

¹ Mixing cover crops suppresses weeds and roto-till
² improves urban soil compaction and infiltration

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⁹ **Keywords:** urban agriculture; soil compaction; weed suppression; roto-till, cover crop mix;
¹⁰ soil infiltration

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¹⁶ **Highlights:**

- ¹⁷ • Roto-till improves urban soil compaction and infiltration vs. no-till
- ¹⁸ • Tractor-till improves compaction but not infiltration and also increases weeds
- ¹⁹ • Cover crop mixes suppress weeds
- ²⁰ • Forage radish yield not affected by till or cover crop mixes
- ²¹ • Roto-till and cover crop mixes help improve soils for urban agriculture

²² Abstract

²³ Urban soils have been degraded by decades of industrial activities, but they also represent
²⁴ opportunities to improve food sovereignty for urban residents practicing urban agriculture.
²⁵ Urban growers often use varying practices of compost, tillage, and cover cropping, yet fur-
²⁶ ther integrated approaches could facilitate by model analyses of how different practices
²⁷ may compare or complement each other. This study examined how tillage methods repre-
²⁸ senting various intensities and cover crop mixes targeting different functions affected agri-
²⁹ cultural variables including soil compaction, water infiltration rate, herbaceous weedy plant
³⁰ pressure, and crop yield. Results showed that both roto- and tractor-till significantly af-
³¹ fected compaction but not yield compared to no-till, and roto-till also improved infiltration,
³² while tractor-till reached deeper soils but allowed denser weed growth. Mixing sorghum-
³³ sudangrass, buckwheat, and cowpea cover crops significantly reduced weed pressure com-
³⁴ pared to other mixtures, and perennials affected compaction but not soil water infiltration
³⁵ under no-till. These results reveal that medium-intensity tillage may offer more balanced
³⁶ trade-offs for initial management, and that cover crops can help reduce weeds under low-till
³⁷ strategies. Overall this study offers evidence detailing effects of various tillage and cover
³⁸ crop styles that can be of use for smallholder urban growers.

³⁹ **1 Introduction**

⁴⁰ Urban soils could improve the livelihoods of most of the world (*Acuto et al., 2018*) by helping
⁴¹ adapt to climate change, slowing erosion and storm-water runoff management, and promot-
⁴² ing local forestry (*Pavao-Zuckerman, 2008*), however, many urban soils are degraded for
⁴³ agriculture, after decades of industrial use, including sealing and structural engineering (*Lal*
⁴⁴ *et al., 2015*). Urban soil issues are notable in post-industrial cities of the mid-western USA,
⁴⁵ where thousands of vacant lots still show high compaction, pH, and chemical contamination
⁴⁶ (*Beniston et al., 2016*). These degraded urban soils also have low organic matter, but also
⁴⁷ being far from carbon saturation (*Stewart et al., 2007*) can increase potential responses to
⁴⁸ intervention (*Kumar and Hundal, 2016; Kuzyakov and Zamanian, 2019*). Single strategies
⁴⁹ like adding compost are popular, and indeed are beneficial for various physical, chemical, and
⁵⁰ biological properties (*Cogger, 2005*), but they also can have limiting side effects like excess
⁵¹ phosphorus (*Small et al., 2019*), which in turn highlights the benefits of simultaneous strate-
⁵² gies, like cover cropping and occasional tillage, that could better target multi-functionality
⁵³ (*Blesh, 2017; Garbach et al., 2017; O'Riordan et al., 2021; Sircely and Naeem, 2012; Tresch*
⁵⁴ *et al., 2018*). Urban agriculture has spread as a response to diverse community needs (*Lon-*
⁵⁵ *don et al., 2021*), from systemic food insecurity to schooling access and labor imbalances,
⁵⁶ and also widely engages non-profits, politicians, and individuals in environmental steward-
⁵⁷ ship addressing public health issues like pollution (*Block et al., 2012; Clendenning et al.,*
⁵⁸ *2016; García-Sempere et al., 2019; Siebert, 2020*). Community-led infrastructure governing
⁵⁹ vacant land additionally means that urban growers invest much of their personal money,
⁶⁰ time, and other limited resources into lot preparation for initial cultivation (*Daftary-Steel et*
⁶¹ *al., 2015*), but often need to move ahead with varying models of holistic approaches (*Gross-*
⁶² *man, 2003*) to jump-starting cultivation in urban soils with industrial legacy effects (*Wade*
⁶³ *et al., 2021*), jeopardizing regionally high yields (*McDougall et al., 2019*).
⁶⁴ Mechanized tilling is one strategy that can offer short-term benefits, but also at the cost

of long-term soil health, especially as mechanical intensity increases. In the short term, tilling can improve soil porosity to lower soil bulk density (*Badalíková, 2010; Hill et al., 1985*), improve nutrient availability (*Wolkowski, 1990*), and control weeds (*Barberi and Lo Cascio, 2001; Cordeau et al., 2020*), thereby also likely improving water infiltration and drainage that can facilitate faster seeding and early crop establishment (*Monti et al., 2001*). However, in the long term (i.e. over five years), soil aggregates can weaken (*Catania et al., 2018; Six et al., 2002*) lead to faster soil erosion (*Richter, 2021*), eventually increasing grower dependency on intense tillage to maintain previous yields (*de Cárcer et al., 2019*), all of which resemble causes of the USA Dust Bowl and even the fall of ancient civilizations (*Amundson et al., 2015; Lal, 2007; Montgomery, 2007*). To combat degradation, no-till and minimal-till have been supported as sustainable alternatives to industrial agri-business farming (*Roger-Estrade et al., 2010; Wang et al., 2006*), although, continuing research is still needed to address different challenges like more weed pressure (*Anderson, 2007*). Since urban growers already have limited access to machinery (*Daniel, 2007*), yet given the short-term benefits of tillage for quick initial productivity, community sharing systems have been set up for tractors and rotary implements, which can lead to mixed or variable management strategies being adopted for urban soil cultivation, which are in need to further study (*Bazzoffi, 1998; Materechera, 2009*).

Cover cropping is another regenerative agriculture practice with old origins, but whose lasting benefits are increasingly recognized (*Perez, 2021; Richter, 2021*), however, more studies could go beyond single species to complementary species mixtures. Cover crops are named so because they cover fallow soils, also continuing root activity and limiting erosion (*García-González et al., 2018*), but benefits can vary by species used. For example, legumes like cowpea (or black-eyed peas, *Vigna unguiculata* subsp. *unguiculata*), clovers (*Trifolium sp.*), and hairy vetch (*Vicia villosa*) have symbiotic root bacteria that fix nitrogen from the air into soil pores where it becomes bioavailable to plants (*Grossman et al., 2005*). Somewhat similarly, buckwheat (*Fagopyrum esculentum*) helps scavenge soil phosphorus (*Possinger et*

92 *al., 2013*), often a limiting macro-nutrient in clay soils (*Mori et al., 2022*), which could also be
93 combined with phosphorus-rich compost to alleviate recurring soil phosphorus deficiencies.
94 Other plants, including grasses like sorghum (*Sorghum bicolor*) can grow deep roots with
95 chemical defenses, called allelopathy, that harm other weed roots (*Weston et al., 1989*).
96 Overall, cover cropping may also increase soil organic matter through complex processes
97 (*King, 2020*), though few studies show direct correlations between soil organic matter and
98 yield (*Oldfield et al., 2019*). Organic yet industrial farms can benefit from specific cover
99 crops, but their mechanization also limits their use to monoculture, where as small urban
100 agriculture can make use of labor that replaces machinery to study new cover crop mixture
101 designs that could accelerate early cultivation efforts. Cover crop mixtures generally remain
102 understudied empirically in agriculture (*Baraibar et al., 2020; Bedoussac et al., 2015; Bourke
103 et al., 2021; Mead and Riley, 1981*), but it could be hypothesized that combining sorghum,
104 cowpea, and buckwheat together would improve soil nitrogen, phosphorus, and weed control,
105 via their root symbioses and chemical defenses. In general, integrated approaches to small-
106 scale urban agriculture could be useful internationally (*Stewart et al., 2013*), but tailored
107 research that informs grower decision-making remains diffuse.

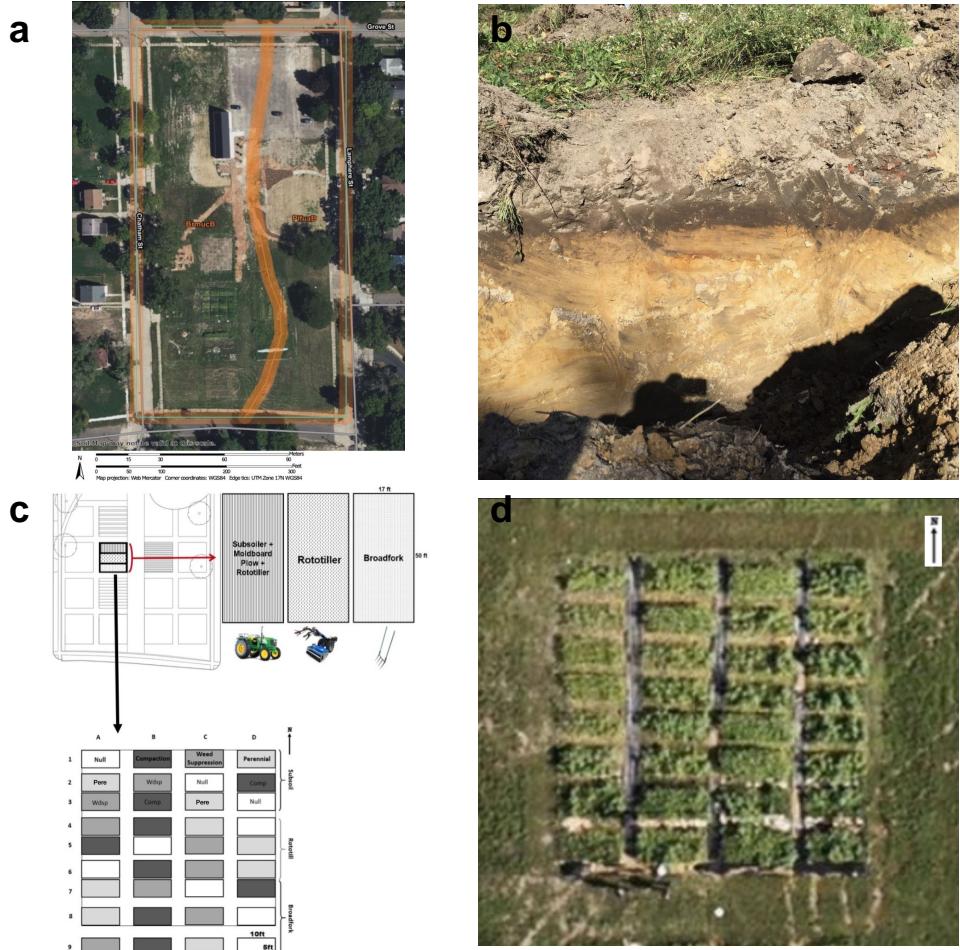
108 In this study, we investigated how different tillage techniques and cover crop species mixes,
109 representing various possible integrated management strategies, affect urban soil functions
110 for agriculture. Tillage methods studied ranged from low intensity using a broadfork to
111 high intensity using a tractor and implements. Additionally, cover crop species mixes were
112 chosen based on target functions including reducing compaction, suppressing weeds, and
113 perenniability (i.e. potential for sustainable re-growth). We hypothesized that both tillage and
114 cover crop mixes would confer similar benefits to soil functions, which would also translate
115 to affect weed pressure and yield. Accordingly, we predicted that roto-till, a moderate-
116 intensity option, would best balance compaction and weed pressure benefits, deepening where
117 soil hardpan layers occur that limit root penetration, and thereby also increase soil water
118 infiltration rates, along with reducing weed cover, density, and diversity. We also expected

¹¹⁹ that the cover crop mix designed against soil compaction would have the deepest depth to
¹²⁰ soil harpan, along with the fastest water infiltration rates compared to other mixes, mostly
¹²¹ due to the deep rooting potential of forage radish (*Raphanus sativus var. longipinnatus*) and
¹²² ryegrass (*Secale cereale*). Finally, we expected that the cover crop mix designed for weed
¹²³ suppression would experience the lowest local weed cover, density, and diversity, due to
¹²⁴ allelopathic chemical defense traits from buckwheat (*Fagopyrum esculentum*) and surghum-
¹²⁵ sudangrass (*Sorghum bicolor x Sorghum bicolor var. sudanese*).

¹²⁶ 2 Methods

¹²⁷ 2.1 Site

¹²⁸ The study site was located at the Michigan State University (MSU) - Detroit Partnership for
¹²⁹ Food, Learning, and Innovation (DPFLI) (42.4, -83.3), a 1.6-ha (4 acres) extension facility
¹³⁰ dedicated to urban agriculture and engaging with local small-scale growers in Detroit, MI,
¹³¹ USA. The climate is temperate with four seasons, with mean annual temperature of ~9.5 C
¹³² (49.1 F) and precipitation at ~787 mm (31 in) (ncdc.noaa.gov). The site was formerly a school
¹³³ building and associated playground until 2016 when it was demolished after closing due to
¹³⁴ low funding and the land became vacant. The habitat is ~1.2 km (~0.8 mi) away from a small
¹³⁵ river, conferring some wetland ecosystem properties like denser soils. It is also surrounded
¹³⁶ by sealed sidewalk and small roads on all four sides, which likely affects runoff and drainage



137 patterns (Fig ??a).

138 Site soils can be classified as Technosols (Fig ??b), given that large metal artifacts can be
 139 found throughout various profiles (*FAO, 2014*), from when the area was filled in with nearby
 140 soils during highway road construction, as was common in mid-western USA industrial man-
 141 ufacturing cities many decades ago in the *1960s* (*Beniston et al., 2016*). Accordingly, the
 142 growing area has both a finer- and coarser-textured side (Fig ??a), and this study was done
 143 on the side with consistent clay of ~37%. Topsoil A horizons are 1-2" (<5 cm) deep, and
 144 subsoil B horizons can be >30.5 cm (1 ft) deep, with a muted yellow color 10YR 8/4 (Fig
 145 ??b). A baseline site-level soil lab assessment determined that the top *4 in* (10 cm) of soils
 146 around the site together have relatively good organic matter at ~2.5 ± 0.3% and nutrient
 147 levels, including concentrations of heavy metals like lead and arsenic which were present
 148 below harmful government human-contact standards (cfpub.epa.gov/ecotox). Site soils were

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

Kind	Variable	Median (n=10)	Deviation	Descriptor
Biological	Organic Matter (%)	2.5	0.3	Very Low
	Respiration (mg per day)	0.2	0.0	Medium
Physical	Aggregate Stability (%)	19.0	4.4	Very Low
Chemical	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

¹⁴⁹ also assessed to have decent but sub-optimal CO_2 respiration rates of 0.2 ± 0.04 mg per day
¹⁵⁰ (Table ??). Initial main concerns limiting productivity include high alkaline pH of $8.1 \pm$
¹⁵¹ 0.1, lowering availability of existing nutrients, as well as weak aggregate stability of $19 \pm$
¹⁵² 4.4, leading to concerns with aeration, infiltration, rooting, crusting when dry, erosion, and
¹⁵³ runoff (Table ??).

¹⁵⁴ 2.2 Design

¹⁵⁵ The study area was a $278 m^2$ ($2992.4 ft^2$) section on the East side of the site under the
¹⁵⁶ former school building that was divided into 36 separate $4.6 m^2$ ($49.5 ft^2$) plots in nine rows
¹⁵⁷ and four columns (Fig ??c). Tillage groups spanned the nine columns in adjacent groups of
¹⁵⁸ three, while cover crop mix treatments spanned the rows with one row per cover crop mix,
¹⁵⁹ totaling 36 plots, or 12 plots per tillage group and nine plots per cover crop mix. Before
¹⁶⁰ applying treatments, approximately $0.2 m^3$ ($8.5 ft^3$) of compost was incorporated into each
¹⁶¹ plot.

¹⁶² Tillage treatments represented methods of increasing intensity available for small scale agri-
¹⁶³ culture, also varying in cost, machinery needed, and sometimes grower preferences (*Drugova*
¹⁶⁴ *et al., 2022*). Specifically, treatments included no-till with a broadfork (*NT*), roto-tiller (*RT*),

¹⁶⁵ and tractor-till (*TT*) with implements. Tractor-till plots were worked with a subsoiler, mold-
¹⁶⁶ board plow, and roto-tiller attached to a tractor up to 30.5 cm (1 ft) deep. Roto-till plots
¹⁶⁷ were treated with a rototiller implement up to 20 cm (7.9 in) deep. Lastly, no-till plots were
¹⁶⁸ worked with only a broadfork up to 10 cm (3.9 in) deep. All tilling was done once early in
¹⁶⁹ the season after one typical compost application and before planting cover crops.

¹⁷⁰ Cover crop mixes were designed primarily based on plants associated with targeted bene-
¹⁷¹ fits, and as possible, relative simplicity of re-seeding and winter-kill (e.g. more heat tolerant)
¹⁷² (*Clark, 2007*). Three mixes were designed to target three functions, with each mix containing
¹⁷³ three different plant species (Table ??). The mix specifically designed to alleviate compaction
¹⁷⁴ generally focused on plants with roots that tend to penetrate and loosen soil well, and ulti-
¹⁷⁵ mately included crimson clover (*Trifolium incarnatum*), forage radish (*Raphanus sativus var.*
¹⁷⁶ *longipinnatus*), and cereal ryegrass (*Secale cereale*). The mix targeting weed suppression
¹⁷⁷ included heat- and drought-tolerant crops that tend to grow rapidly, allowing them to out-
¹⁷⁸ compete other plants—the taxa chosen were sorghum-sudangrass (*Sorghum bicolor x Sorghum*
¹⁷⁹ *bicolor var. sudanese*), cowpea/black-eyed pea (*Vigna unguiculata subsp. unguiculata*), and
¹⁸⁰ buckwheat (*Fagopyrum esculentum*). Lastly, a mix was dedicated to perennial cover crops,
¹⁸¹ which in contrast to annuals can survive the winter and thus tend to accumulate biomass
¹⁸² and establish before spring weeds—this mix included hairy vetch (*Vicia villosa*), red clover
¹⁸³ (*Trifolium pratense*), and wheat (*Triticum aestivum*). We also had a null control group
¹⁸⁴ consisting of established vegetation within the plot, where no additional seeds were sown.

¹⁸⁵ 2.3 Sampling

¹⁸⁶ Soil compaction was measured with a penetrometer (*AgraTronix #08180*) in four randomly
¹⁸⁷ selected spots within each quarter of every plot, as the depth where resistance was 2 MPa
¹⁸⁸ (290.1 psi, *lbs in⁻²*), which is considered hardpan that roots typically cannot penetrate (*Cor-*
¹⁸⁹ *rea et al., 2019*). Measurements were recorded to the nearest 2.5 cm (1 inch) on dry days.

Table 2: Cover crop mixes

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

190 Soil water infiltration down to 10 cm (8.75 in) depth was measured using a 16.5 (9.5 in)
 191 wide aluminum cylinder, set away from dense vegetation and any impeding large roots, and
 192 recording the time up to 160 sec for 1 L (32 fl oz) to pass through, representing a typical
 193 local rainfall onto ~0.10 m² (~1 ft²) of soil area (waterdata.usgs.gov).

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

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

205 Sampling was done in July and October 2019 and the following Spring.

206 **2.4 Statistics**

207 Field space limited strict plot replication for treatment combinations ($n=3$), and thus in-
208 ference from advanced nested mixed models (*Silk et al., 2020*), so analysis focused on spe-
209 cific hypotheses tested using simpler, more conservative non-parametric tests that make few
210 underlying assumptions about data and thus appropriate for data with lower replication.
211 Kruskal-Wallis tests were run for tillage and cover crop treatments separately, with alpha
212 corrections from 0.05 to 0.01 under multiple comparisons to descriptively parse any treatment
213 interactions, and overall significant treatment effects were followed up by post-hoc Wilcoxon
214 pairwise tests with Holm-corrected p-value adjustments. All data were centered at plot-level
215 medians, often more robust than means, and where applicable pooled across sampling times
216 given no preliminary significant variation along this axis, together with minimal relevance
217 to focal hypotheses in field studies (*Davies and Gray, 2015*), and was a general solution to
218 uneven sampling across response variables, minimally increasing statistical power ($n>3\text{-}6$).
219 For clarity, results figures were designed to reflect statistical models and grouping transpar-
220 ently. Significant treatment effect sizes were estimated with η^2 (*Tomczak and Tomczak,*
221 *2014*) and raw median differences at finer pairwise levels. All calculations and analyzes
222 were done in R version 4.2.0 (2022-04-22) (*R Core Team, 2022*) with useful functions from
223 the packages *tidyverse* 1.3.1 (*Wickham et al., 2019*), *rstatix* 0.7.0 and *ggpubr* 0.4.0 (*Kassam-*
224 *bara, 2021*). Data and code are stored at github.com/nmedina17/must, documented using R
225 packages *here* 1.0.1 (*Müller, 2020*), *bookdown* 0.26 (*Xie, 2022a*), *measurements* 1.4.0 (*Birk,*
226 *2019*), *taxize* 0.9.100 (*Chamberlain et al., 2020*), *knitr* 1.39 (*Xie, 2022b*), and *rmarkdown*
227 2.14 (*Allaire et al., 2022*) .

228 **3 Results**

229 **3.1 Compaction**

230 Compaction was affected significantly overall by tillage treatments ($H = 38.2$, $df = 2$, n
231 = 72, $p = <0.0001$) by ~52.4% across cover crop treatments (Fig 1a). Tractor-till had
232 the largest significant effect on depth to hardpan compared to no-till ($p_{adj} = <0.0001$),
233 deepening the depth to hardpan by ~9.4 cm (3.7 in, or ~83.3%) compared to no-till, down
234 to $\sim 20.6 \pm 4.6$ cm (8.1 ± 1.8 in) across all cover crop mixes. Roto-till also had a marginally
235 significant effect on depth to hardpan compared to no-till ($p_{adj} = 0.1$), deepening the depth
236 to hardpan by ~9.4 cm (3.7 in, or ~83.3%) compared to no-till, down to $\sim 13.8 \pm 1.9$ cm
237 (5.4 ± 0.7 in). The overall effect from tillage stemmed from significant effects among the
238 perennial ($p_{adj} = <0.01$) and weed suppression ($p_{adj} = <0.01$) mixes (Fig 1a). The
239 effect of roto-till was more pronounced in the perennial mix ($p_{adj} = <0.01$), where depth
240 to hardpan was about twice as deep as in no-till plots (Fig 1a). There was also a significant
241 difference of ~6.9 cm (2.7 in, or ~50%) between tractor- and roto-till among all cover crop
242 mixes (Fig 1a).

243 Compaction was not affected by cover crops among tillage groups overall ($H = 2$, $df = 3$,
244 $n = 72$, $p = 0.57$), but was significantly affected by cover crops specifically under no-till
245 conditions ($p_{adj} = <0.01$) (Fig 1b). Under no-till, the perennial mix had significantly
246 shallower depth to hardpan compared to both null ($p_{adj} = <0.01$) and weed suppression
247 mixes ($p_{adj} = <0.01$), raising the depth to hardpan by ~2.5 cm (1 in, or ~16.7%) compared
248 to each mix, up to $\sim 12.5 \pm 7.4$ cm (4.9 ± 2.9 in) below the soil surface (Fig 1b).

249 **3.2 Infiltration**

250 Soil infiltration was significantly affected by tillage ($H = 8.5$, $df = 2$, $n = 48$, $p = 0.01$)
251 and marginally significantly by cover crop mix ($H = 5.9$, $df = 3$, $n = 48$, $p = 0.1$) (Fig

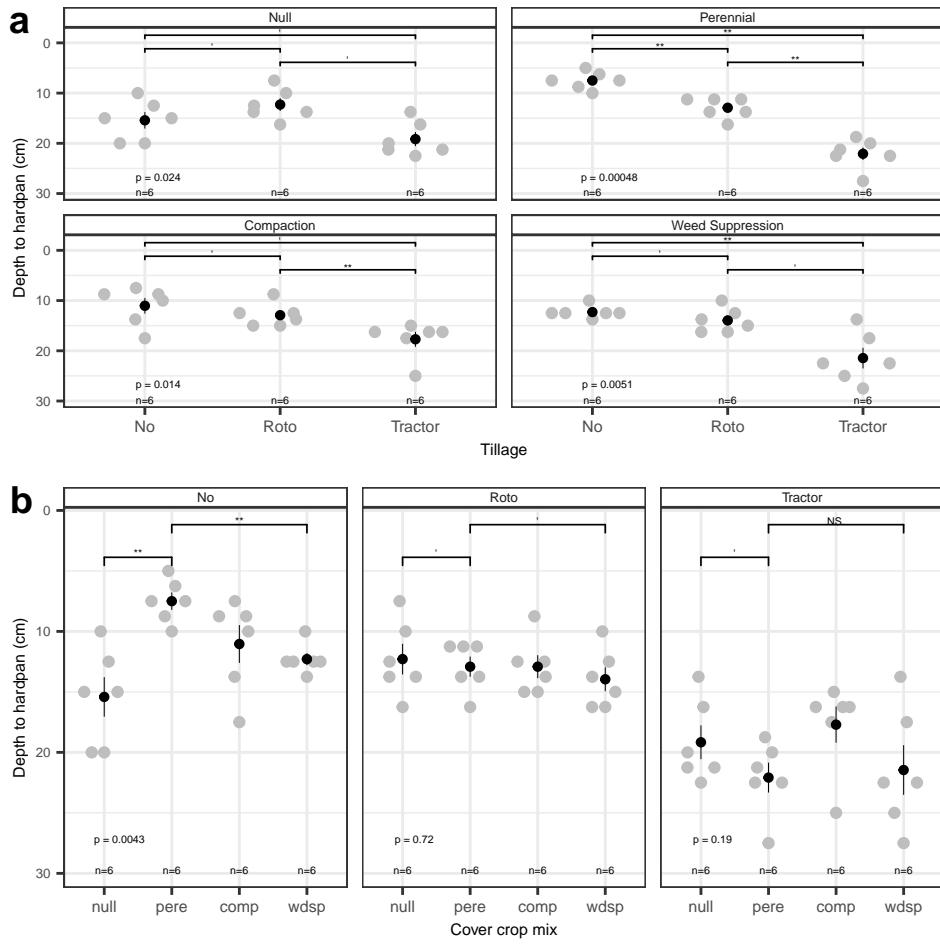


Figure 1: Compaction data (a) by tillage, and (b) cover crop mix. Gray dots show plot medians and black point ranges show group mean \pm 1 std error and may be small. Significant pairwise post-hoc Wilcoxon test outcomes shown (***) $p < 0.0001$, ** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, *, $p < 0.1$,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

252 2). Roto-till had significantly faster infiltration compared to no-till ($p_{adj} = 0.027$) and
 253 marginally significantly compared to tractor-till ($p_{adj} = 0.1$), speeding up infiltration by
 254 $\sim 14.5\%$ compared to each tillage groups, up to $\sim 13.4 \pm 10.7$ mL per sec (0.2 ± 0.2 gal per
 255 min) (Fig 2a).

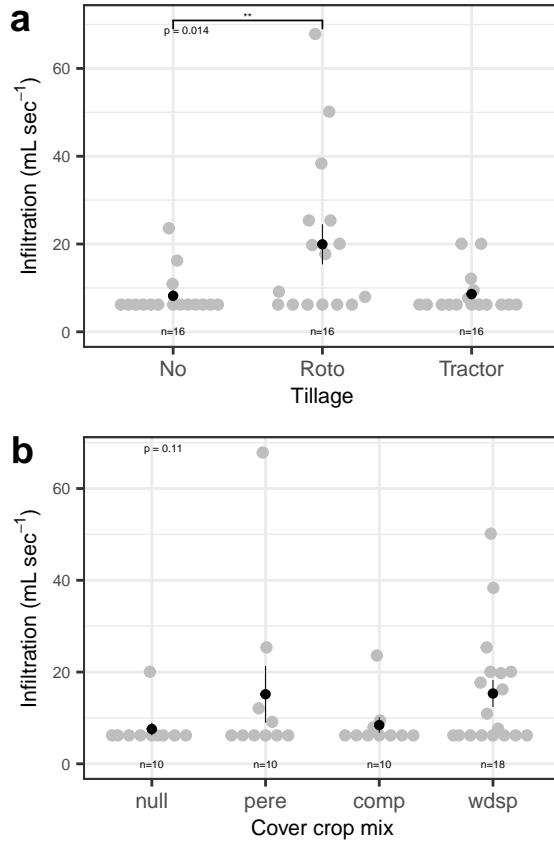


Figure 2: Infiltration data (a) by tillage, and (b) cover crop mix. Gray dots show plot medians and black point ranges show group mean ± 1 std error and may be small. Significant pairwise post-hoc Wilcoxon test outcomes shown (**** $p < 0.0001$, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, * $p < 0.1$,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

256 3.3 Weed pressure

257 Weed density was overall significantly affected by tillage ($H = 6.5$, $df = 2$, $n = 72$, $p =$
 258 0.039) by $\sim 25.1\%$, although weed cover ($H = 1.6$, $df = 2$, $n = 72$, $p = 0.44$) and richness
 259 ($H = 0.2$, $df = 2$, $n = 36$, $p = 0.92$) were not (Fig 3a). Weeds under tractor-till were

significantly denser compared to no-till ($p_{adj} = 0.06$) and marginally significantly compared to roto-till ($p_{adj} = 0.1$), denser by $\sim 6.5\%$ compared to each tillage group, up to $\sim 8 \pm 2$ stems per m^{-2} .

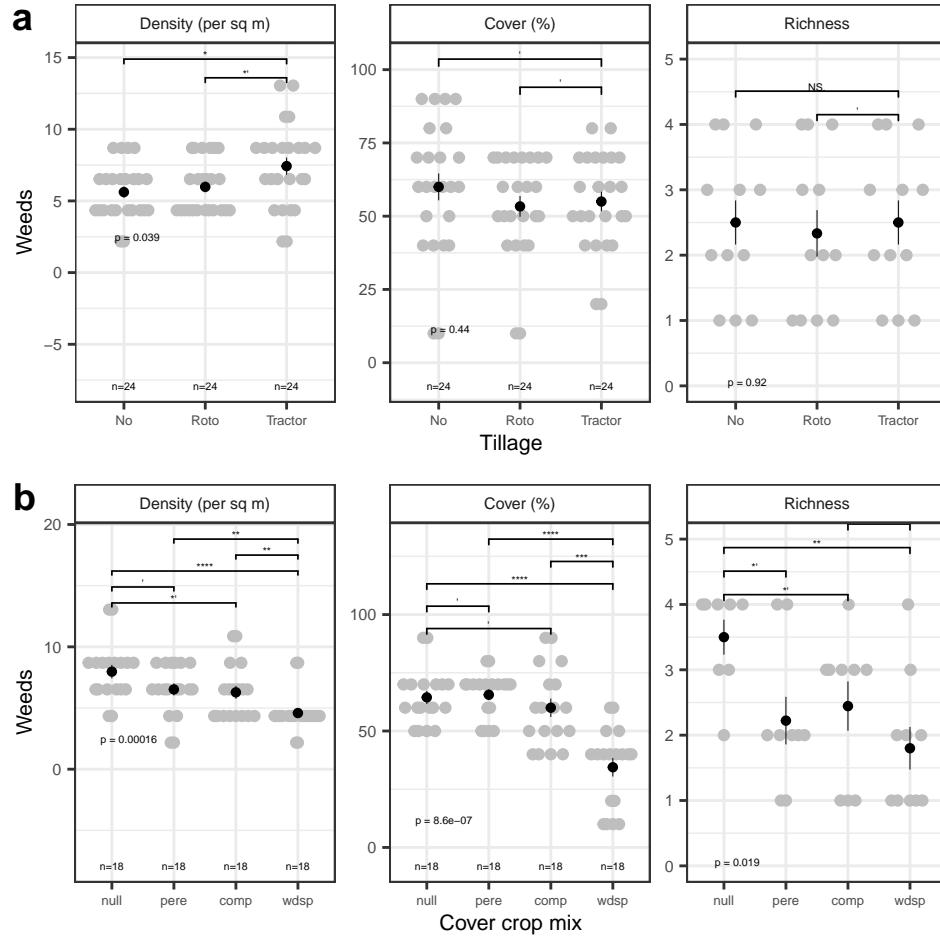


Figure 3: Weeds data (a) by tillage, and (b) cover crop mix. Gray dots show plot medians and black point ranges show group mean ± 1 std error and may be small. Significant pairwise post-hoc Wilcoxon test outcomes shown (***) $p < 0.0001$, (**) $p < 0.001$, (*) $p < 0.01$, (*) $p < 0.05$, (*) $p < 0.1$,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

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 $\sim 6.5\%$, weed cover ($H = 31$, $df = 3$, $n = 72$, $p = <0.0001$) lowering overall by $\sim 0.5\%$, and weed richness ($H = 10$, $df = 3$, $n = 36$, $p = 0.019$) also lowering overall by $\sim 5.5\%$ (Fig 3b). The weed 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 ($p_{adj} = <0.001$), perennial ($p_{adj} = 0.017$), and compaction ($p_{adj} = 0.025$) mixes, by $\sim 4 \text{ stems m}^{-2}$ ($\sim 50\%$), down to $\sim 4 \text{ stems per m}^{-2}$. 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 $\sim 20 \text{ stems m}^{-2}$ ($\sim 33.3\%$), down to $\sim 40 \pm 15\%$. 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 taxa.

3.4 Yield

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

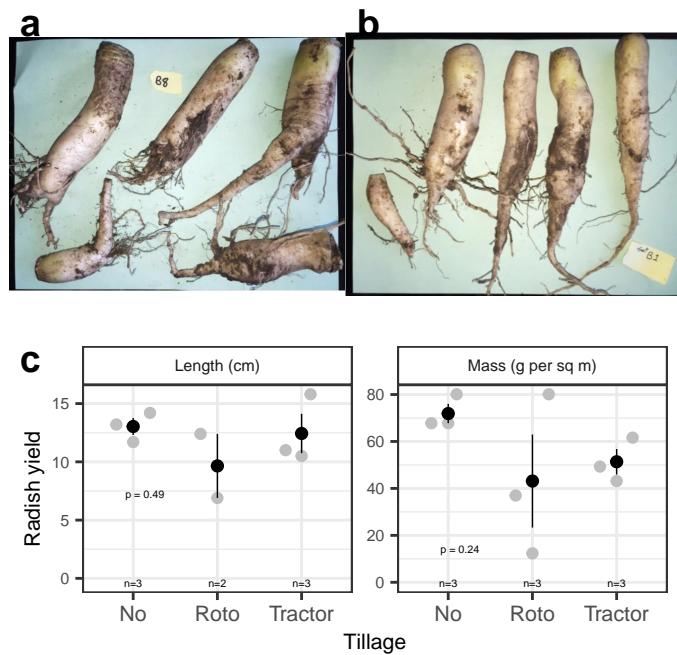


Figure 4: Yield data (a) from no-till, (b) tractor-till, and (c) all tillage groups. Gray dots show plot medians and black point ranges show group mean ± 1 std error and may be small. Photo credits: Naim Edwards.

²⁸⁰ **4 Discussion**

²⁸¹ Overall this study informs urban soil management by supporting the use of tillage to address
²⁸² compaction issues and improve infiltration, together with cover crops to also reduce weed
²⁸³ pressure. We hypothesized that cover crop use would be comparable to tillage effects, which
²⁸⁴ was in part supported, because overall tillage significantly deepened the depth to hardpan by
²⁸⁵ ~0.5 (Fig 1a), which was within the range of effect sizes measured among the various cover
²⁸⁶ crop mixes within the no-till treatment (Fig 1b). Additionally, infiltration was significantly
²⁸⁷ affected by tillage, with roto-till showing the fastest rates (Fig 2a), which agreed with our
²⁸⁸ predictions. Furthermore, weed pressure was significantly affected by both cover crop mixes
²⁸⁹ and tillage (Fig 3); although effects from cover crop mixes, especially the weed suppression
²⁹⁰ mix, were more widespread among multiple measured variables (Fig 3b). Despite these
²⁹¹ significant effects on soils, infiltration, and weeds, yields did not respond to tillage treatments
²⁹² in this study.

²⁹³ Short-term soil compaction issues are commonly alleviated by annual tilling (*Badalíková,*
²⁹⁴ *2010; Salem et al., 2015*), and in addition to validating this practice, this study showed
²⁹⁵ that cover cropping can also be used to manage compaction under no-till, although effects
²⁹⁶ vary by mixture of taxa used. Under tillage, this study validates that tillage intensity
²⁹⁷ corresponds negatively with compaction (measured as depth to hardpan), and additionally
²⁹⁸ clarifies that tractor-till can alleviate compaction in slightly deeper soils below main root
²⁹⁹ zones under $\sim 20.6 \pm 4.6$ cm (8.1 ± 1.8 in), as well as that roto-till can be useful under
³⁰⁰ perennial crops, although under annuals, no-till can be just as effective as roto-till, saving
³⁰¹ grower time, energy, and cost for areas with crops harvested before rooting surpasses ~ 10
³⁰² cm (4 in) (*Krause and Black, 1995*). For urban Technosol soils, however, it is worth noting
³⁰³ that some initial tillage may help remove large metal artifacts and legacy construction debris
³⁰⁴ like rebar, wires, cables, bricks, cinder blocks, and pipes, that could limit root growth under
³⁰⁵ stricter no-till management. Additionally, results suggest that when used together, tillage

may obscure varying but notable effects of cover crops on compaction, however, cover crops would still provide separate benefits to soils, like available 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*). Other studies have generally found similar results (*Ozpinar and Cay, 2006*), suggesting short-term benefits of tillage to soil functions, while acknowledging long-term costs.

Water infiltration is a key function of wide interest for urban environmental management, needed to not only increase available root water, but also reducing erosion and potentially contaminated storm-water runoff and flooding (*Masoner et al., 2019*) after even 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 micro-pores bind water less tightly, allowing soil water 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, and 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 compost benefits to infiltration. Overall, this study supported the use of roto-till, but not no-till or tractor-till, against a one inch rain event, since both others showed rates of only $\sim 6.2 \pm 0$ mL per sec (0.1 ± 0 gal per min), which would likely be associated with more rain water

333 runoff and soil erosion, worse field drainage, and pooling or flooding into roads. Regarding
334 cover crops, this study suggests that cover crop mixes can generally affect infiltration, though
335 specifically perennials may not have notable significant effects on infiltration rates, despite
336 detectable effects on compaction. Based on these findings, roto-till (alongside compost) can
337 be an effective practice to specifically improve urban soil water infiltration, at least in the
338 short-term, after which no-till may prevail (*Cusser et al., 2020*).

339 In urban settings, weed suppression not just alleviates competition with crops that may
340 already be stressed, but also lowers human health risks, including asthma and other respira-
341 tory issues stemming from allergens like pollen (*Katz and Carey, 2014*), and this study shows
342 evidence that cover crops may be better at this than tilling (*Barberi and Lo Cascio, 2001;*
343 *Cordeau et al., 2020*). Tractor-till alleviated the deepest soil compaction but at the cost of
344 showing the highest density of the two most common weeds, velvet leaf (*Abutilon theophrasti*)
345 and pigweed (*Palmer amaranth*). This may have been due to their fast-growing weed life
346 histories, which can grow denser roots in looser soil with varying microbes (*Korneykova et*
347 *al., 2021*), possibly helping explain slower infiltration, with roots that could re-sprout more,
348 clonally and/or from seed banks (*Hesse et al., 2007*). Most notably for weed suppression, the
349 targeted mix consisting of sorghum-sudangrass, buckwheat, and cowpea indeed significantly
350 reduced both weed density and richness by about half compared to the other cover crop
351 mixes. This result agrees with other studies pairing buckwheat and sorghum-sudangrass
352 (*Smith et al., 2015*), and may have occurred due to any of several reasons—competitive ex-
353 clusion of other weeds by either taxon, such via allelopathic chemical root defenses (*Weston*
354 *et al., 1989*), competition for light (*Liu et al., 2009*), better phosphorus mining and use by
355 buckwheat (*Zhu et al., 2002*), facilitation or amplification of these listed effects by cowpea’s
356 added nitrogen supply (*Martins et al., 2003; Sanginga et al., 2000*), and/or existing adapta-
357 tions to poor dry soils (*Bàrberi et al., 2018*) allowing high biomass accumulation. Given both
358 effectiveness and relative ease of re-seeding and winter-kill, this weed suppression mix could
359 serve well to frame crop beds, keeping out encroaching weeds, or to reduce weed pressure in

³⁶⁰ an area that might be planted in the fall or following season.

³⁶¹ Despite overall significant effects by tillage on compaction, infiltration, and weeds, tillage
³⁶² did not significantly affect radish yield, which in fact agrees with other similar studies, in
³⁶³ contrast to common hypotheses. As is, this study does not rule out more complex rela-
³⁶⁴ tionships between soil compaction, infiltration, and crop yield, as suggested by emerging
³⁶⁵ ideas (*Ryan et al., 2007; Vandermeer and Perfecto, 2017*). With further replication, fu-
³⁶⁶ ture similar studies no-till might be expected to show slightly higher yields (*Nunes et al.,*
³⁶⁷ *2018*), due to resulting longer-term reservoirs of water and nutrients, like from mulched com-
³⁶⁸ post, less reliance on transient influxes from infiltration (*Schlegel et al., 2015; Schlegel and*
³⁶⁹ *Havlin, 1995*), and better soil structure (*Du et al., 2015; Sheehy et al., 2015*). However,
³⁷⁰ despite these reasonable hypotheses, recent studies appear to converge with results shown
³⁷¹ here, namely that benefits to soil from no-till may not scale up to detectably affect yields
³⁷² (*Martínez et al., 2016; Pittelkow et al., 2015; VandenBygaart, 2016*). While forage radish
³⁷³ may not itself respond to management, it may still confer benefits to surrounding soils, even-
³⁷⁴ tually reducing compaction and building soil structure over time, such as with minimal or
³⁷⁵ no mechanical tillage (*Chen and Weil, 2010; Lawley et al., 2011*). Together with others, this
³⁷⁶ study suggests a need for future studies to tie yield to land management strategies, includ-
³⁷⁷ ing in urban clay soils, to aid small-scale growers in addressing legacy compaction and pH
³⁷⁸ issues, potentially acknowledging short-term benefits of occasional tillage (*Blanco-Canqui*
³⁷⁹ *and Wortmann, 2020; Ekboir, 2001*).

³⁸⁰ Taken together, this study presents findings that, in addition to validating previous stud-
³⁸¹ ies supporting general tillage for short-term soil fertility, also supports the targeted use of
³⁸² medium-intensity roto-till and cover crop mixtures (*Chapagain et al., 2020*) specifically for
³⁸³ weed suppression. This study serves as a model demonstration of both widely-accessible and
³⁸⁴ effective strategies for growing on re-purposed urban soils after industrial land-use turnover.
³⁸⁵ Overall, we advocate for the maximal use of cover crop mixes for various target functions,
³⁸⁶ with medium-intensity tillage to jump-start urban cultivation.

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³⁹¹ Authors declare no conflicts of interest.

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³⁹⁵ **Author contributions**

³⁹⁶ NE conceived, designed, and performed the study; NE and NM helped collect data; NM
³⁹⁷ analyzed data; NE wrote the initial report. All authors wrote and revised second draft; NM
³⁹⁸ wrote the third draft; all authors revised later drafts.

³⁹⁹ **Data statement**

⁴⁰⁰ Data and code stored at github.com/nmedina17/must.

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