Mixing cover crops suppresses weeds and roto-till improves urban soil compaction and infiltration

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Abstract

Urban soils have been degraded by decades of industrial activities, but they also represent opportunities to improve food sovereignty for urban residents practicing urban agriculture. Urban growers often use varying practices of compost, tillage, and cover cropping, but without distinguishing their benefits to optimize integrated approaches. This study examined how tillage methods representing various intensities and cover crop mixes targeting different functions affected agricultural variables including soil compaction, water infiltration rate, herbaceous weedy plant pressure, and crop yield. Results showed that both roto- and tractor-till significantly affected compaction but not yield compared to no-till, and roto-till also improved infiltration, while tractor-till reached deeper soils but allowed denser weed growth. Mixing sorghum-sudangrass, buckwheat, and cowpea cover crops significantly reduced weed pressure compared to other mixtures, and perennials affected compaction but not soil water infiltration under no-till. These results reveal that medium-intensity tillage may offer more balanced trade-offs for initial management, and that cover crops can help reduce weeds under low-till strategies. Overall this study offers evidence detailing effects of various tillage and cover crop styles that can be of use for smallholder urban growers.

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Keywords: urban agriculture; soil compaction; weed suppression; roto-till, cover crop mix; soil infiltration

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Highlights:

- Roto-till improves urban soil compaction and infiltration vs. no-till
- Tractor-till improves compaction but not infiltration and also increases weeds
- Cover crop mixes suppress weeds
- Forage radish yield not affected by till or cover crop mixes
- Roto-till and cover crop mixes help improve soils for urban agriculture

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1 Introduction

Urban soils have the potential to improve the livelihoods of most of the world *(Acuto et al., 2018)* via implications for climate adaptation, erosion and storm-water runoff management, and local forestry *(Pavao-Zuckerman, 2008)*, but many urban soils are in poor health for cultivation after decades of industrial use, including sealing and structural engineering *(Lal et al., 2015)*. This is especially notable in post-industrial cities of the mid-western USA, where many vacant lots remain on soils can have relatively high compaction, pH, and chemical contamination *(Beniston et al., 2016)*. Degraded urban soils with low organic matter are also likely far from organic carbon saturation *(Stewart et al., 2007)*, making the potential benefit from tailored agricultural management large *(Kumar and Hundal, 2016; Kuzyakov and Zamanian, 2019)*. However, popular single strategies like organic compost amendments to urban gardens, while widely beneficial across many physical, chemical, and biological properties *(Cogger, 2005)*, can also have other side effects like excess phosphorus *(Small et al., 2019)*, which highlights the benefits of new and ongoing research studies of urban soil management, especially of integrated approaches for soil multi-functionality *(Blesh, 2017)* including cover cropping, tillage, diverse mulching, and others. In response to various needs, urban agriculture continues to expand as local communities and non-profit organizations revitalize and establish a diversity of new green initiatives including landscaping to improve local access to healthy food and a cleaner and safer environment *(Block et al., 2012; Clendenning et al., 2016; García-Sempere et al., 2019; Siebert, 2020).* Urban growers in particular often invest relatively large amounts of money, time, and resources from accessible capital into amending soils for vegetable production *(pers. comms.)*, thereby improving the potential impact of research for promising accessible urban soil remediation strategies, which remains limited beyond compost *(Grossman, 2003).*

Mechanized tilling has long been a regular strategy improve short-term arability, among others like adding compost, although research studies increasingly report soil degradation after long-term and intensive tillage. Short-term tillage benefits include larger soil pores and lower soil bulk density *(Badalíková, 2010; Hill et al., 1985)*, and potentially more available nutrients *(Wolkowski, 1990)* with less potential weed regeneration *(Barberi and Lo Cascio, 2001; Cordeau et al., 2020)*, making tillage useful against soil compaction and associated water infiltration and drainage issues, which can facilitate faster seeding and crop establishment early in the season *(Monti et al., 2001).* However, longer-term side effects of excessive and/or very intensive tillage include weaker soil aggregate stability and structure *(Catania et al., 2018; Six et al., 2002)*, increasing dependence on tillage to maintain past yields *(de Cárcer et al., 2019)*, and faster soil erosion *(Richter, 2021)*, which has more recently led to events like the USA Dust Bowl, and historically poses an existential threat to agricultural societies when combined with other stressors *(Amundson et al., 2015; Lal, 2007; Montgomery, 2007).* In response, sustainable and regenerative agriculture theories promote no-till or minimal-till management approaches like broadfork tools to re-focus on soil health and fertility *(Roger-Estrade et al., 2010; Wang et al., 2006)*, which comes with different challenges like stronger pressure from weeds *(Anderson, 2007)*, highlighting a role for continuing research into diverse no-till strategies. For urban growers, machinery can also be cost-prohibitive, and limited access to agricultural loans *(Daniel, 2007)* has resulted in affected communities adapting by organizing equipment sharing systems, which can be more practical in denser urban housing arrangements compared to diffuse rural ones. This variation in accessibility of machinery can promote mixed tillage strategies by urban growers including tractor- and/or roto-till, which likely have different effects on soil and weed issues, but there remains little public documentation comparing benefits of various tillage styles on remediating urban soils *(Bazzoffi, 1998; Materechera, 2009)*, which slows the innovation of tailored management strategies for the array of urban grower goals.

Cover cropping has been another long-recommended strategy of sustaining longer-term yields by maintaining soil fertility *(Perez, 2021; Richter, 2021)*, although current strategies could be improved from relying on single species to designing complementary species mixes. The namesake benefit of cover crops is to cover the soil in areas without active cultivation, which maintains root activity and weakens erosion *(García-González et al., 2018)*, but different species will also vary in the benefits they can provide based on physiological traits. For example, legumes like cowpea (or black-eyed peas, *Vigna unguiculata subsp. unguiculata*), clovers (*Trifolium sp.*), and hairy vetch (*Vicia villosa*) are popular cover crops because of their additional symbioses with root bacteria that fix nitrogen from the air into soils where it is more available for future crop use *(Grossman et al., 2005)*. Similarly, buckwheat helps scavenge soil phosphorus *(Possinger et al., 2013)*, which is often a limiting macro-nutrient in clay soils *(Mori et al., 2022)*, and could also be combined with compost that is usually high in phosphorus to address recurring soil phosphorus deficiencies. Other plants, including grasses like sorghum (*Sorghum bicolor*), tend to grow deep roots, or have other traits like allelopathic chemical defenses, that compete with weeds enough to keep them suppressed over time *(Weston et al., 1989)*. Broader implications of cover cropping also include higher soil organic matter, though the underlying processes remain complex *(King, 2020)*, and few studies show direct correlations between soil organic matter and yield *(Oldfield et al., 2019)*.

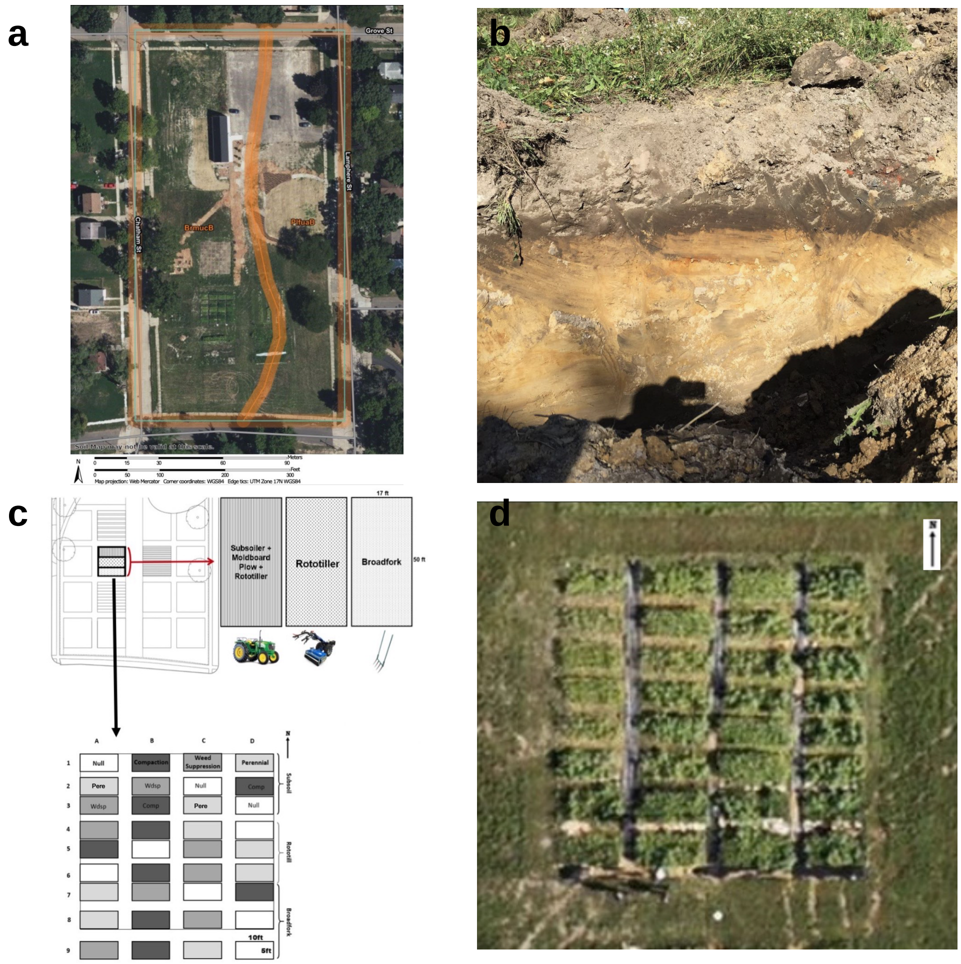
Furthermore, while large rural organic farms can benefit from incorporating specifically-chosen cover cropping into their mechanized operations, the reliance of urban agriculture more on labor over machinery offers an opportunity to develop new cover cropping systems that combine seeding and terminating different species together to improve the potential efficiency of soil remediation efforts. For example, sorghum, cowpea, and buckwheat could be combined into a mixed strategy that can increase soil nitrogen, soil phosphorus, and suppress weeds via deep and shallow roots with allelopathic chemical defenses, although cover crop synergisms generally remain understudied *(Bedoussac et al., 2015; Bourke et al., 2021; Mead and Riley, 1981)*. An integrated complex approach to optimizing cover cropping systems including interspecific species interactions are well-posed to be validated by research studies in urban agriculture followed by adaptation to rural agriculture, and even international implications *(Stewart et al., 2013)*.

In this study, we investigated how different tillage techniques and cover crop species mixes affect soil physical properties and yield. Tillage methods ranged from high disturbance using a tractor and implements to minimal disturbance with a broadfork. Cover crop species mixes were selected based on target functions including reducing compaction, suppressing weeds, and perenniality, or potential for sustainable re-growth. We hypothesized that both tillage and cover crop mixing would confer similar benefits to soil functions, which would translate to weed pressure and yield. Accordingly, we predicted that roto-till, a moderate soil disturbance, would best balance compaction and weed pressure benefits, deepening where soil hardpan layers occur that limit root penetration, and thereby increase soil water infiltration rates, and also reduce weed cover, density, and diversity. We also expected that the cover crop mix designed against soil compaction would have the deepest soil harpan depth and highest water infiltration rates compared to other mixes, mostly due to the deeper rooting potential by forage radish (*Raphanus sativus var. longipinnatus*) and ryegrass (*Secale cereale*). Finally we expected that the cover crop mix designed for weed suppression would experience the lowest local weed cover, density, and diversity, due to allelopathic chemical defense traits from buckwheat (*Fagoprum esculentum*) and surghum-sudangrass (*Sorghum bicolor x Sorghum bicolor var. sudanese*).

2 Methods

2.1 Site

The study site was located at the Michigan State University (MSU) - Detroit Partnership for Food, Learning, and Innovation (DPFLI) (42.4, -83.3), a 1.6-ha (4 acres) extension facility dedicated to urban agriculture and engaging with local small-scale growers in Detroit, MI, USA. The climate is temperate with four seasons, with mean annual temperature of ~9.5 C (49.1 F) and precipitation at ~787 mm (31 in) (ncdc.noaa.gov). The site was formerly a school building and associated playground until 2016 when it was demolished after closing due to low funding and the land became vacant. The habitat is ~1.2 km (~0.8 mi) away from a small river, conferring some wetland ecosystem properties like denser soils. It is also surrounded by sealed sidewalk and small roads on all four sides, which likely affects runoff and drainage



patterns (Fig ??a).

Site soils can be classified as Technosols (Fig ??b), given that large metal artifacts can be found throughout various profiles *(FAO, 2014)*, from when the area was filled in with nearby soils during highway road construction, as was common in mid-western USA industrial manufacturing cities many decades ago in the *1960s (Beniston et al., 2016).* Accordingly, the growing area has both a finer- and coarser-textured side (Fig ??a), and this study was done on the side with consistent clay of ~37%. Topsoil A horizons are 1-2” (<5 cm) deep, and subsoil B horizons can be >30.5 cm (1 ft) deep, with a muted yellow color 10YR 8/4 (Fig ??b). A baseline site-level soil lab assessment from Cornell determined that the top *4 in (10 cm)* of soils around the site together have relatively good organic matter at ~2.5 ± 0.3% and nutrient levels, including concentrations of heavy metals like lead and arsenic *(data not shown)* which were present below harmful government human-contact standards (cfpub.epa.gov/ecotox).

The soils were also assesed to have decent but sub-optimal CO_2 respiration rates of 0.2 ± 0 mg per day (Table ??). Some main concerns limiting productivity include high alkaline pH of 8.1 ± 0.1, lowering availability of existing nutrients, as well as weak aggregate stability of 19 ± 4.4, leading to concerns with aeration, infiltration, rooting, crusting when dry, erosion, and runoff (Table ??).

Table 1: Baseline Soil Health Assessment (Cornell, Ithaca, NY, USA)

Variable	Median (n=10)	Deviation	Descriptor
Organic Matter (%)	2.5	0.3	Very Low
Respiration (mg per day)	0.2	0.0	Medium
Aggregate Stability (%)	19.0	4.4	Very Low
pH	8.1	0.1	Poor
Phosphorus (ppm)	2.2	1.0	Medium
Potassium (ppm)	103.8	36.3	Optimal
Iron (ppm)	6.0	4.4	Optimal
Magnesium (ppm)	463.6	24.9	Optimal
Manganese (ppm)	42.1	4.9	Optimal
Zinc (ppm)	3.8	2.9	Optimal
Heavy metals (Pb, Al, As, Cu)	-	-	Safe

2.2 Design

The study area was a 278 m^2 (2992.4 ft^2) section on the East side of the site that was divided into 36 separate 4.6 m^2 (49.5 ft^2) plots in nine rows and four columns (Fig ??c). Tillage groups spanned the nine columns in adjacent groups of three, while cover crop mix treatments spanned the rows with one row per cover crop mix, totaling 26 plots, or 12 plots per tillage group and nine plots per cover crop mix. Before applying treatments, approximately 0.2 m^3 (8.5 ft^3) of compost was incorporated into each plot.

One aggregated sample per tillage group was collected and analyzed for chemistry using modified Morgan-extractable protocols at the MSU soil test lab (moebius-clune16?) and analysis was also conducted on the compost.

Tillage treatments represented methods of increasing intensity available for small scale agriculture, also varying in cost, machinery needed, and sometimes grower preferences *(Drugova et al., 2022)*. Specifially, treatments included no-till with a broadfork *(NT)*, roto-tiller *(RT)*, and tractor-till *(TT)* with implements. Tractor-till plots were worked with a subsoiler, moldboard plow, and roto-tiller attached to a tractor up to 30.5 cm (1 ft) deep. Roto-till plots were treated with a rototiller implement up to 20 cm (7.9 in) deep. Lastly, no-till plots were worked with only a broadfork up to 10 cm (3.9 in) deep. All tilling was done once early in the season after compost application.

Cover crop mixes were designed primarily based on plants associated with targeted benefits, and as possible, relative simplicity of re-seeding and winter-kill (e.g. more heat tolerant) *(Clark, 2007)*. Three mixes were designed to target three functions, with each mix containing three different plant species (Table **??**). The mix designed to alleviate compaction generally focused on plants with roots that tend to penetrate and loosen soil well, and ultimately included crimson clover (*Trifolium incarnatum*), forage radish (*Raphanus sativus*), and cereal ryegrass (*Secale cereale*) . The mix targeting weed suppression included heat- and drought-tolerant crops that tend to grow rapidly, allowing them to outcompete other plants–the taxa chosed were sorghum-sudangrass (*Sorghum bicolor x Sorghum bicolor var. sudanese*), cowpea/black-eyed pea (*Vigna unguiculata subsp. unguiculata*), and buckwheat (*Fagopyrum esculentum*). Lastly, a mix was dedicated to perennial cover crops, which in contrast to annuals can survive the winter and thus tend to accumulate biomass and establish before spring weeds–this mix included hairy vetch (*Vicia villosa*), red clover (*Trifolium pratense*), and wheat (*Triticum aestivum*). We also had a null control group consisting of established vegetation within the plot, where no additional seeds were sown.

Table 2: Cover crop mixes

Function	Plants	Binomial
Weed Suppression	Sorghum-Sudangrass	Sorghum bicolor x S. bicolor var. sudanese
	Cowpea/Black-Eyed Pea	Vigna unguiculata subsp. unguiculata
	Buckwheat	Fagopyrum esculentum
Perennial	Hairy Vetch	Vicia villosa
	Red Clover	Trifolium pratense
	Wheat	Triticum aestivum
Compaction	Forage Radish	Raphanus sativus var. longipinnatus
	Crimson Clover	Trifolium incarnatum
	Cereal Ryegrass	Secale cereale
Null	Existing vegetation (no manipulation)	-

2.3 Sampling

Soil compaction was measured with a penetrometer *(AgraTronix #08180)* in four randomly selected spots within each quarter of every plot, as the depth where resistance was 2 MPa (290.1 psi, $lbs\ in^{-2}$), which is considered hardpan that roots typically cannot penetrate *(Correa et al., 2019)*. Measurements were recorded to the nearest *2.5 cm (1 inch)* on dry days in July and October 2019.

Soil water infiltration down to 11.1 cm *(8.75 in)* depth was measured using a 16.5 *(9.5 in)* wide aluminum cylinder, and recording the time up to 160 sec for *1 L (32 fl oz)* to pass through, which represented a typical rainfall amount onto ~0.10 m^2 (~1 ft^2) of soil area (waterdata.usgs.gov).

Weed pressure was measured using percent cover, richness, and density, following similar studies *(Storkey and Neve, 2018)*. Weed cover was estimated as the total proportion of plot area covered by any weed biomass, descretized into intervals of ten. Weed richness, a measure of diversity, was recorded by counting the number of unique morphospecies observed in each plot. Finally, weed density was measured as the number of stems of either of the two most abundant weed taxa, pigweed (*Amaranthus viridis*) and velvetleaf (*Abutilon theophrasti*), also descretized into intervals of ten up to 50 stems per plot.

Five forage radish (Brassica *Raphanus sativus var. longipinnatus*) roots were randomly selected from each plot in the compaction treatment and measured for length, individually, and wet weight, as a cluster. The length of a radish root was measured from the hypocotyl, or root cap, to where the root became ~6.3 mm (~1/4 in) wide.

2.4 Statistics

Field space limited strict plot replication for combined treatments (n=3), and thus inference from advanced nested mixed models *(Silk et al., 2020)*, so analysis focused on specific hypotheses tested using simpler, more conservative non-parametric tests that make few underlying assumptions about data and thus appropriate for data with lower replication. Kruskal-Wallis tests were run for tillage and cover crop treatments separately, with alpha corrections from 0.05 to 0.01 under multiple comparisons to descriptively parse any treatment interactions, and overall significant treatment effects were followed up by post-hoc Wilcoxon pairwise tests with Holm-corrected p-value adjustments. All data were centered at plot-level medians, often more robust than means, and where applicable pooled across sampling times given no preliminary significant variation along this axis, together with minimal relevance to focal hypotheses in field studies *(Davies and Gray, 2015)*, and was a general solution to uneven sampling across response variables, minimally increasing statistical power (base

n > 3-6). For clarity, results figures were designed to reflect statistical models and grouping transparently. Significant treatment effect sizes were estimated with eta^2 *(Tomczak and Tomczak, 2014)* and simpler raw median differences at finer pairwise levels. All calculations and analyzes were done in R version 4.2.0 (2022-04-22) *(R Core Team, 2022)* with useful functions from the packages *tidyverse* 1.3.1 *(Wickham et al., 2019)*, *rstatix* 0.7.0 and *ggpubr* 0.4.0 *(Kassambara, 2021)*. Data and code are stored at nmedina17.github.com/must, documented using R packages *here (Müller, 2020)*, *bookdown (Xie, 2022a)*, *measurements (Birk, 2019)*, *taxize (Chamberlain et al., 2020)*, *knitr (Xie, 2022b)*, and *rmarkdown (Allaire et al., 2022)* .

3 Results

3.1 Compaction

Compaction was affected significantly overall by tillage treatments (H = 38.2, df = 2, n = 72, p = <0.0001) by ~52.4 % across cover crop treatments (Fig 1a). Tractor-till had the largest significant effect on depth to hardpan compared to no-till (p_{adj} = <0.0001), deepening the depth to hardpan by ~9.4 cm (3.7 in, or ~83.3%) compared to no-till, down to ~20.6 ± 4.6 cm (8.1 ± 1.8 in) across all cover crop mixes. Roto-till also had a marginally significant effect on depth to hardpan compared to no-till (p_{adj} = 0.1), deepening the depth to hardpan by ~9.4 cm (3.7 in, or ~83.3%) compared to no-till, down to ~13.8 ± 1.9 cm (5.4 ± 0.7 in). The overall effect from tillage stemmed from significant effects among the perennial (p_{adj} = *<0.01*) and weed suppression (p_{adj} = *<0.01*) mixes (Fig 1a). The effect of roto-till was more pronounced in the perennial mix (p_{adj} = *<0.01*), where depth to hardpan was about twice as deep as in no-till plots (Fig 1a). There was also a significant difference of ~6.9 cm (2.7 in, or ~50%) between tractor- and roto-till among all cover crop mixes (Fig 1a).

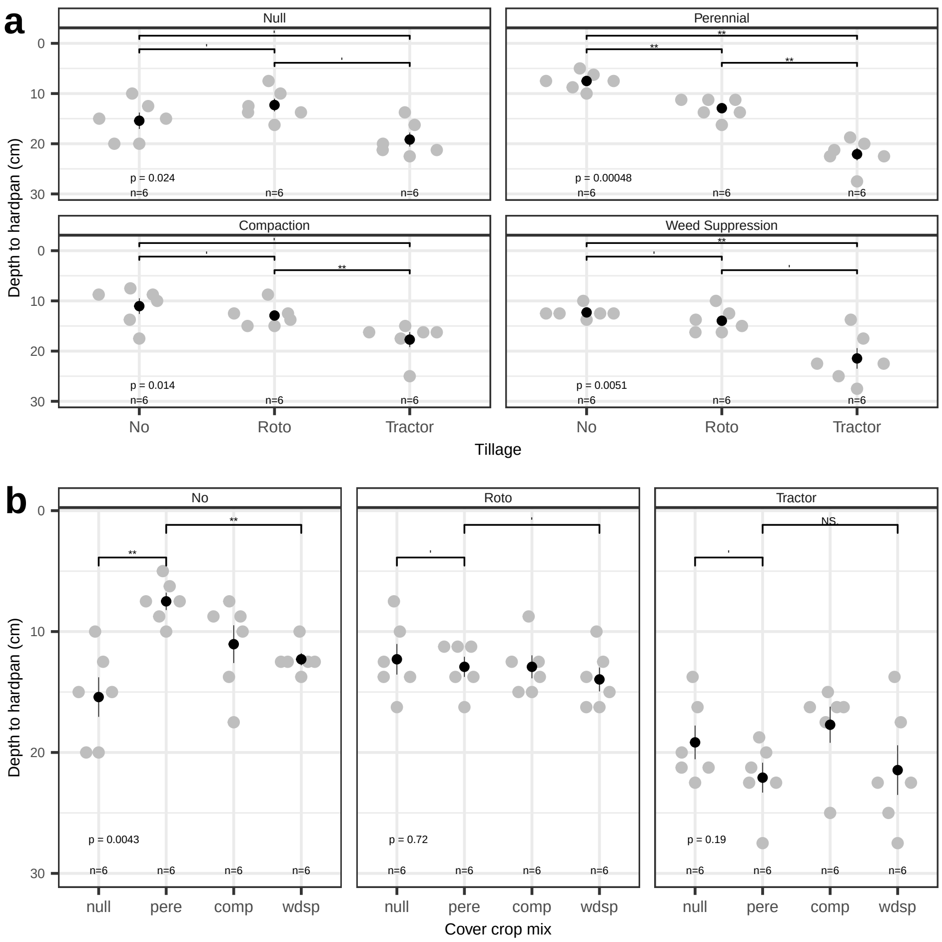


Figure 1: Compaction data (a) by tillage, and (b) cover crop mix. Gray dots show plot medians and black point ranges show group mean ± 1 std error and may be small. Significant pairwise post-hoc Wilcoxon test outcomes shown (**** $p < 0.0001$, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, *' $p < 0.1$, ' $p > 0.1$ or NS)

Compaction was not affected by cover crops among tillage groups overall ($H = 2$, $df = 3$, $n = 72$, $p = 0.57$), but was significantly affected by cover crops specifically under no-till conditions ($df = 3$, $n = 6$, $p_{adj} = <0.01$) (Fig 1b). Under no-till, the perennial mix had significantly shallower depth to hardpan compared to both null ($p_{adj} = <0.01$) and weed suppression mixes ($p_{adj} = <0.01$), raising the depth to hardpan by ~2.5 cm (1 in, or ~16.7%) compared to each mix, up to ~12.5 ± 7.4 cm (4.9 ± 2.9 in) below the soil surface (Fig 1b).

3.2 Infiltration

Soil infiltration was significantly affected by tillage ($H = 8.5$, $df = 2$, $n = 48$, $p = 0.01$) and marginally significantly by cover crop mix ($H = 5.9$, $df = 3$, $n = 48$, $p = 0.1$) (Fig 2). Roto-till had significantly faster infiltration compared to no-till ($p_{adj} = 0.027$) and marginally significantly compared to tractor-till ($p_{adj} = 0.1$), speeding up infiltration by ~14.5 % compared to each tillage groups, up to ~ 13.4 ± 10.7 mL per sec (0.2 ± 0.2 gal per min) (Fig 2a).

3.3 Weed pressure

Weed density was overall significantly affected by tillage ($H = 6.5$, $df = 2$, $n = 72$, $p = 0.039$) by ~25.1 %, although weed cover ($H = 0.2$, $df = 2$, $n = 36$, $p = 0.92$) and richness ($H = 1.6$, $df = 2$, $n = 72$, $p = 0.44$) were not (Fig 3a). Weeds under tractor-till were marginally significantly denser compared to no-till ($p_{adj} = 0.059$) and roto-till ($p_{adj} = 0.11$), denser by ~6.5 % compared to each tillage group, up to ~ 7.6 ± 1.6 *stems per* m^{-2} .

All measured weed variables were affected significantly by cover crop mix, including weed density ($H = 20.1$, $df = 3$, $n = 72$, $p = 0.00016$) changing overall by ~6.5 %, weed cover ($H = 31$, $df = 3$, $n = 72$, $p = <0.0001$) changing overall by ~-0.5 % , and weed richness ($H = 10$, $df = 3$, $n = 36$, $p = 0.019$) changing overall by ~-5.5 % (Fig 3b). The weed

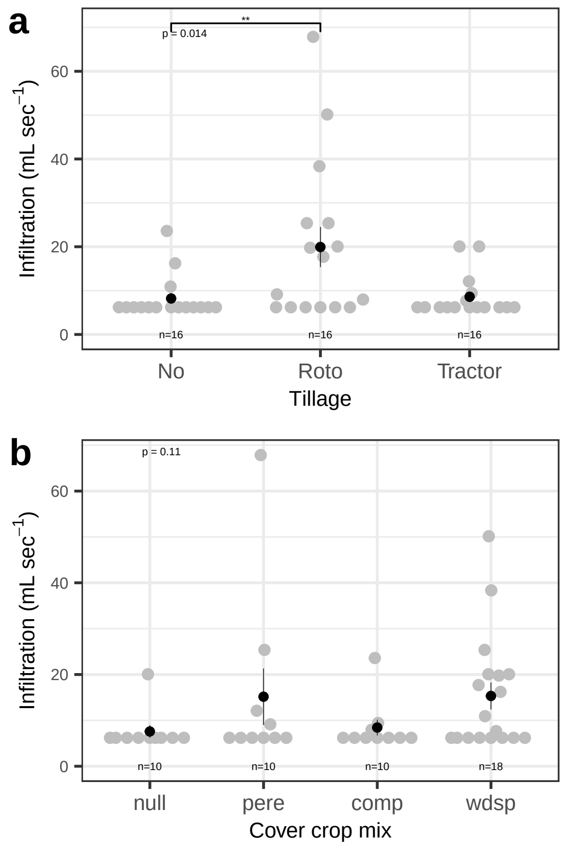


Figure 2: Infiltration data (a) by tillage, and (b) cover crop mix. Gray dots show plot medians and black point ranges show group mean ± 1 std error and may be small. Significant pairwise post-hoc Wilcoxon test outcomes shown (**** p < 0.0001, *** p < 0.001, ** p < 0.01, * p < 0.05, *' p < 0.1, ' p > 0.1)

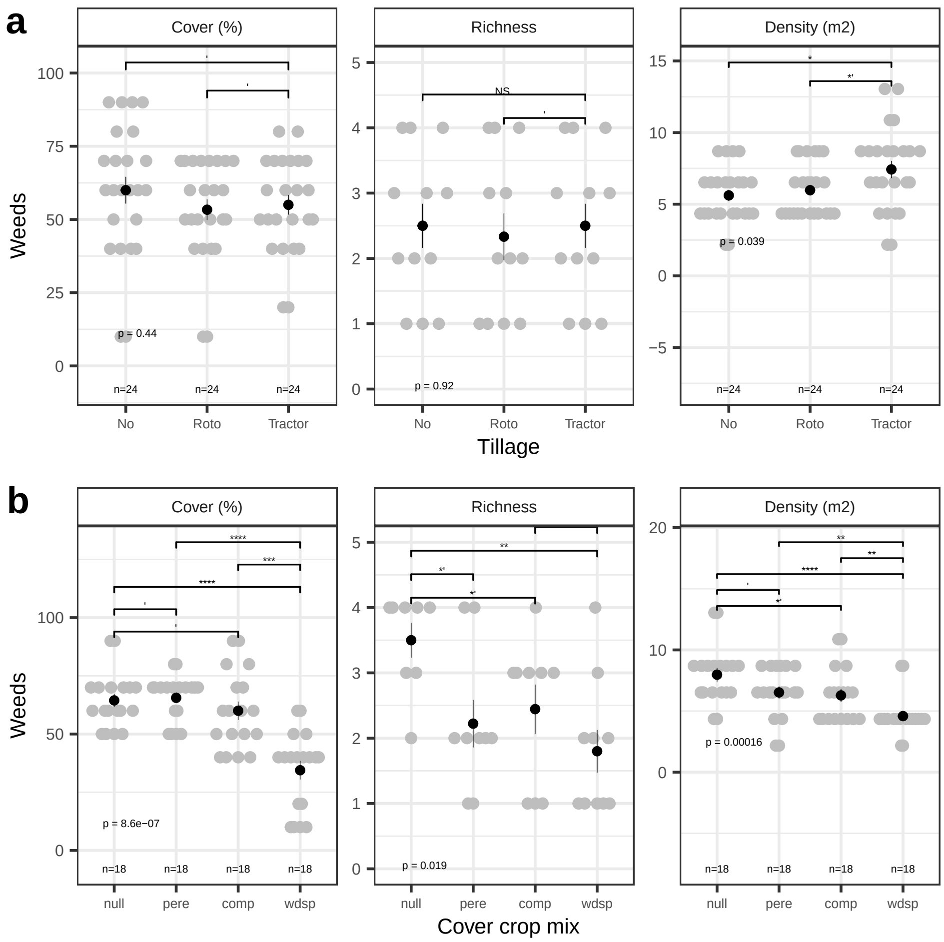


Figure 3: Weeds data (a) by tillage, and (b) cover crop mix. Gray dots show plot medians and black point ranges show group mean ± 1 std error and may be small. Significant pairwise post-hoc Wilcoxon test outcomes shown (**** p < 0.0001, *** p < 0.001, ** p < 0.01, * p < 0.05, *' p < 0.1, ' p > 0.1 or NS)

suppression mix had the most detectable effects on both weed density and cover. The weed suppression mix significantly lowered weed density compared to all other cover crop mix treatments, namely the null (p_{adj} = 2e-04), perennial ($p_{adj} = 0.017$), and compaction ($p_{adj} = 0$) mixes, by ~-4.3 *stems m*$^{-2}$ (-6739.4 *stems in*$^{-2}$, or ~-50%), down to ~ 4.3 ± 0 *stems per m*$^{-2}$. The weed suppression mix also significantly lowered weed cover compared to all other cover crop mix treatments, namely the null ($p_{adj} = <0.0001$), perennial ($p_{adj} = <0.0001$), and compaction ($p_{adj} = 0.00093$) mixes, by ~20 *stems m*$^{-2}$ (3.1×10^4 *stems in*$^{-2}$, or ~33.3%), down to ~ 40 ± 14.8% . Finally, the null mix showed significantly higher richness compared to the weed suppression mix ($p_{adj} = 0.03$) and marginally significantly compared to perennial ($p_{adj} = 0.1$) and compaction ($p_{adj} = 0.2$) mixes, up to ~ 4 ± 0 %. –> –> –> –> –> –>

3.4 Yield

Radish yield was not significantly affected by tillage ($H = 1.4$, $df = 2$, $n = 8$, $p = 0.5$), and centered at ~ 67.8 ± 0 *g m*$^{-2}$ (0.1 ± 0 *lbs m*$^{-2}$) and ~ 13.2 cm (5.2 in) long (Fig 4).

4 Discussion

Overall this study informs urban soil management by supporting the use of tillage to address compaction issues and improve infiltration, together with cover crops to also reduce weed pressure. Our hypothesis was partially supported, because overall tillage significantly deepened the depth to hardpan by ~0.5 (Fig 1a), which was within the range of effect sizes measured among the various cover crop mixes within the no-till treatment (Fig 1b). Additionally, infiltration was significantly affected by tillage, with roto-till showing the fastest rates (Fig 2a), which agreed with our predictions. Furthermore, weed pressure was significantly affected by both cover crop mixes and tillage (Fig 3), although effects from cover crop

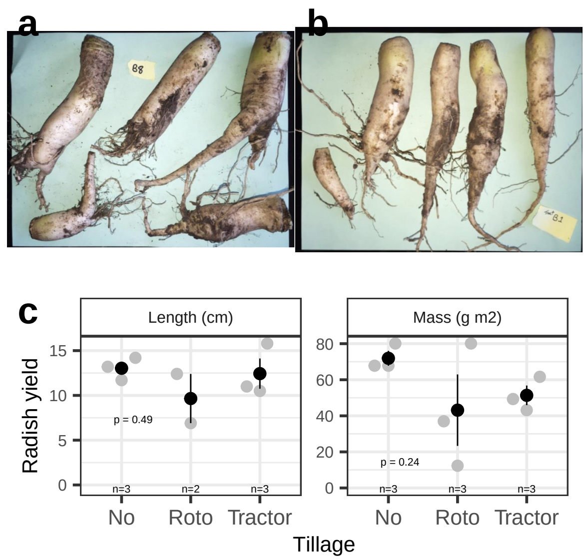


Figure 4: Yield data (a) from no-till, (b) tractor-till, and (c) all tillage groups. Gray dots show plot medians and black point ranges show group mean ± 1 std error and may be small. Photo credits: Naim Edwards.

mixes, especially the weed suppression mix, were more widespread among multiple measured variables (Fig 3b). Despite these significant effects on soils, infiltration, and weeds, yields did not respond to tillage treatments.

Short-term soil compaction issues are commonly alleviated by annual tilling *(Badalíková, 2010; Salem et al., 2015)*, and in addition to validating this practice, this study showed that cover cropping can also be used to manage compaction under no-till, although effects vary by mixture of taxa used. Under tillage, this study validates that tillage intensity corresponds negatively with compaction (measured as depth to hardpan), and additionally clarifies that tractor-till can alleviate compaction in slightly deeper soils below main root zones under ~20.6 ± 4.6 cm (8.1 ± 1.8 in), as well as that roto-till can be useful under perennial crops, although under annuals, no-till can be just as effective as roto-till, saving grower time, energy, and cost for areas with crops harvested before rooting surpasses *~10 cm (4 in) (Krause and Black, 1995)*. However for urban technosol soils, tilling can beneficially remove large metal artifacts and legacy construction debris like rebar, wires, cables, bricks, cinder blacks, and pipes, all of which could limit root growth under strict no-till management. Tillage might also obscure cover crop effects on compaction, although cover crops may still provide other benefits, like soil macro-nutrients *(Chapagain et al., 2020)*. Under no-till, this study found that perennial crop mixes can have significant effects on compaction, but rather than deep roots loosening soils, in some cases depth to hardpan can instead become shallower. This may be due to dense root mats that can form under grasses *(Douglas et al., 1992)* like sorghum-sudangrass, which could further fill already limited pore space in densely-structured clay soils, helping water to pool under the soil surface *(Hoogmoed and Bouma, 1980)*. Overall other studies have found similar results *(Ozpinar and Cay, 2006)*, suggesting short-term benefits of tillage to soil functions (yet long-term costs).

Water infiltration is a key function to improve urban soil functioning for agriculture by minimizing erosion and improving root available water, as well as mitigating storm-water runoff and potentially contaminated flooding *(Masoner et al., 2019)* that often occurs after short heavy rains, due to soil sealing by concrete near hillslopes *(Dreelin et al., 2006)*. This study found that roto-till resulted in significantly faster infiltration compared to no-till, unlike tractor-till, suggesting that roto-till management can generally be effective for improving infiltration and drainage. This result could be explained by medium intensity roto-till increasing soil macro-porosity, which compared to soil micro-pores bind water less tightly allowing to flow faster *(Gerke, 2006)*. In contrast, the tractor diffused tillage energy across deeper soil volume, lowering the density of any added soil macro-pores and thereby making it easier for soil particles to settle back together, whereas no-till may have needed more time to improve macro-porosity via organic matter effects on soil structure *(King, 2020)*. It is also possible that this result could be explained by compost incorporation, where tractor-till similarly incorporated compost more diffusely throughout the soil profile, diluting any compost benefits to infiltration. Against a one inch rain event, this study supported the use of roto-till, but not no-till or tractor-till, which showed rates of only ~ 6.2 ± 0 mL per sec (0.1 ± 0 gal per min), which would likely result in runoff pooling in roads and soil erosion. Regarding cover crops, this study suggests that cover crop mixes can generally affect infiltration, though specifically perennials may not have notable significant effects on infiltration rates, despite detectable effects on compaction. Based on these findings, roto-till together with compost may be an effective strategy to improve urban soil water infiltration in the short-term, even if no-till may appear to have more evidence as a longer-term strategy *(Cusser et al., 2020).*

Weed suppression is important for reducing competition with crops as well as asthma and respiratory health risks from pollen *(Katz and Carey, 2014)*, and can also be achieved by tilling *(Barberi and Lo Cascio, 2001; Cordeau et al., 2020)*, but this study additionally suggests that cover crops may be more likely to be effective. Tractor-till, while able to combat relatively deep soil compaction, resulted in the highest weed density of the two most common weeds, velvet leaf (*Abutilon theophrasti*) and pigweed (*Palmer amaranth*), whose root density may have also slowed soil water infiltration rates. This may have been due to fast-growing weed life histories taking advantage of looser soil, such as to re-sprout clonally, and/or looser soil facilitating the establishment of weed seed banks *(Hesse et al., 2007).* However more notably, the targeted weed suppression mix of sorghum-sudangrass, buckwheat, and cowpea significantly reduced both weed density and richness by about half compared to the other cover crop mixes. This result agrees with other studies pairing buckwheat and sorghum-sudangrass *(Smith et al., 2015)*, and may have occurred due to competitive exclusion by sorghum-sudangrass and/or buckwheat via allelopathic chemical root defenses *(Weston et al., 1989)* or competition for light *(Liu et al., 2009)*, better phosphorus mining and use by buckwheat *(Zhu et al., 2002)*, facilitation or amplification of these previous effects by cowpea's added nitrogen supply *(Martins et al., 2003; Sanginga et al., 2000)*, and/or existing adaptations to poor dry soils *(Bàrberi et al., 2018)* allowing high biomass accumulation. Given both effectiveness and relative ease of re-seeding and winter-kill, this weed suppression mix can be used to frame crop beds, keeping out encroaching weeds, or to reduce weed pressure in an area that might be planted in the fall or following season.

Despite overall significant effects by tillage on compaction, infiltration, and weeds, tillage did not significantly affect radish yield. As is, this study does not rule out more complex relationships between soil compaction, infiltration, and crop yield, as suggested by emerging ideas *(Ryan et al., 2007; Vandermeer and Perfecto, 2017)*. However, with further replication, it is possible that no-till would show slightly higher yields, validating some similar studies *(Nunes et al., 2018)*. Overall yields can respond more to longer-term reservoirs of water and nutrients like mulched compost compared to shorter-term, transient influxes brought by infiltration processes *(Schlegel et al., 2015; Schlegel and Havlin, 1995)*. As a result, it is possible that similar alternative soil management practices like no-till combined with compost and mulching application may lead to better yields, although the translation of no-till benefits to soil structure *(Du et al., 2015; Sheehy et al., 2015)* on yield are not guaranteed *(Martínez et al., 2016)* nor do they appear to be widespread *(Pittelkow et al., 2015; VandenBygaart, 2016)*. Additionally, other studies suggest that forage radish can be an effective cover crop in reducing compaction and building soil structure, with minimal or no mechanical tillage *(Chen and Weil, 2010; Lawley et al., 2011)*. However ultimately this study suggests the need for future studies of processes tying yield to land management strategies particularly in similar urban clay soils with legacy compaction and pH concerns under smallholder management and possibly including occassional tillage *(Blanco-Canqui and Wortmann, 2020; Ekboir, 2001)*.

Taken together, this study presents data that, in addition to validating previous studies supporting general tillage for short-term soil fertility, also supports the partial use of medium-intensity roto-till and cover crop mixtures *(Chapagain et al., 2020)* specifically for weed suppression. This study serves as a model demonstration of both widely accessible and effective strategies for growing on re-purposed urban soils after urban land-use turnover. We advocate for the maximal use of cover crop mixes for various target functions, with medium-intensity tillage to jump-start urban cultivation.

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6 Author contributions

NE conceived, designed, and performed the study; NE and NM collected data; NM analyzed data; NE and NM wrote the paper; NE, NM, and EA revised the paper.

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8 Declaration of interests

Authors declare no conflicts of interest.

9 Data statement

Data and code available at nmedina17.github.com/must.

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