Introduction

Urban soils have the potential to improve the livelihoods of most of the world *(Acuto, Parnell, and Seto 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, Negassa, and Lorenz 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, Lal, and Mercer 2016)*. Degraded urban soils with low organic matter are also likely far from organic carbon saturation *(C. E. 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, Dressler, and Richards 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 *(Hill, Horton, and Cruse 1985; Badalíková 2010)*, and potentially more available nutrients *(Wolkowski 1990)* with less potential weed regeneration *(Barberi and Lo Cascio 2001; Cordeau, Baudron, and Adeux 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, Venturi, and Elbersen 2001)*. However, longer-term side effects of excessive and/or very intensive tillage include weaker soil aggregate stability and structure *(Six et al. 2002; Catania et al. 2018)*, 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 *(Lal 2007; Montgomery 2007; Amundson et al. 2015)*. 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 *(Wang et al. 2006; Roger-Estrade et al. 2010)*, 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, Byrne, and Breen 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, Harmon, and Mueller 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, Bradford, and Wood 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 *(Mead and Riley 1981; Bedoussac et al. 2015; Bourke et al. 2021)*. 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 *(R. 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*).

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