kg^{-1})	58.0		

Field experimental design

The study area was a 278 m^2 (3,000 ft^2) plot divided into 36 separate 4.6 m^2 (50 ft^2) plots (Fig. 1b). These plots were sectioned into 9 rows with 4 columns each (Fig. 1c). There were 12 plots per tillage group, and, prior to soil disturbance and preparation, we sampled soil within each tillage group to establish a baseline. One aggregated sample per tillage group area was collected and analyzed for chemistry using modified Morgan extractable protocols at the Cornell Soil Health Laboratory (Moebius-Clune et al. 2016) and by the MSU Soil and Plant Nutrient Laboratory. Approximately 0.24 m^3 (8.5 ft^3) of compost was incorporated into each plot and analysis was also conducted on the compost.

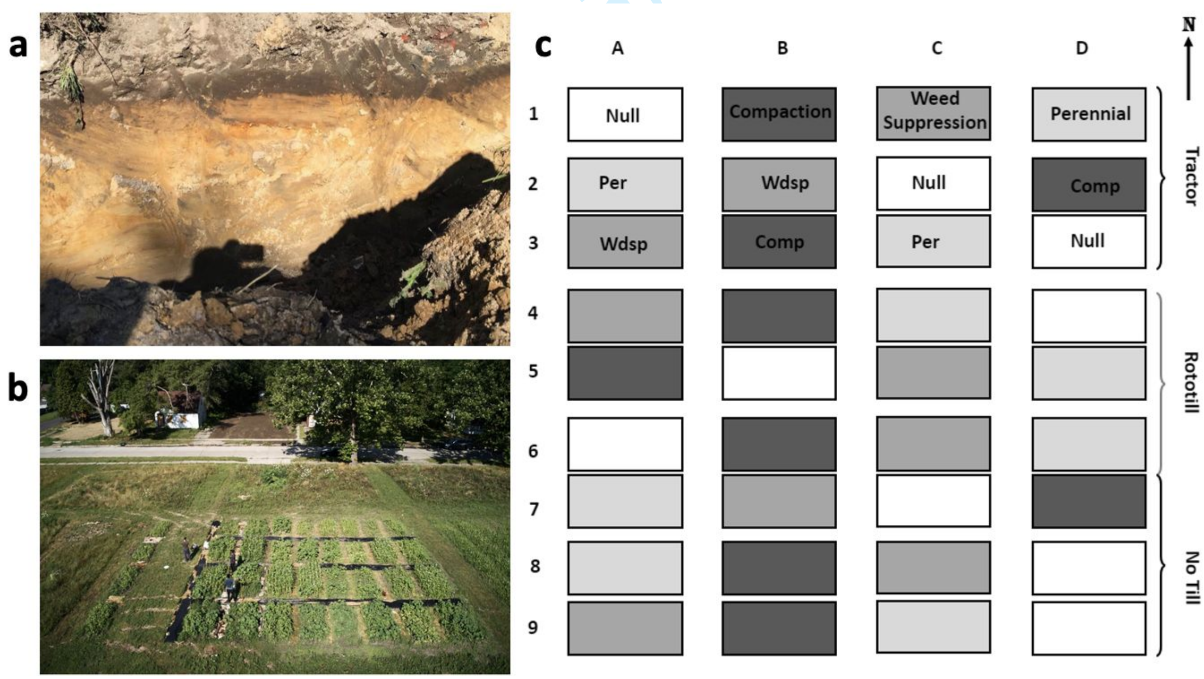

Figure 1. (a) Soil profile of an area near the research plots at the MSU-DPFLI. (b) Research plot five weeks after seeding, and (c) Field layout of plots (1.5 x 3 m^2, or 5 x 10 ft^2) by tillage

group and cover crop mix: Null = no mix added, Compaction (Comp), Weed Suppression (Wdsp), Perennial (Per).

Tillage

Three tillage techniques were tested: 1) no-till with a broadfork (NT) , 2) moderate with a rototiller (RT), and 3) intensive tractor till (TT) with implements. Tractor tilled plots were worked with a subsoiler, moldboard plow, and rototiller attached to a tractor, and rototilled plots were tilled by a BCS two-wheel tractor. These methods represent a spectrum of soil management practices for small scale agriculture. They were selected based on varying tillage philosophies, costs of implementation, and degree of mechanization.

Cover crops

Cover crop mixes were selected based on targeted outcomes associated with specific plant varieties. We tested the performance of three mixes composed of three different plant species (see Table 2). The compaction mix of crimson clover, forage radish, and cereal ryegrass contains plants with roots that penetrate and loosen soil (Williams & Weil 2004). The weed suppression mix consisted of heat- and drought-tolerant crops that grow rapidly, allowing them to outcompete other plants. Lastly, the perennial mix was made up of plants that would survive past one growing season and return in the spring, adding additional biomass and outcompeting early season weeds.

Table 2. Cover crops used in each mix with targeted function for a temperate urban agriculture site.

Name / Function	Cover crop mix
Perennial	Hairy vetch (*Vicia villosa*)
	Red clover (*Trifolium pratense*)
	Wheat (*Triticum aestivum*)
Compaction	Crimson clover (*Trifolium incarnatum*)
	Forage radish (*Raphanus sativus*)
	Cereal Ryegrass (*Secale cereale*)
Weed suppression	Buckwheat (*Fagopyrum esculentum*)
	Cowpea (*Vigna unguiculata*)
	Sorghum-Sudangrass (*Sorghum bicolor x S. bicolor var. sudanese)*
Null	Established vegetation / soil seed bank

Data Collection

Compaction

Compacted soil reduces root growth (Grant, 1993) and is also more susceptible to erosion. Here we used a soil penetrometer to measure compaction within each subplot. Four samples were taken per plot, and the average depth at which the penetrometer read 300 pounds per square inch (psi), or 2 MPa, was recorded. (Beyond 2 MPa is considered hardpan impenetrable by plant roots.) Readings were taken of the depth at which the pressure gauge read 300 psi (2 MPa), which is the maximum pressure at which plant roots are estimated to be able to penetrate the soil (Duiker 2002). Sampling was conducted at two separate time periods: "Early" in July, and "Late" in October. The change in depth per plot indicates changes in soil compaction. Samples were taken on dry days and recorded to the nearest inch.

Infiltration

We measured the water infiltration rate to determine the soil's capacity to drain water. This has implications for managing stormwater runoff and holding water for plant roots. Ultimately, infiltration and patterns in soil water content will have effects on realized yields, although the relationships may not always be straightforward.

The infiltration rate was calculated by recording the amount of time it took for 32 fluid ounces (946 mL) to drain into the soil, which is similar to the amount of typical rainfall on 0.092 m^2 (1 ft^2) per rain event (United States Geological Services, n.d.). We cleared the soil surface of debris and cut vegetation low enough to observe the surface. Then, we pressed a

1.36 kg (48 ounce) aluminum can about one inch deep into the soil and poured the water in. The maximum time allowed was 160 seconds.

Weed density and species richness

We quantified weed species richness and overall density within each treatment by counting how many weed species were present and also identifying the most common species and counting their relative abundance. Weed species richness was measured by counting the number of each species of weeds with ≥ 1 individual in a plot. Weed density was measured as the relative cover of the top 2 most abundant weed species, pigweed (*Palmer amaranth*) and velvetleaf (*Abutilon theophrasti*), using a comparative scale of 0-5 (multiples of ten) with 0 indicating neither species present and 5 indicating 50 or more individuals of either species. Weed richness was estimated as the relative abundance of weed species within a plot using a scale of 1-10 with one indicating only one species observed to ten being ten species present.

Yield

Forage radish (*Raphanus sativus*) roots were measured for length (individually) and wet weight with foliage attached (pooled), and we sampled five radishes per plot. The length of a radish root was measured from the hypocotyl, or root cap, to where the root became 6.35 mm (1⁄4 inch) wide.

Statistical analyses

An Analysis of Variance (ANOVA) was performed on compaction data, averaged by plot, using base functions in RStudio v1.2.1335 (R Core Team 2019). Kruskal-Wallis tests were run on weed abundance, richness, and radish yield data. Statistical tests focused on comparing tillage groups and cover crop mixes and were performed using plot-level means of data subsets with balanced sampling for the variables tested. Specifically, compaction analyses included all cover crop treatments, infiltration analysis focused on weed suppression plots to exclude cases of puddling (i.e. no drainage after 160 sec), and radish yield and root length analysis used compaction plots. This was justified because cover crop mix did not significantly affect compaction, making variation among related data like water infiltration and root growth more dependent on tillage.

RESULTS

Compaction

Tractor tilling significantly reduced compaction ($F_{2, 66} = 47.91$, $p << 0.0001$) by ≥ 50% or 7.6 cm or 3" (to ~20.3 cm or 8" depth) compared to the both other tillage techniques in all cover crop treatments ($t_{2, 66} = 8$, $p < 0.0001$) (Fig. 2). The average depth of compaction was not significantly different between no-till and rototilled plots ($t_{3, 66} = -1.28$, $p = 0.41$). The effects of tilling on compaction were most pronounced for the perennial plant mix, although compaction was not significantly affected by cover crop treatments ($F_{3, 66} = 1.26$, $p = 0.30$). No-till plots had the widest range in compaction depth from approximately 7.6 - 20.3 cm or 3 - 8" and included the most compacted plots. Rototilled plots averaged close to 12.7 cm or 5'' depth to hardpan. Across all treatments, compaction tended to increase by 1.27 - 2.54 cm or 0.5 - 1" between the Early and Late sampling.

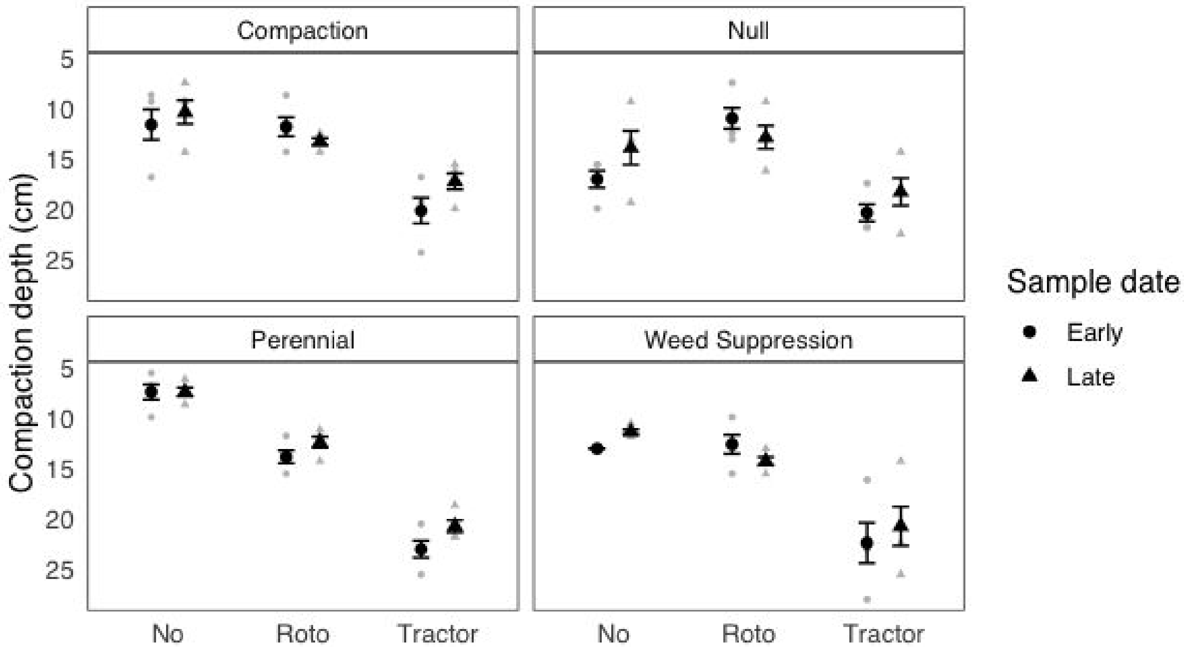

Figure 2. Observed (gray) and mean ±1 SE (black) depths to soil hardpan (measured using a penetrometer for different tillage methods, cover crop treatments (n = 3), and sample dates, in a temperate clayey urban agriculture site.

Infiltration

Infiltration was significantly affected by tillage group ($x^2_2 = 5.81$, p = 0.05), where rototilled plots had the highest rate followed by tractor tilled plots (Fig. 3). No-till plots had the slowest infiltration rates. Each tillage group absorbed water faster during the early (July) sampling date than later in the season (October), with the greatest mean difference 22.18 mL sec^{-1} (~0.75 fl oz sec^{-1}) appearing among rototilled plots. The average infiltration rate in July for rototilled plots drained all of the rain water in close to 30 seconds at 40 mL sec^{-1} (1.35 fl oz sec^{-1}), whereas the no-till and tractor tilled plots required over two minutes. In October (Late), all of the plots required more than two minutes to drain 946.4 mL or 32 oz. During this part of the season, none of the no-till or tractor tilled plots drained the 946.4 mL or 32 oz in the allotted time.

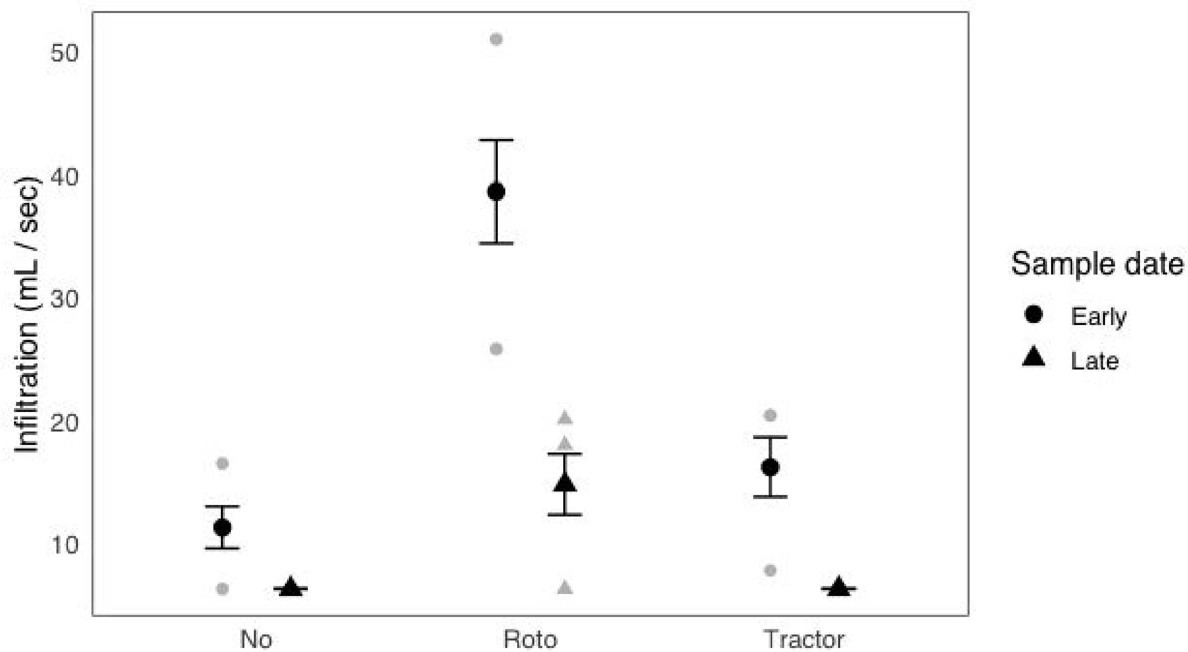

Figure 3. Observed (gray) and mean ±1 SE (black) field soil infiltration rates for different tillage (n = 3) and sample dates, in a temperate clay-rich urban agriculture site.

Weed density and richness

Weed density was significantly affected by cover crop mix ($x^2_3 = 20.07$, p = 0.0002) and significantly by the tillage method ($x^2_2 = 6.47$, p = 0.04) (Fig. 4). Similarly, weed richness was significantly affected by cover crop mix ($x^2_3 = 30.97$, p << 0.0001), yet not by tillage method ($x^2_2 = 1.64$, p = 0.44) (Fig. 3b). The weed suppression cover crop mix had the strongest effect on both weed species density and richness. This mix of sorghum-sudangrass, buckwheat, and cowpea reduced the presence of the two focal common weeds, pigweed (*Palmer amaranth*) and velvetleaf (*Abutilon theophrasti*), regardless of tillage treatment. The perennial cover crop mix seemed to show weed density that increased most consistently with tilling method intensity.

We also monitored weed species presence and diversity in the spring of the following growing season, and the weed suppression mix plots had fewer early season weeds than the other plots as well ($x^2{}_3 = 10.00$, p = 0.02; $x^2{}_2 = 0.17$, p = 0.92). From June to September, the other cover crop mixes did not significantly reduce weed pressure and actually performed similarly to our null group plots that only had weed seeds in them (Fig. 4). However, the wheat, rye, vetch, and clovers continued to grow from the Fall into the following Spring and did reduce weed presence compared to the null group in the spring. Thus, although the other mixes did not reduce weeds in the summer or warm season, they were more effective at suppressing cool season weeds.

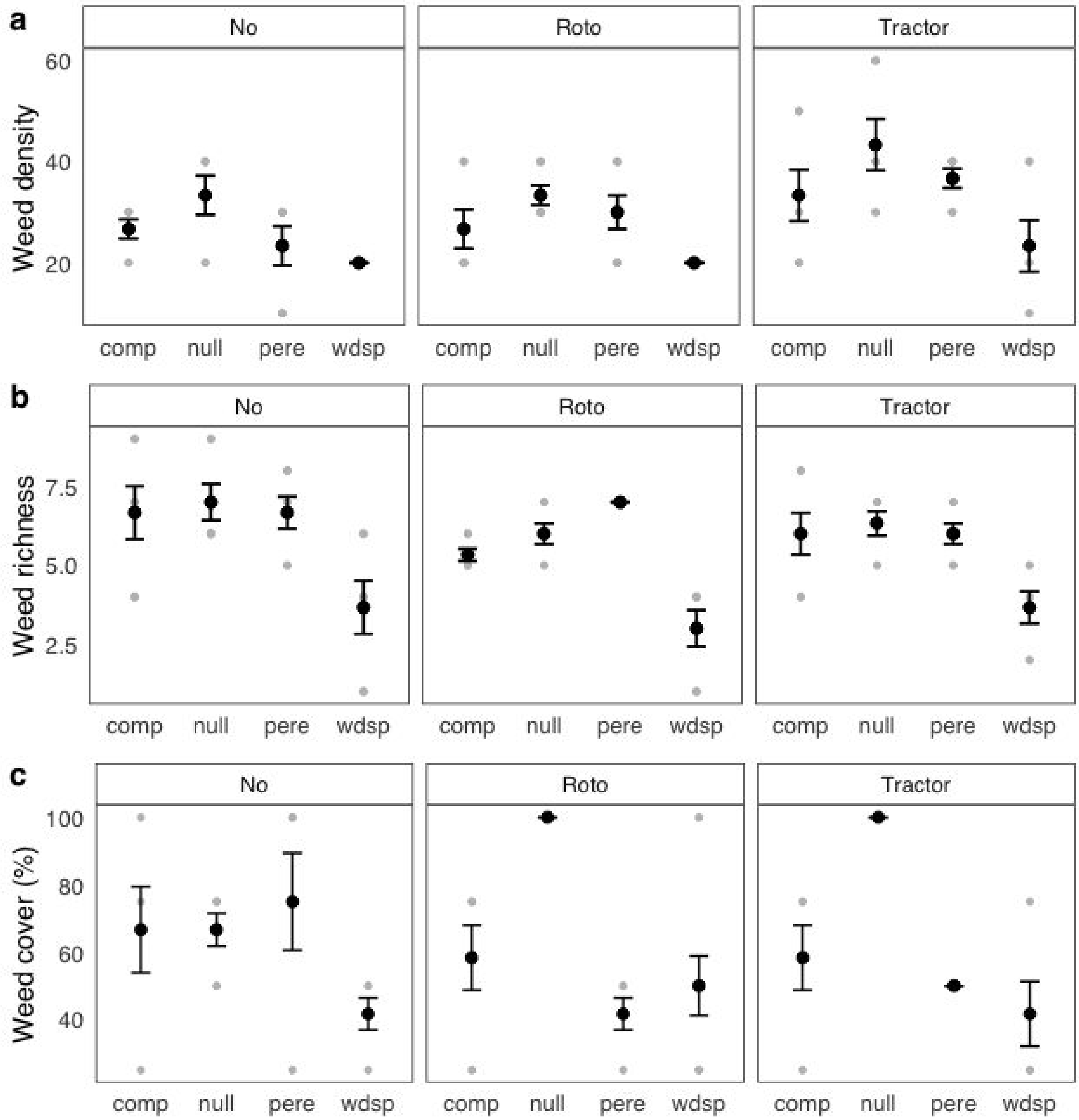

Figure 4. Observed (gray) and mean (black) ±1 SE (a) density, and (b) richness of weed species per plot from different cover crop and tillage treatments ($n = 3$) in a temperate clay-rich urban agriculture site. Density is the frequency of the two most abundant weed species: pigweed (*Palmer amaranth*) and velvetleaf (*Abutilon theophrasti*). Richness is the diversity (number) of different weed species within a plot. "comp": compaction; pere: perennial; wdsp: weed suppression.

Forage Radish Weight and Root Length

Average forage radish plant weight and root length did not vary significantly among tillage treatments ($x^2_2 = 1.44$, p = 0.49; $x^2_2 = 2.87$, p = 0.24). However, radish plants did tend to grow the largest in no-till plots (Fig. 5). The longest radishes grew close to 21.6 cm or 8.5 inches, and the average length of all sampled radishes was 11.68 cm or 4.6 inches. Forty percent of radishes sampled grew past the average compaction depth 11.43 cm (4.5 inches) in the no-till and tractor till plots.

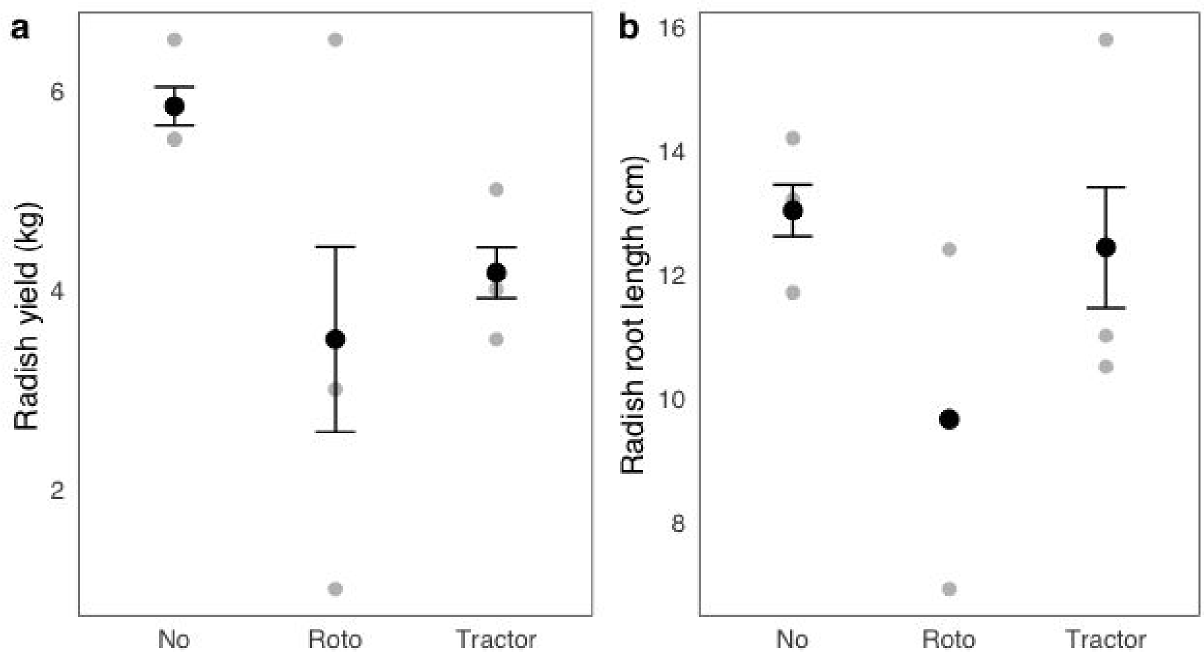

Figure 5. Observed (gray) and mean (black) (a) yield, and (b) maximum root length of forage radish from different tillage treatments in a temperate clayey urban agriculture site.

DISCUSSION

Our data indicated that tilling significantly reduced compaction over a single growing season in both rototilled and tractor tilled plots (Fig. 1). However, several no-till plots reached similar depths to rototilled plots, which suggests rototilling is not significantly more effective than no-till at reducing compaction. Forage radish plant weight with foliage responded better in no-till plots that rototill and tractor tilled plots and average weights in the tilled groups were similar . This was supported by detecting significantly higher radish yields in no-till compared to rototill and tractor till plots, while simultaneously measuring faster infiltration in rototill plots. We also observed significant suppression of weed species diversity and overall density in the cover crop mix plots named for that targeted function, showing that the weed suppression mix used in this study can directly be applied in soils like these.

Tillage

Two reasons for tilling soil are reducing compaction and killing weeds. In this experiment, both tractor and rototilling reduced compaction, loosening soil at lower depths than the no-till method (Fig. 2). Tractor tilling with a subsoiler, moldboard plow, and rototiller likely created a high soil disturbance from the soil surface to depths as low as 30.48 cm or 12 inches. The data show that greater levels of soil disturbance increased the density of the two most common weeds, velvet leaf (*Abutilon theophrasti*) and pigweed (*Palmer amaranth*), and decreased the diversity of other weed species (Fig. 4).

The results show that the intensity of tillage corresponds negatively to compaction depth. This effect also lasts throughout the growing season, even though the average depth of compaction tended to decrease over the growing season (Fig. 2). Specifically, tractor tilled soils appeared to have a greater loss in compaction depth compared to no-till soils. This is probably a combination of the natural tendency for clay soils to increase in compaction over time and weather conditions, limiting plant root penetration of soil to depths that would maintain soil looseness (Boswell et al. 2020) Our data align with our previous predictions and other studies (Özpinar & Çay, 2005).

Depending on what crops are grown, addressing compaction may not be an immediate issue. Multiple crops have shallow root systems or are harvested before roots grow over 10.16 cm or 4 inches into the soil. If crops do not require deep root systems, a no-till method may suffice (Krause & Black, 1995), eliminating the time, energy, and costs of tilling. An important observation for urban soil management was that rototilling and tractor tilling in particular exposed and removed debris from soil that would have remained in place with a no-till system. The debris consisted of construction materials like rebar, wires, cables, bricks, cinder blocks, and pipes as well as other refuse.

Finally, the reduction in compaction in the rototilled plots (Fig. 2) may indicate that plant roots from both cover crops and weeds can reduce compaction. Over multiple seasons, if crops with deep root systems are used, tilling may loosen soils at lower depths and facilitate deeper roots to establish more quickly than no-till. Roots that penetrate to lower depths in soil allow plants to increase their access to nutrients and the water (Arshad, 1990).

Infiltration

Soil's ability to absorb water is critical for stormwater management, minimizing erosion, and making water available to plant roots. Rototilled plots had the fastest infiltration early in the growing season (Fig. 3). This coincides with predictions compared to no-till plots, but is the opposite of what we expected when compared to more deeply disturbed tractor tilled plots. This may be explained by how compost was incorporated into the plots.

For the no-till plots, compost was simply mulched on the surface, and after passing through this layer, water accumulated on the more compacted layer beneath. In rototilled plots, compost was incorporated into the top six inches creating a more porous soil with organic matter throughout. Compost in the tractor tilled plots was mixed in deeper than the other two treatments and may have become too sparse. Thus, these more clayey soils were not porous enough to infiltrate water at high rates. The infiltration rate decreased regardless of tillage treatment between the sampling dates, which was consistent with the pattern of increased compaction throughout the season. The rate was so slow in the no-till and tractor till plots that these soils were draining less than one hundredth of a gallon in one minute. This suggests that most water from a one inch rain event would result in runoff. We posit that maintaining porosity and deeper compaction depths will allow soils to infiltrate water at rates that can absorb 2.54 cm or 1 inch rain events. Based on our findings, rototilling and incorporating additional compost, may be an effective method to improve water infiltration during the driest time of year. Rototilling disturbed the soil enough to reduce compaction, but not to the extent where organic matter was lost or highly dispersed.

Weed suppression

Overall weed density tended to be highest in tractor-tilled plots (Fig. 4). This was likely due to increased soil disturbance exposing seeds in the soil seed bank and creating open space for weeds to emerge. Higher weed density is an additional downside to the tillage of similar soils by tractor, along with lower infiltration rates. Regardless of tillage treatment, the weed suppression mix of sorghum-sudangrass, buckwheat, and cowpea significantly reduced both weed density and species richness by more than a factor of two in some plots compared to the other cover crop mixes. This result is supported by recommendations from other studies that pair buckwheat and sorghum-sudangrass (Smith et. al, 2015). Weed richness may have decreased due to competitive exclusion by sorghum-sudangrass via allelopathy, and by buckwheat via better phosphorus mining and use (Jabran 2017; Zhu et al. 2002).

The weed suppression mix can be utilized to frame crop beds, keeping out encroaching weeds, or to reduce weed pressure in an area that will be planted in the fall or following season. The buckwheat and sorghum-sudan grass grows quickly in poor soils and even dry conditions. These plants accumulate a lot of biomass, which allows them to shade out weeds. They also can be mowed to prevent re-seeding and winter-kill, making them easier crops to manage than crops that require more maintenance. This experiment was designed to require no management after seeding (i.e. no irrigation, weeding, or mowing). Under these conditions, most of the cover crops did not perform well, and were probably inhibited by the warm and dry summer conditions. Crops in other mix treatments used here usually prefer to be sown in the cooler early season (United States Department of Agriculture, 2015). This experiment highlighted crops could be used in clayey soils under these conditions: forage radish, buckwheat, cowpea, and sorghum-sudangrass. Aside from reducing weeds for crop production, weed suppression can reduce pollen counts and the likelihood of direct contact with people (Katz et al. 2014; Katz & Carey 2014). In urban areas this has implications for serving communities where asthma and respiratory illness is common, as well as preventing exposure to weeds that may cause irritation. Under managed landscapes could have cover crops sowed to alleviate some of these urban issues.

Yield and root length

Forage Radish tended to grow the most in no-till plots, which was unexpected based on the higher compaction in these plots. We posit that the radishes benefited from having more access to the nutrients in the compost that was simply mulched on the top two inches of the no-till plots. The compost in the other tillage treatments was incorporated throughout the soil of other plots and less available. It was also surprising that yield did not correspond with faster infiltration, since no-till plots had slower infiltration compared to rototilled plots. This suggests a more nuanced relationship between infiltration and root crop yield unlike the relationship between infiltration and compaction. Yield responds more to more stable or longer-term reservoirs of water and nutrients, such as those in mulched compost, than to shorter-term or more transient influxes brought by infiltration processes (Schlegel & Havlin 2017). Furthermore, more stable reservoirs of water and nutrients may also foster more productive associations with soil microbes, which serve as an additional source of available nutrients for plant roots. In these cases, soil microbe availability might depend less on pH. These data suggest that similar alternative soil management practices like no-till combined with compost and mulching application gives better yields. Thus, forage radish can be an effective cover crop in reducing compaction and building soil structure, with minimal or no mechanical tillage (Chen, 2010). Our study also warrants future studies on the processes tying yield to land management in similar soils.

ACKNOWLEDGEMENTS

Hidden for submission.

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