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Evaluation of Nature-Based and Traditional Solutions for Urban Soil Decompaction

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Abstract. Background: Urban forests play a significant role in mitigating the adverse effects of climate change by absorption of greenhouse gases and carbon sequestration. However, soil compaction caused by anthropogenic activities can be a major detriment to urban forest health. Method: Two potential nature-based soil decompaction solutions (addition of earthworms, nitrogen-fixing white clover cropping) were evaluated in combination with existing soil decompaction systems (vertical mulching, woodchip surface layer). Effects on soil quality (bulk density, organic matter, pH, estimated nitrogen release, cotton strip degradation, and earthworm counts) and tree health (diameter at breast height [DBH], canopy density, root dry mass) were then monitored over 3 years. Results: All decompaction treatments independently and in combination significantly reduced soil decompaction and improved tree growth with little difference recorded between treatments. Over time, however, earthworm populations migrated from the treated decompacted soil into the surrounding untreated compacted soil, in turn, significantly improving soil quality allowing for enhanced root growth outside the treated area. Conclusion: A long-term, sustainable, nature-based solution exists for professionals involved in urban tree management to improve compacted soil quality and subsequent tree health.

Keywords. Compaction; Cover Crop; Plant Health Care; Root Growth; Soil Biological Activity; Soil Management; Urban Soils.

INTRODUCTION

Urban forests, which may consist of remnant woodlands, trees, shrubs, and associated vegetation integrated into urban environments such as towns, cities, streets, residential areas, parklands, and green belts, provide crucial ecosystem services. These services include heat mitigation, ultraviolet light protection, reduction of stormwater runoff, absorption of atmospheric pollutants, conservation of biodiversity, and enhancement of human health (Miller et al. 2015; Keeler et al. 2019). Additionally, urban forests play a significant role in counteracting the negative effects of global climate change through the absorption of greenhouse gases and carbon sequestration (Bastin et al. 2019; Cimburova and Pont 2021). The global implementation of urban forests for heat mitigation and carbon sequestration can substantially contribute to limiting the increase in global temperatures to 1.5 °C above preindustrial levels (IPCC 2018).

Anthropogenic activities, including infrastructure installation and maintenance, urban development, and pedestrian and vehicular traffic, are significant contributors to soil compaction in urban landscapes (Day et al. 1995; Smiley 2001; Sax et al. 2017; Rahman et al. 2019). When soil bulk density surpasses the root-limiting bulk density value for a specific soil texture, root elongation is inhibited, while root branching and radial thickening increase (Day and Bassuk 1994). This results in reduced root system growth and diminished soil nutrient uptake (Gliński and Lipiec 1990). Compacted soils exacerbate winter waterlogging due to decreased water infiltration and percolation and intensify drought stress during summer months due to reduced water holding capacity and an increased proportion of hygroscopic water (Grey et al. 2018). Therefore, soil compaction is recognized as a major constraint to urban tree health (Hascher and Wells 2007; Scharenbroch and Watson 2014; Watson et al. 2014).

New urban developments, such as housing estates, typically require a designated area of greenspace, which includes grass, trees, or other vegetation, for recreational or aesthetic purposes within an urban environment (Elderbrock et al. 2020). The required extent of greenspace varies across countries, states, and counties. When the greenspace area is substantial, decompacting the entire landscape may not be economically feasible with existing technologies. These technologies include soil tilling with pneumatic soil excavation tools, such as AirSpade® (Guardair Corporation, Massachusetts, USA), vertical mulching, and soil fracturing techniques like Scoop and Dump. These methods can be employed individually or in combination (Day and Harris 2008; Fite 2008; Day et al. 2009; Scharenbroch 2009; Kuncheva 2015; Sax et al. 2017; Miron and Millward 2024). However, without soil decompaction, the mortality rate of landscape plantings can be high (Ackerman et al. 2021).

Nature-based solutions (NBS) are increasingly being adopted by cities globally to enhance urban forest health and preserve their ecosystem services, such as carbon sequestration and emission offsetting (Kong et al. 2021; Cong et al. 2023). The European Commission defines NBS as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits, and help build resilience" (Castellari et al. 2021). Although NBS theoretically offer a cost-effective and alternative approach to soil decompaction, research on applying NBS to urban soil remediation is virtually nonexistent (Ferreira et al. 2021).

In woodland and forest environments, soil decompaction occurs naturally through the activity of subterranean organisms such as earthworms (AHDB 2018). Earthworms are often referred to as "ecosystem engineers" due to their significant physical and chemical contributions to pedogenesis (soil formation), decomposition, and nutrient recycling (Le Bayon et al. 2017). The practice of using earthworms for composting and enhancing soil fertility in agricultural lands has been well-established for many years (Ahmed and Al-Mutairi 2022). Earthworms alleviate soil compaction and enhance soil structure by creating tunnels and burrows, which aerate the soil and facilitate water infiltration (Barré et al. 2009). As they consume organic matter, they transport materials to different locations before final digestion, resulting in the continuous mixing of organic and inorganic materials throughout the soil profile, thereby improving soil fertility and porosity (Bottinelli et al. 2010). The introduction of earthworms to compacted urban soils has received limited attention (Blouin et al. 2013). However, it has been observed that naturally occurring earthworm populations generally decline in response to urban soil engineering processes (Maréchal et al. 2021).

White clover (*Trifolium repens* L.) is a stoloniferous, perennial plant known for its ability to symbiotically fix atmospheric nitrogen (N)(Awmack et al. 2007). It has been widely utilized in agriculture and more recently in forestry as a sustainable alternative to synthetic nitrogen fertilizers (Herron et al. 2021). Under optimal conditions, white clover can achieve nitrogen fixation rates of 600 to 700 kg N/ha/year (Crush 1987). Additionally, white clover can indirectly enhance crop yields when used as a cover crop by promoting arbuscular mycorrhizal fungi infection and increasing populations of ammonium-oxidizing bacteria and phosphorus-solubilizing microbiota (Awmack et al. 2007; Deguchi et al. 2007; Brtnicky et al. 2021). Despite its benefits, the use of white clover as an understory plant to enhance biological activity and soil fertility in compacted urban soils has not been studied.

The objective of this research was to develop a sustainable, nature-based soil decompaction solution for urban landscapes. Specifically, the study evaluated the bioremediatory potential of earthworms and white clover in compacted urban soils, in combination with traditional soil decompaction methods such as vertical mulching and woodchip mulching. This approach also allowed for the comparison of nature-based solutions (NBS) with traditional soil decompaction technologies. The individual and combined effects of these treatments on soil and tree health were assessed over 3 years by measuring various physical, chemical, and biological metrics. These metrics included tree diameter at breast height (DBH), tree canopy density, root dry mass, soil bulk density, estimated nitrogen release (ENR), soil organic matter, pH, earthworm count, and a cotton strip assay as an indirect measure of soil biological activity.

MATERIALS AND METHODS

Experimental Site

The study was conducted at Stockley Park, Hayes, England (51° 30′ 36.00″ N; 0° 26′ 38.40″ E), between 2017 and 2020. Stockley Park is a 60+ ha business park containing over 140,000 trees and shrubs located in the London Borough of Hillingdon in the United Kingdom. It is owned and managed by Stanhope PLC. Due to the high volume of pedestrian and vehicular traffic, frequently used landscape maintenance machinery, and the continual development of new urban infrastructure (car parks and business buildings), soil compaction has become a serious problem that has detrimentally impacted tree growth and development throughout the park. These symptoms were visibly manifest as crown die-back, poor canopy coverage, limited stem extension, and leaves yellowing and turning necrotic. A soil assessment determined that the soil type throughout Stockley Park was clay loam and bulk density within the experimental area ranged between 1.75 to 1.87 g/cm^3. These values are higher than the root limiting bulk density (1.47 g/cm^3) for a clay texture (Klopp 2023) indicating that tree root growth may be impeded. In support of this, waterlogging during wet weather was a frequent annual problem and a lack of surface vegetation was observed within the study area, both observations are indicative of excessive soil compaction (Percival et al. 2023). In addition, excavation of 10 soil pits (20 cm × 20 cm × 20 cm) within the experimental area prior to treatments commencing found the soil was devoid of worms.

Experimental Design and Treatment Application

Five vistas consisting of *Tilia × europea* (diameter at breast height [DBH] 45.4 cm ± 4.0 cm; height 22.2 m ± 0.5 m) were identified within Stockley Park. Within each vista, 7 treatment plots 2 m × 3 m in dimension were identified such that 2 trees (10 trees in total per treatment) were situated within each plot and each consecutive plot had a 2-m spacing between them. The 7 treatments were as follows:

1. Control. No soil decompaction work was undertaken.
2. Vertical mulching (VM). Holes (30-cm deep, 7.5-cm wide) were drilled using a mechanical auger at 30 × 30 cm distances. The first row of holes was drilled 10 cm from the peripheral edge of the plot inwards and then at 30-cm spacings along the breath and height of the plot in an oblong shape. This resulted in 70 drill holes per plot. Due to the poor quality of the soil (heavy compacted clay loam), the holes were backfilled with a Biochar (5%) + John Innes No 3 (sandy loam, peat, horticultural sand [7:3:2]; 92%) + slow-release organic fertilizer (nitrogen[N]:phosphorus[P]:potassium[K] = 5:3:3 + 9% trace elements.; 3%). The original soil cores were discarded. The biochar used in this experiment was derived from English oak (*Quercus robur* L.) and ash (*Fraxinus excelsior* L.) produced in a SuperChar 100 Mk I kiln at 600 °C for 2 hours which, when cooled, was crushed to pass through a 5-mm grade sieve to ensure all particles were less than 5-mm diameter prior to use. Biochar was also selected as a soil amendment as previous research has shown that soil amendment with this product can induce long term positive effects on improving quality of heavily compacted soils (Percival et al. 2023; Fite et al. 2011).
3. Five-cm woodchip mulch (WCM) over the compacted surface. Woodchip mulch was created from 5- to 10-cm diameter branches of European lime (*Tilia × europea* L.) and English oak (*Q. robur* L.) that were pruned from trees located within Stockley Park and chipped with a commercial brush chipper to produce 4- to 6-cm-long chips. Pruning was conducted when the trees were fully dormant (February), so no foliage was present on the tree. WCM was applied to the respective treatment plots *circa* 3 to 4 weeks after chipping to a depth of 10 cm.
4. VM + WCM.
5. VM + WCM + worms. For this study two species of native earthworm were used: *Dendrobaena veneta* and *Lumbricus terrestris*. *L. terrestris* is known for significant vertical movement in soils while *D. veneta* is responsible for significant horizontal plane movement potentially providing a mixing action down to 1 m deep. Worms were obtained commercially in boxes with each box containing 50 earthworms (25 of each species [Worms Direct, Grange Avenue, Chelmsford, United Kingdom]). One box was used per plot, equivalent to 8 worms per m^2 of soil, a worm count associated with reasonable soil fertility (Chauhan 2014). Worms were removed from each box and placed into a 45-cm-wide × 5-cm-deep hole dug by hand using a garden shovel. The hole was then gently backfilled with soil and watered thoroughly. Worms were planted at such a shallow depth as *Dendorobaena veneta*, an epigeic species, lives on or close to the soil surface. Consequently, planting too deep would have a significant impact on their survival (Blouin et al. 2013).

6. VM + white clover (WC). White clover (Trifolium repens) seed was obtained from a commercial supplier (The Grass Seed Store, Heath Hill Farm, Gloucestershire, UK) and sown at the manufacturer recommended rate of 1.5 g per m^2 to each treatment area following vertical mulching.
7. VM + white clover + worms.

The addition of worms directly to the compacted soil or sowing a crop of white clover as independent and solitary treatments onto the surface of the compacted soil were not viable options (data unpublished). Without soil decompaction, clover seed germination was limited (25% to 30%) and of those seedlings that germinated 80% to 90% died within 7 to 10 days. Research elsewhere has shown that increased bulk density generally correlates with reduced white clover seed germination and plant vigour (Haruna et al. 2020). Likewise, work by Capowiez et al. (2012) showed that in response to compaction earthworms move above ground to avoid these unfavorable soil zones while Maréchal et al. (2021) concluded that soil engineering and soil isolation processes in urban landscapes tend to result in decreased worm populations depending on the type of engineering process. Although clover germination rates and spread over time were not quantified in this study, it was noticeable that where VM was applied germination rates were highest on and around the VM holes. Over time this allowed the WC to establish and spread over the entire plot.

Each trial site was then protected from human ingress by installing 1.5-m-height tape around the peripheral edge of each experimental vista. During the 3-year experimental period, no management interventions such as irrigation or fertilization occurred.

Unless otherwise stated treatment effects on soil and tree health were assessed annually. Measurements of bulk density, organic matter, ENR, cotton strip assay, root dry mass, and earthworm populations were made within the treated plot (i.e., the area of soil that had been decompacted)(treatments 1 to 7) and 1 m outside the treatment plot where the area had not been decompacted. The area chosen outside the treatment plot for these measurements was the other side to the 2-m space between plots. The reason for this was to determine if, over time, treating a compacted soil in a specific way resulted in the surrounding compacted soil becoming decompacted.

Diameter at Breast Height (DBH)

The stem location at 1.3 m height was initially marked on each tree to allow measurements at the same location in different years. Measurements were made annually in late September (26 to 29) when, according to Paembonan et al. (1990), trunk diameter and height growth during a growing season will be close to cessation. All girth records were converted to diameter in this study. Tree height was also recorded over the study. However, effects on DBH reflected that of height (i.e., treatment causing the greatest effects on height also resulted in the greatest DBH). For reasons of clarity, effects on height are not presented.

Tree Canopy Density

Tree canopy density was based on the United States Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis (FIA) program. The FIA crown foliage estimate is obtained from a pair of perpendicular side views of the tree supported with digital photographs taken vertically below the canopy that are scanned into the FIA program (Winn and Araman 2010). Measurements were taken towards the end of the growing season (2017, 2018, and 2019 September 1 to 2). Tree canopy density was chosen as a measurement rather than canopy spread for two reasons. (1) As trees were planted in a vista then canopy overlap occurred making accurate readings difficult. (2) Due to the high degree of soil compaction, canopy thinning due to premature leaf loss could be observed. Consequently, it was decided that refoliation was a better metric of treatment effects rather than canopy coverage.

Bulk Density (Soil Compaction)

To account for soil variation bulk density was calculated for each plot from 3 soil cores based on a 1-m "V" pattern as stipulated under United Kingdom soil sampling procedures (Tytherleigh et al. 2008). Soil cores were taken with a slide hammer and a corer head which measured 20 cm in length and had a 5-cm cutting edge diameter. Any mulch and the top 2 cm of the soil core were discarded, and the remaining core was trimmed to 7.5 cm in length. The cores were transferred to aluminum trays and dried at 65 °C for 7 days or until the mass remained unchanged. The dry mass was then used to calculate bulk density (g/cm^3). As the VM holes had been drilled 10 cm inwards from the peripheral edge of the plot and at 30-cm spacings, thereafter, care was taken to ensure a drilled VM hole was not sampled for bulk density measurements.

Estimated Nitrogen Release (ENR), Soil Organic Matter, and pH

Estimated nitrogen release (ENR), soil organic matter content, and soil pH were measured for each plot to assess the chemical component of compaction. These analyses were undertaken by a United Kingdom Accreditation Service (UKAS) accredited laboratory: Cawood Scientific Ltd. T/A NRM, Bracknell, UK. Soil samples were collected as outlined in the Natural England technical information note TIN035: 3 soil cores (5 cm wide × 25 cm deep) taken at 1.0-m intervals in a "V" pattern were amalgamated into 1 sample and oven dried for 72 hours (Tytherleigh et al. 2008). Soil pH was determined by calibrating a pH meter (SevenExcellence™ pH meter S400-Std-Kit) over a pH range of 4 to 7 using standard buffers. In order to achieve a soil:water ratio of 1:2, 5 grams of sieved (4 mm), air-dried soil was placed into a 100-mL centrifuge tube and 10 mL of deionized water was added. The soil sample and deionized water were stirred vigorously for 15 seconds and left to stand for 30 minutes to equilibrate with ambient CO_2 and temperature. A pH electrode was placed in the soil/distilled water solution, swirled carefully, and the pH value was taken to the nearest 0.01. Between samples, the electrode was rinsed with deionized water. Soil organic matter (SOM) was estimated using the loss on ignition method (i.e., combustion in an oven at 360 °C with 100 g of air-dried sieved [2 mm] soil for 6 hours and measuring weight loss). Estimated nitrogen release was calculated based on SOM, soil temperature, soil moisture, and soil texture (National Resource Management, Coopers Bridge, Bracknell, UK).

Earthworm Count

Earthworm population size is a popular metric for overall soil health due to their role in nutrient cycling, soil aggregation, soil aeration, and water infiltration. For this study, 3 soil pits (20 cm × 20 cm × 20 cm) per plot were dug in a "V" pattern and the excavated soil was placed on a mat. The soil was broken up by hand and the number of earthworms per pit counted (AHDB 2018). The 20-cm pits were dug between the VM holes which were drilled at 30-cm spacings, meaning space was available for excavation without disturbing the VM drill holes.

Cotton Strip Assay

The cotton strip assay is a field test used to assess the biological component of a soil. For this study, 3 strips (20 cm × 15 cm) of unbleached calico cotton per plot were buried 20 cm below the soil surface for 3 weeks where they were then gently lifted and washed in water to remove the soil. The amount of decomposition on the strips was determined on a visual percentage basis (Reid and Cox 2005).

Root Dry Mass

At year 3, 5-cm-diameter, 20-cm-deep soil cores (393 cm^3) were removed per plot and any leaf litter, organic matter, and vegetation were removed from the top of the core. Soil was separated from the roots using a 4-mm screen mesh and the roots were oven dried at 85 °C for 48 hours. Root dry mass per treatment was calculated from the average root dry mass of the 5 cores. Cores were removed in a "X" pattern starting at the top of the treatment plot in-between the VM drilled holes and taken at 1-m spacings.

Statistical Analysis

Both parametric and non-parametric statistical analyses were employed as appropriate (Tables 1 to 8). Parametric data were analyzed using analysis of variance (ANOVA), and differences between means were assessed using Tukey's honestly significant difference test ($P = 0.05$) where applicable. For non-parametric data, values within a column followed by the same letter are not significantly different, as determined by Bonferroni-adjusted pairwise comparisons of estimated marginal means from a generalized linear model (GLM) with $\alpha = 0.05$. All statistical analyses were conducted using R version 4.2.1 (R Development Core Team, Vienna, Austria).

RESULTS

Diameter at Breast Height (DBH)(Table 1)

Irrespective of treatment, by month 4 a significant increase ($P < 0.05$) in DBH was recorded with one exception; vertical mulching alone, where DBH was not significantly greater than non-treated control tree values. By month 16, all treatments significantly ($P < 0.05$) increased DBH compared to controls with no significant difference between treatments recorded. The percent increase in DBH at month 16 ranged from 228% (vertical mulching alone) to 380% (VM + WCM + worms). By month 28, a significant difference ($P < 0.05$) between treatments was also recorded. VM + WCM + worms provided the greatest increase in DBH (298%) compared to non-treated control trees while vertical mulching alone provided the least increase in DBH (167%) compared to non-treated control trees.

Tree Canopy Density (Table 2)

At months 4 and 16, tree canopy density was significantly ($P < 0.05$) increased compared to non-treated control trees following the soil decompaction treatments VM + WCM with and without (month 16 only) worms, VM + white clover with and without worms.

Table 1. The influence of soil decompaction on diameter at breast height (DBH)(percent increase) over a 3-year period. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Month 4	Month 16	Month 28
Control	0.80a	0.64a	0.94a
VM	1.46ab	2.10b	2.51b
WCM	1.56b	2.23b	2.83bc
VM + WCM	1.71b	2.61b	3.28bc
VM + WCM + worms	2.20b	3.07b	3.75c
VM + WC	1.70b	2.25b	2.76bc
VM + WC + worms	2.29b	2.12b	3.19bc
Significance over time			
Month (time)	0.608		
Treatment	< 0.001		
Month (time) × treatment	0.167		

Numbers within a column followed by a common letter are not significantly different according to Tukey's honestly significance test ($P = 0.05$). For treatment descriptions, see Materials and Methods.

Table 2. The influence of soil decompaction on tree canopy density over a 3-year period. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Month 4	Month 16	Month 28
Control	47.5a	49.0a	50.0a
VM	50.0ab	52.0ab	55.5ab
WCM	50.5ab	53.5ab	57.5bc
VM + WCM	52.5ab	56.0bc	61.0bcd
VM + WCM + worms	54.5b	57.0bc	62.5cd
VM + WC	54.5b	57.5bc	64.5de
VM + WC + worms	54.5b	60.0c	68.5e
Significance over time			
Month (time)	0.602		
Treatment	0.010		
Month (time) × treatment	0.200		

Numbers within a column followed by a common letter are not significantly different according to Tukey's honestly significance test ($P = 0.05$). For treatment description, see Materials and Methods (Winn and Araman 2010).

All remaining treatments had no significant effect on tree canopy density at month 4 and 16. By month 28, all soil decompaction treatments had significantly ($P < 0.05$) increased tree canopy density compared to non-decompacted control trees with one exception; vertical mulching only where tree canopy density was not significantly different from control trees but statistically equivalent to WCM and VM + WCM treated trees. The greatest treatment effects on tree canopy density at month 28 were recorded following a VM + white clover + worms and the least effects following a vertical mulch treatment alone.

Bulk Density (Table 3)

Treated plot; soil decompacted: All soil decompaction systems significantly ($P < 0.05$) lowered the degree of soil compaction at months 4, 16, and 28 after treatment compared to the non-decompacted control soil. In addition, a significant ($P < 0.05$) difference in bulk density values was recorded between treatments. At month 4, the VM + WC + worms treatment provided the greatest reduction in bulk density values (16.1%) while woodchip mulch alone provided the least (6.1%) compared to non-decompacted control soils. At months 16 and 24, WCM + white clover + worms provided the greatest reduction in bulk density values (24.3% and 27.1% respectively) while woodchip mulch alone provided the least (14.4% and 16.6% respectively). Irrespective of treatment, soil bulk density values were always lower at each sampling point (months 4, 16, 28) over time. However, there was no significant influence of treatment over time.

Soil compacted; 1 m outside the treated plot: All treatments significantly ($P < 0.05$) lowered the degree of soil compaction at month 16 and 28 outside the treated area. However, the degree of soil compaction alleviation significantly ($P < 0.05$) differed between treatments. The greatest degree of soil decompaction at months 16 and 28 was recorded in both earthworm amendment treatments: VM + WCM + worm addition and VM + WC + worm addition.

Organic Matter (Table 4)

Treated plot; soil decompacted: In most cases, all soil decompaction treatments significantly ($P < 0.05$) increased the soil organic matter content from month 4 to month 28. Exceptions include the application of a woodchip mulch layer alone (month 4), vertical mulching alone (months 16 and 28), and VM + WCM + worm addition (month 28) where the organic matter content did not significantly differ from the non-decompacted control soil. Over the 3-year period, the greatest increase in soil organic matter

Table 3. The influence of soil decompaction on bulk density over a 3-year period. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Month 4	Month 16	Month 28	Month 16	Month 28
	Inside canopy			Outside canopy	
Control	1.80d	1.81c	1.81c	1.80d	1.80d
VM	1.68c	1.50b	1.40a	1.69c	1.62c
WCM	1.69c	1.55b	1.51b	1.68c	1.60c
VM + WCM	1.64bc	1.41a	1.40a	1.66c	1.60c
VM + WCM + worms	1.59ab	1.37a	1.32a	1.43a	1.49b
VM + WC	1.66bc	1.41a	1.38a	1.68c	1.59c
VM + WC + worms	1.51a	1.38a	1.37a	1.54b	1.38a
Significance over time					
Month (time)	0.967			0.943	
Treatment	< 0.001			0.001	
Month (time) × treatment	< 0.001			0.387	

Numbers within a column followed by a common letter are not significantly different according to Tukey's honestly significance test ($P = 0.05$). For treatment description, see Materials and Methods.

content was recorded following the VM + WCM treatment (41.3% averaged over months 4, 16, and 28). Vertical mulching alone provided the least degree of soil organic matter (8.53% averaged over months 4, 16, and 28).

Soil compacted; 1 m outside the treated plot: All soil decompaction treatments significantly ($P < 0.05$) increased the soil organic matter content at months 16 and 28 except for vertical mulching alone where no significant effects on soil organic matter content were recorded. The greatest increase in soil organic matter content was recorded following a VM + WCM layer (32.2% averaged over months 16 and 28). Vertical

Table 4. The influence of soil decompaction on soil organic matter content over a 3-year period. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Month 4	Month 16	Month 28	Month 16	Month 28
	Inside canopy			Outside canopy	
Control	4.56a	5.04a	4.97a	5.23a	5.21a
VM	5.33bc	5.47ab	4.97a	5.71ab	5.29a
WCM	5.15ab	7.23de	7.22b	6.44c	6.50bc
VM + WCM	5.87c	7.30e	7.48b	6.90c	6.90c
VM + WCM + worms	5.89c	6.08bc	5.63a	6.32bc	6.14b
VM + WC	5.60bc	7.17de	7.44b	6.39bc	6.43bc
VM + WC + worms	5.73bc	6.61cd	6.86b	6.52c	6.09b
Significance over time					
Month (time)	0.070			0.644	
Treatment	< 0.001			0.041	
Month (time) × treatment	< 0.001			0.270	

Numbers within a column followed by a common letter are not significantly different according to Tukey's honestly significance test ($P = 0.05$). For treatment description, see Materials and Methods.

Table 5. The influence of soil decompaction on soil ENR (estimated nitrogen release)(g/m^2) over a 3-year period. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Month 4	Month 16	Month 28	Month 16	Month 28
	Inside canopy			Outside canopy	
Control	15.0a	15.3a	14.6a	15.4a	14.9a
VM	16.0ab	16.6ab	17.4b	15.9ab	16.0ab
WCM	18.3c	19.5cd	19.8c	16.7b	17.6cd
VM + WCM	16.6b	20.3d	20.5c	17.0b	18.3d
VM + WCM + worms	16.2ab	16.8ab	17.6b	16.4ab	16.9bc
VM + WC	17.1bc	19.4cd	19.1c	16.7b	17.7cd
VM + WC + worms	16.9bc	18.0bc	17.3b	16.0ab	16.7bc
Significance over time					
Month (time)	0.420			0.390	
Treatment	< 0.001			0.001	
Month (time) × treatment	< 0.001			0.050	

Numbers within a column followed by a common letter are not significantly different according to Tukey's honestly significance test ($P = 0.05$). For treatment description, see Materials and Methods.

mulching alone provided the least degree of soil organic matter (5.4% averaged over months 16 and 28).

ENR (Table 5)

Treated plot; soil decompacted: In most cases, all soil decompaction treatments significantly ($P < 0.05$) increased the soil ENR from month 4 to month 28. Exceptions include vertical mulching alone and VM + WCM + worms (months 4 and 16) treatments where the soil ENR did not significantly differ from the non-decompacted control soil. At month 28, however, all soil decompaction treatments significantly ($P < 0.05$) increased the soil ENR compared to the non-decompacted control soil. At month 28, the greatest increase in soil ENR was recorded following a VM + WCM layer compared to non-decompacted control soil. Vertical mulching + WC + worms provided the least degree of soil ENR compared to non-decompacted control soil.

Soil compacted; 1 m outside the treated plot: At month 16, most soil decompaction treatments increased soil ENR but not significantly so. Exceptions include WCM alone, VM + WCM, and VM + WC where ENR values were significantly ($P < 0.05$) higher than non-decompacted control soil. At month 28, all soil decompaction treatments significantly ($P < 0.05$) increased soil ENR with one exception; vertical mulching alone where ENR values did not significantly vary from non-decompacted control soil. The greatest increase in soil ENR was recorded following a VM+ WCM layer compared to non-decompacted control soil. Vertical mulching alone provided the least degree of soil ENR compared to non-decompacted control soil.

pH (Data Not Shown)

Irrespective of soil decompaction treatment or area treated (inside or 1 m outside of the canopy), no significant effects on soil pH were recorded throughout the 3-year study. Soil pH ranged from a minimum of 7.03 (application of a woodchip mulch [month 4]) to a maximum of 7.39 (VM + WC [month 4 and 16], VM + WC + worms (month 4), VM + WCM + worms (month 16).

Cotton Strip Assay (Table 6)

Treated plot; soil decompacted: At month 28, all treatments significantly ($P < 0.05$) enhanced calico strip degradation rates compared to non-decompacted control soil. Such a response indicates all soil decompaction treatments enhanced soil biological activity. However, the degree of soil biological activity recorded as assessed by the magnitude of calico strip degradation rates differed between each soil decompaction treatment. For example, the highest degradation rates were recorded following the VM + WCM + worms treatment while the lowest degradation rates were recorded following the VM only treatment.

Table 6. The influence of soil decompaction on calico strip degradation at month 28. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Inside canopy	Outside canopy
Control	11.0a	8.5a
VM	31.5b	9.5a
WCM	40.0c	9.0a
VM + WCM	57.0d	10.5a
VM + WCM + worms	72.0e	47.0c
VM + WC	32.5b	10.0a
VM + WC + worms	38.0bc	32.5b
Significance of treatment	< 0.001	< 0.001

Numbers within a column followed by a common letter are not significantly different according to Tukey's honestly significance test ($P = 0.05$). For treatment description, see Materials and Methods.

Soil decompacted; 1 m outside the treated plot: Only two soil decompaction treatments significantly ($P < 0.05$) enhanced calico strip degradation rates; VM + WCM + worms and VM + WC + worms. All remaining treatments had no significant effect compared to non-decompacted control soil, although calico strip degradation rates ranged between 8.5% to 10.5% higher than non-decompacted control soil.

Root Dry Weight (Table 7)

Treated plot; soil decompacted: All soil decompaction treatments increased root dry weight compared to non-decompacted control soil. Increased root dry weight ranged from 30.5% (VM + WC) to 129% (VM + WCM + worms) however these increases were not statistically significant from non-decompacted control soil.

Soil decompacted; 1 m outside the treated plot: Similarly, most soil decompaction treatments increased root dry weight compared to non-decompacted control soil. However, these differences were not statistically significant. Increased root dry weight ranged from 4.7% (VM + WCM) to 53.6% (VM + WCM + worms).

Earthworm Count (Table 8)

Treated plot; soil decompacted: At months 16 and 28, only two soil decompaction treatments significantly ($P < 0.05$) enhanced worm counts; VM + WCM + worms, VM + WC + worms compared to non-decompacted control soil. All remaining soil decompaction treatments had no significant effect on worm counts.

Soil decompacted; 1 m outside the treated plot: Similarly, only the VM + WCM + worms and VM + WC + worms significantly ($P < 0.05$) enhanced worm counts compared to non-decompacted control soil at month 16 and 28. All remaining soil decompaction treatments had no significant effect on worm counts.

Table 7. The influence of soil decompaction on root dry weight (mg/g soil dry weight) at month 16. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Inside canopy	Outside canopy
Control	0.743a	0.742a
VM	1.094a	0.868a
WCM	1.349a	0.928a
VM + WCM	1.576a	0.777a
VM + WCM + worms	1.687a	1.140a
VM + WC	0.962a	0.638a
VM + WC + worms	1.319a	1.164a
Significance of treatment	0.350	0.414

Numbers within a column followed by a common letter are not significantly different based on Bonferroni-adjusted pairwise comparisons of estimated marginal means from a generalized linear model (GLM) with α = 0.05. For treatment description, see Materials and Methods

DISCUSSION

While it is appreciated that the performance of trees in response to the soil decompaction treatments evaluated in our study is influenced by multiple interacting factors, for the sake of clarity, these factors are discussed individually in this paper.

Decompaction Over Time

All soil decompaction treatments used in this study significantly reduced soil compaction as measured by bulk density at 4 months post-treatment. This significant reduction persisted at 28 months post-treatment. The study results demonstrate a progressive decrease in compaction levels at each sampling interval, with values at 16 months being lower than those at 4 months, and values at 28 months being lower than those at 16 months. However, these differences were

Table 8. The influence of soil decompaction on earthworm count at Month 16 and 28. VM (vertical mulching); WCM (wood chip mulching); WC (white clover).

Treatment	Month 16	Month 28	Month 16	Month 28
	Inside canopy		Outside canopy	
Control	0.2a	0.3a	0.1a	0.2a
VM	0.3a	0.3a	0.3a	0.3a
WCM	0.5a	0.0a	0.4a	0.2a
VM + WCM	0.3a	0.1a	0.4a	0.2a
VM + WCM + worms	2.6b	1.0b	2.9b	1.2b
VM + WC	0.7a	0.4a	0.7a	0.7ab
VM + WC + worms	2.1b	1.0b	2.2b	1.2b
Significance over time				
Month (time)	0.559		0.653	
Treatment	< 0.001		< 0.001	
Month (time) × treatment	0.993		0.762	

Numbers within a column followed by a common letter are not significantly different based on Bonferroni-adjusted pairwise comparisons of estimated marginal means from a generalized linear model (GLM) with α = 0.05. For treatment description, see Materials and Methods.

not statistically significant. This trend may continue in the long term, if recompaction due to anthropogenic activities is prevented (Percival et al. 2023).

Effects of Decompaction on Above- and Belowground Growth

The effects of decompaction were evident above ground through a significant increase in tree growth, specifically in diameter at breast height (DBH) and canopy density. In urban landscapes, increases in canopy coverage achieved through nature-based solutions are considered beneficial due to enhanced ecosystem services such as carbon sequestration, absorption of atmospheric pollutants, and UV light shade protection (European Commission 2015, 2016). Below ground, positive effects of decompaction included increased organic matter, estimated nitrogen release (ENR), cotton strip degradation, root dry mass, and earthworm counts. Notably, a significant difference in the degree of decompaction alleviation was observed between treatments. For instance, the most substantial improvements in tree growth and soil quality were generally observed following the VM + WCM + worm addition treatment. Conversely, VM alone improved growth and soil quality to a lesser extent. The choice of a specific soil decompaction system can be significantly influenced by economic costs, which are determined by factors such as the soil surface area to be decompacted, the degree of compaction (heavy or light), and the time required to complete the task (Percival et al. 2023).

Vertical Mulching

Although vertical mulching is recognized as a method for decompacting soils in urban landscapes, previous studies have found few significant effects on soil quality (Morris et al. 2009; Percival et al. 2023). A disadvantage of vertical mulching is that the bulk soil between the holes remains largely uncompacted (Morris et al. 2009). However, the results of this trial differed from other tree-related studies. In this trial, holes were spaced at 30 cm rather than 50 cm, and the soil cores removed by the augering process were replaced with a more suitable growing medium (topsoil, biochar, fertilizer). This spacing system is more like that used in agriculture, where researchers have shown that vertical mulching can be an effective soil decompaction strategy and a means of improving soil microbial activity and plant quality (Kuncheva 2015; Nandhini et al. 2021). Based on the results of this study, greater consideration of vertical mulching, as modified in our study, as a means of soil decompaction in urban landscapes may be warranted.

Mulching

The benefits of a woodchip mulch layer on soil quality are well-documented, including fertilization, enhancement of organic matter, maintenance of soil temperature and moisture, and weed suppression (Chalker-Scott 2007; Scharenbroch 2009). However, few studies have evaluated the long-term (3 to 5 year) impacts of a woodchip mulch layer on soil quality and fertility. Among the available studies, Scharenbroch and Watson (2014) concluded that a woodchip mulch provided a cost-efficient and effective treatment for alleviating soil compaction, improving soil quality, and stimulating the growth of *Acer rubrum* and *Betula nigra*. In a 5-year trial conducted by Percival et al. (2023), a woodchip mulch layer was found to be an effective and inexpensive method for improving the soil quality of several heavily compacted soils within a primarily forested 403-ha Site of Special Scientific Interest (SSSI) in the United Kingdom. Additionally, Fite et al. (2011) investigated the effects of air-tilling, fertilizer, and mulch application, both singly and in combination, at 4 urban sites located in Pennsylvania, South Carolina, and Massachusetts, USA. They concluded that air-tilling combined with the incorporation of fertilizer and a woodchip mulch layer was the most effective in improving soil quality. Consistent with the findings of Scharenbroch and Watson (2014) and Fite et al. (2011), a woodchip mulch layer provided a simple and relatively inexpensive method for long-term soil structure improvement and created a soil environment beneficial for root growth. However, few, if any, studies have evaluated the effect of applying a woodchip mulch in combination with vertical mulching. The results of this study indicate that combining these soil decompaction treatments resulted in greater positive effects on tree diameter at breast height (DBH), canopy density, and root dry weight (mg/g soil dry weight), as well as increased soil quality (estimated nitrogen release, organic matter content, calico strip degradation, bulk density) compared to each treatment alone. Consequently, the results suggest that a combined woodchip mulch layer with vertical mulching provides arborists with an alternative method for long-term soil decompaction, creating a soil environment beneficial for root and subsequent tree growth.

Earthworms

Earthworms, through their burrowing activity, play a major role in the structural and functional heterogeneity of soils (AHDB 2019). Earthworm counts are recognized as a proxy for soil health and biological activity (Riches et al. 2013; AHDB 2018). The application of earthworms to improve soil fertility, alleviate soil compaction, enhance soil porosity, and boost agricultural crop yield has been acknowledged for many years (Riches et al. 2013; Thomsen et al. 2019). Earthworms consume leaf mold, decomposing wood particles, dead insects, and organic matter. As these materials pass through their digestive system, they are digested, chemically modified by gut flora, and excreted as worm casts. Consequently, earthworms increase the bioavailability of organic materials and produce a biological form of nitrogen readily available to plants (Singh and Sinha 2022). Upon death, earthworm carcasses contribute to the organic mix, enhancing soil fertility and structure.

Urban landscapes, due to anthropogenic activities such as soil compaction and contamination, combined with limited rooting and soil volumes, tend to have inherently low earthworm populations (Smetak et al. 2007; Maréchal et al. 2021). As a result, the practice of adding earthworms to urban soils has been minimally studied. Available studies, such as Smetak et al. (2007), recorded significant variation in earthworm density across different urban areas, including parklands and residential areas with varying irrigation and fertilizer usage. Regardless of the urban area, a noticeable trend was the decrease in bulk density as each urban system matured, which correlated with increases in earthworm population density.

Supporting the findings of Smetak et al. (2007), our study shows that the addition of earthworms, in combination with VM and a woodchip mulch layer, provided the greatest degree of soil decompaction at all sampling dates over the 3-year trial. Additionally, a calico cotton strip assay used in this trial as a quantitative measure of organic matter decomposition (Reid and Cox 2005) indicated the highest levels of decomposition in worm-amended soil combined with VM and a woodchip mulch layer, suggesting this treatment promoted the greatest degree of biological and microbial activity below ground (Reid and Cox 2005). Indeed, earthworm casts have been shown to be enriched with microbial populations, increasing microbial activity in soil, as well as nutrient mineralization and release (Ojha and Devkota 2014). These positive influences below ground may account for this decompaction treatment having the greatest effect on DBH and root dry weight, as well as being the second most effective treatment for enhancing tree canopy density.

Sustainable Soil Decompaction

One of the primary objectives of this study was to develop a sustainable soil decompaction system, wherein once an area of land had been decompacted, the soil would be amended in a manner that facilitates the decompaction of the surrounding compacted soil over time. This study hypothesized that earthworm migration from the decompacted area into the compacted area would achieve this. The study recorded such a response. At 28 months, at a distance of 1 m from the decompacted area, the soil bulk density of worm-amended soil ranged from 1.49 to 1.38 g/cm^3, whereas non-decompacted control soil had a bulk density of 1.80 g/cm^3. Earthworm migration within soils can vary significantly from 0.5 to 6.0 m per year, depending on soil temperature, compaction, drainage, soil organic carbon content, and hydromechanical conditions (Butt et al. 1995; Ruiz et al. 2021). The reduction in soil bulk density outside the decompacted area to levels suitable for root growth likely explains the higher calico cotton strip degradation and worm counts, indicators of soil biological activity, compared to non-worm-amended soils. Consequently, the greater decompacted soil volume accounts for worm-amended soils having the most positive effect on tree growth in terms of DBH, root mass, and canopy density increase.

The results of this study indicate that earthworm inoculation offers potential as an integral component of sustainable land decompaction practices. However, whether earthworm and subsequent soil decompaction extended beyond 1 m outside the treated area was not quantified in this experiment. It is crucial to emphasize that earthworms should not be regarded as a panacea in soil restoration (Butt 2008). The timing of their introduction needs to be combined with some degree of decompaction if compaction levels are inherently high. The provision of nutrients, such as organic matter, is essential to allow amended earthworm populations to establish, reproduce, and survive in the initial weeks after inoculation. It has been shown that many beneficial soil organisms can naturally re-establish ambient population levels quickly, whereas others, due to poor colonization ability, may require direct assistance. Earthworms, renowned for their numerous benefits to soil quality, fall into the latter category (Butt et al. 1995; Butt 2008).

Clover

White clovers (*Trifolium repens* spp.) have been identified as an ideal 'living mulch' for planting between rows of fruit bushes or trees (Parveaud et al. 2012). The use of white clover as a living mulch may have potential for urban landscapes, as it has been identified as an ideal plant to contend with the harsh edaphic conditions prevalent in towns and cities. White clover plants are perennial nitrogen producers with a dense, shallow root mass that protects soil from erosion and suppresses weeds. A white clover mulch has also been shown to reduce compaction and fine particulate matter (dust) caused by vehicular traffic (Beniston and Lal 2012). White clover has the potential to convert exposed bare soil into biologically active soil, providing a habitat for beneficial organisms both above and below the soil surface (Awmack et al. 2007; SARE 2007).

Sowing a white clover crop following vertical mulching was shown to induce numerous positive benefits in this study. Bulk density values within the decompacted area were among the lowest recorded for all decompaction treatments applied. The addition of worms resulted in even lower bulk density values within and outside the treated area. Furthermore, in parallel with earthworm treatments, soil biological activity was enhanced (greater calico cotton strip degradation), as was tree growth (DBH, root mass, canopy density). The influence of a white clover crop on soil biology concerning urban trees is not well-documented. However, in a 5-year study by Parveaud et al. (2012), white clover sown between rows in an organic peach orchard significantly improved root density, earthworm populations, water infiltration rate, nitrogen content, and water availability. In silvopastoral systems, which combine tree and pasture production, white clover was shown to be a good choice of species due to its tree growth-promoting properties (López-Díaz et al. 2009).

CONCLUSIONS

The influence of two nature-based soil decompaction solutions, using earthworms and white clover cropping in conjunction with traditional soil decompaction systems (vertical and conventional woodchip mulching), was evaluated on soil quality and tree growth. All decompaction systems assessed reduced soil compaction and improved soil quality and tree growth; however, significant differences between treatments were identified. A treatment combining traditional methods (vertical mulching and woodchip mulch) with a potential nature-based solution involving earthworm soil amendment proved to be the most effective in enhancing the physical, chemical, and biological properties of compacted urban soil over a 3-year period. Importantly, over time, the degree of compaction in the surrounding soil decreased, with earthworm migration identified as a contributing factor. The results demonstrate that an effective, sustainable soil decompaction method exists, providing arborists with a nature-based option to improve compacted soils within urban landscapes. This treatment significantly enhanced root and canopy growth, thereby increasing the ecosystem benefits provided by trees, which could potentially help mitigate the adverse effects of global climate change.

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