The Ohio Chapter ISA's research committee is responsible for locating and disseminating research findings that affect Ohio tree care professionals and tree care. This is a summary of the findings provided by the committee.

The Influence of Soil Decompaction and Amendments on Soil Quality

The research focuses on the impact of soil compaction on urban trees and evaluates different decompaction methods, including air spading, vertical mulching, biochar application, and woodchip mulching.

Over 5 years, the study assessed the individual and combined effects of these techniques on soil quality, considering factors such as bulk density, organic matter, vegetation ground cover, root growth, and earthworm counts.

The most effective treatment for heavily compacted soil is a combination of air spading, biochar, and woodchip mulch, although it is also the most expensive and time-consuming. Woodchip mulch alone is the most cost-effective treatment. Air spading alone is reasonably practical and can be enhanced by adding woodchip mulch. Vertical mulching, combined with biochar, has little influence on soil quality over the 5 years.

The study underscores the importance of adopting effective long-term soil decompaction measures to improve the survival of urban trees in compacted soils resulting from human activities.

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The Influence of Soil Decompaction and Amendments on Soil Quality

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Abstract. Urban soil is often compacted during anthropogenic activities, which presents a challenging substrate for tree growth. Two techniques for decompacting soils (air spading and vertical mulching) were evaluated alone and in combination with the soil amendment biochar and/or a woodchip mulch. Effects on soil quality (bulk density, organic matter, vegetation ground cover, cotton strip degradation, root dry mass, and earthworm counts) were monitored over 5 years. A combined treatment of air spading, biochar, and a woodchip mulch layer proved optimal in improving the soil quality of a heavily compacted soil over the 5-year period. This treatment was, however, the most expensive and time-consuming. A woodchip mulch was the most effective of the individual treatments and the most cost-effective. Air spading alone proved reasonably effective in improving soil quality over the 5-year study period. Effects of air spading could be improved by addition of a woodchip mulch. Vertical mulching alone or in combination with biochar had little influence on soil quality over 5 years. Results demonstrated that effective long-term soil decompaction measures exist for arborists to improve compacted soils.

Keywords. Air Tillage; Compaction; Plant Health Care; Root Growth; Soil Biological Activity; Soil Management; Urban Soils.

INTRODUCTION

Soil compaction within the urban landscape is frequently caused by anthropogenic activity (grey infrastructure installation and maintenance, urban development, pedestrian and vehicular traffic) and is negatively associated with soil quality (Day and Bassuk 1994; Day et al. 1995; Smiley 2001; Sax et al. 2017; Rahman et al. 2019). Construction activities occurring during urban development and building tasks may intentionally compact soil in order to make grade alterations or construct roads. Soil compaction, however, directly reduces soil pore space and pore continuity, resulting in reduced gas exchange between the atmosphere and soil surface. If soil bulk density exceeds the root limiting bulk density value for the respective soil texture, root elongation decreases, and root branching and radial thickening increases, further limiting the spread of the root system and decreasing the uptake of essential soil nutrients (Gliński and Lipiec 1990; Day and Bassuk 1994). Trees growing in compacted soils also tend to experience winter waterlogging due to slowed water infiltration and percolation, summer drought stress due to reduced water-holding capacity, and increased proportion of hygroscopic water. Furthermore, soil compaction results in detrimental effects on soil flora and fauna, increasing a tree's disposition to root-borne diseases such as *Phytophthora* and *Armillaria*. Consequently, soil compaction is recognised as a major constraint to urban tree survival (Hascher and Wells 2007; Scharenbroch and Watson 2014; Watson et al. 2014).

To remediate soil compaction, a few management strategies can be adopted, such as air spading, vertical mulching, soil application of biochar, and/or a woodchip mulch layer across the compacted soil surface. Air spading is functionally similar to conventional mechanical tilling but uses a hand-held air excavation tool, which transforms pressured air generated from a compressor into a jet of supersonic air. The supersonic air fractures compacted soil into smaller aggregates and has been shown to be highly effective in decompacting soils, increasing soil aeration, and promoting root growth while inflicting limited damage to existing tree root systems (Smiley 2005; Day and Harris 2008; Day et al. 2009).

Vertical mulching involves creating a series of shallow holes 20 to 30 cm deep in and around the root zone and filling them with mixtures of high-quality topsoil, soil improvers such as compost, perlite, and/or vermiculite, inorganic or organic fertilizers, and/or mycorrhizal inoculants (Morris et al. 2009; Kuncheva 2015). The removal of soil to create holes can be performed with either an air excavation tool or an earth auger.

Biochar is the solid co-product of biomass pyrolysis: a technique used for carbon-negative production of second-generation biofuels. Biochar can be applied as a soil amendment, where it permanently sequesters carbon from the atmosphere as well as improving soil structure, nutrient retention, and crop productivity (Blackwell et al. 2009; Elad et al. 2012; Schaffert et al. 2022). Indirect evidence exists that biochar will aid in the reduction of soil compaction by altering the physical nature of most soils through increasing the soil surface area and enhancing soil pore space (Blackwell et al. 2009).

Woodchip mulches are regularly used within urban landscapes to improve soil quality. Woodchip mulches are applied to the surface of the soil from near the base of the tree trunk to at least the canopy edge at a depth of 5 to 10 cm. The beneficial effects of a woodchip mulch are numerous and include improved soil moisture, mitigated temperature fluctuations, weed suppression, soil/root-borne disease suppression, and enhanced soil fertility (Chalker-Scott 2007; Scharenbroch 2009).

Few if any studies have examined the long-term benefits of these systems individually and in combination on soil quality and fertility (Smith 1978; Kalisz et al. 1994; Morris et al. 2009). The aim of this research was to evaluate 3 decompaction methods (air spading, vertical mulching, application of a woodchip mulch) and a biochar soil incorporation individually and in combination with each other. The evaluation was conducted by assessing alterations to the physical, chemical, and biological properties of a heavily compacted soil over a 5-year period.

MATERIALS AND METHODS

Experimental Site

The study was conducted at Hatfield Forest, a 403.2-ha biological Site of Special Scientific Interest in Essex, United Kingdom (51°51'26", 0°13'46"). Hatfield Forest is also a National Nature Reserve and a Nature Conservation Review site. It is owned and managed by the National Trust. Soils throughout the forest have been identified as clay loam. Hatfield Forest can receive more than 10,000 visitors daily during the summer months. Consequently, multiple grass paths or "Rides" exist throughout the forest for visitors. Over time, soil compaction caused by human activity has become a serious problem. Prior to treatments, 4 Rides were identified. Bulk density of the Rides ranged between 1.73 and 1.80 g/cm^3. Consequently, soil densities were higher than the growth-limiting bulk density (1.50 g/cm^3) for a clay-loam texture, and root-growth impairment was highly likely. In support of this, waterlogging during wet weather was a frequent and annual problem, and a total lack of vegetation on the soil surface was observed at the 4 sites selected for study.

Experimental Design and Treatment Application

For each of the 4 heavily compacted Rides selected for study within Hatfield Forest, one experimental site per Ride was identified. Within each site, 9 treatments in 3 × 3 m plots with a 1-m spacing between plots were used as below:

1. Control: no soil decompaction work was undertaken.
2. WCM: addition of 5 cm of woodchip mulch over the compacted surface.
3. AS: the entire 3 × 3 m plot was air spaded (AirSpade® 2000, Concept Engineering Group, Verona, Pennsylvania, USA) to a depth of 25 to 30 cm.
4. AS + WCM.
5. AS + B: air spading and incorporation of biochar at 5% by volume.
6. AS + B + WCM.
7. VM: 30-cm deep, 7.5-cm wide holes were drilled for vertical mulching using a mechanical auger at 30 × 30 cm distances. The soils removed by the process were decompacted by hand and, where necessary, a wooden mallet was used to backfill the holes.
8. VM + B: only the decompacted soil was amended with biochar at 5% by volume.
9. VM + B + WCM.

Woodchip mulch was created from 5- to 8-cm diameter branches of silver birch (*Betula pendula* Roth.) and English oak (*Quercus robur* L.) that were pruned from trees located within Hatfield Forest and chipped with a commercial brush chipper to produce 4- to 6-cm long chips. Each mulch (50% silver birch, 50% English oak) was applied to the respective treatment plots immediately after chipping. The mulch was made when trees were fully dormant (February 2016) when no foliage was present on the tree.

The biochar used in this experiment was derived solely from English oak (*Q. robur* L.) and produced in a SuperChar 100 Mk I kiln (Carbon Gold, Clevedon, United Kingdom) 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.

Each trial site was then protected from possible animal and/or human ingress by installing 2 × 3 m (height and length, respectively) wooden fencing around the peripheral site edge of each experimental site, and each Ride was closed to public access by installing 2 × 3 m (height and length, respectively) wooden fencing at the entrance and end of each Ride.

During the 5-year experimental period, no management interventions (irrigation, fertilization, etc.) of any site occurred.

Bulk Density (Soil Compaction)

Bulk density measurements were taken prior to treatment application (February 2016) and annually throughout the study (2017–2021). 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, to account for soil variation (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).

Soil Organic Matter and pH Measurements

Soil organic matter content and soil pH were measured for each plot annually 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, United Kingdom. Soil samples were collected as outlined in the Natural England technical information note TIN035: 3 soil cores taken at 1-m intervals in a "V" pattern were amalgamated into one sample and oven dried for 72 h (Tytherleigh et al. 2008). Soil pH was determined by calibrating a pH meter (SevenExcellence™ pH meter S400-Std-Kit, Mettler-Toledo LLC, Columbus, Ohio, USA) over a pH range of 4 to 7 using standard buffers. Then 5 g of sieved (4-mm), air-dried soil was placed into a 100-mL centrifuge tube, and 10 mL deionized water was added to achieve a soil:water ratio of 1:2. The soil sample and deionized water were stirred vigorously for 15 seconds and left to stand for 30 minutes to equilibrate with atmospheric CO_2 and warm to room temperature. A pH electrode was placed in the soil/distilled water solution, swirled carefully, and the pH value taken to the nearest 0.01. Between samples, the electrode was rinsed with deionized water. Soil organic matter was estimated using the loss on ignition method, i.e., combustion of 100 g of air-dried, sieved (2-mm) soil in an oven at 360 °C for 6 hours followed by measuring weight loss.

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 and percolation. For each plot, 3 soil pits (20 × 20 × 20 cm) 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 were counted (AHDB 2018).

Cotton Strip Assay

The cotton strip assay is a field test used to assess the biological component of the soil. For each plot, 3 strips (20 × 15 cm) of unbleached calico cotton were buried 20 cm below the soil surface for 3 weeks; 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 5 (February 2021), when the mulch layer had degraded, 5 soil cores 5 cm in diameter and 20 cm deep (393 cm^3) were removed per plot, and any leaf litter, organic matter, and vegetation were removed from the top of the core. Within each plot, cores were only removed from areas where vegetation was observed growing. 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.

Vegetation Ground Cover

The coverage of all the vascular plants, bryophytes, lichens, bare soil, litter, and dead wood were estimated according to János (2006). The degree of which each plot was covered with vascular plants was assessed visually at year 5 (February 2021) and expressed as a percentage (Arideep and Madhoolika 2018).

Statistical Analysis

The data was analyzed using analysis of variance (ANOVA) and, where appropriate, differences between means were determined using Tukey's honest significance test ($P = 0.05$) using Genstat 19th edition software (VSNi International Ltd., Hemel Hempstead, United Kingdom).

RESULTS

Bulk Density (Table 1)

Air spading (treatments 3 to 6) had the most immediate effect on alleviating soil compaction: bulk density values were significantly lower ($P < 0.05$) than the non-decompacted control soil at the end of year one (February 2017). By year 5, the bulk density of treatments 3 to 6 were still significantly lower than the control soil and, in most cases, all vertically mulched plots (treatments 7 to 9). For years 1 to 5, bulk density values of the vertical mulch plots with a biochar soil amendment with or without a woodchip mulch (treatments 8 and 9) were significantly lower ($P < 0.05$) than the control soil. In the case of vertical mulching with a native soil backfill (treatment 7), bulk density was significantly lower than the control in years 1 and 2. For years 3 to 5, however, bulk density was not significantly different from the control soil. Application of a woodchip mulch alone (treatment 2) significantly reduced bulk density for years 1 to 5 compared to the control soil.

Organic Matter (Table 2)

Application of a woodchip mulch layer alone or in combination with air spading and/or biochar (treatments 2, 4, and 6, respectively) and a vertical mulching combination with biochar-amended soil and a woodchip mulch layer (treatment 9) had the most significant effect on soil organic matter content. Following these treatments, soil organic matter content was significantly increased compared to the non-decompacted control soil in years 1 and 2. Air spading and vertical mulching alone (treatments 3 and 7, respectively) or in combination with biochar-amended soil (treatments 5 and 8) had no significant effect on soil organic matter for years 1 to 5 when compared to control plots. For years 3 to 5, soil organic matter was, in the majority of cases, significantly higher than the control soil with the following exceptions: woodchip mulch (treatment 2, years 3 to 5), air spading in

Table 1. The influence of air spading (AS) and vertical mulching (VM) alone and in combination with a layer of woodchip mulch (WCM) and/or biochar (B) soil amendment on bulk density over 5 years.

Treatment	Year 1	Year 2	Year 3	Year 4	Year 5
1. Control	1.80c	1.80e	1.77c	1.79d	1.81e
2. WCM	1.70b	1.73d	1.60b	1.55b	1.53c
3. AS	1.45a	1.50b	1.47a	1.52b	1.60d
4. AS + WCM	1.43a	1.48ab	1.43a	1.49ab	1.41a
5. AS + B	1.40a	1.47ab	1.49a	1.48ab	1.44ab
6. AS + B + WCM	1.39a	1.42a	1.49a	1.45a	1.50bc
7. VM	1.70b	1.69cd	1.71c	1.75cd	1.78e
8. VM + B	1.69b	1.72d	1.63b	1.68c	1.64d
9. VM + B + WCM	1.66b	1.64c	1.60b	1.51ab	1.51c

Numbers within a column followed by a common letter are not significantly different according to Tukey's honest significance test ($P = 0.05$).

Table 2. The influence of air spading (AS) and vertical mulching (VM) alone and in combination with a layer of woodchip mulch (WCM) and/or biochar (B) soil amendment on soil organic matter over 5 years.

Treatment	Year 1	Year 2	Year 3	Year 4	Year 5
1. Control	2.8a	2.9a	2.7a	2.9a	2.9ab
2. WCM	4.1b	3.6bc	3.4abc	3.5ab	3.5bc
3. AS	2.6a	3.2ab	2.9ab	3.1ab	3.3bc
4. AS + WCM	4.4b	4.2cd	3.5bc	3.6b	3.7c
5. AS + B	2.8a	3.1ab	3.2abc	3.4ab	3.2abc
6. AS + B + WCM	4.6b	4.3d	4.4d	3.7b	3.5bc
7. VM	3.1a	2.7a	2.9ab	3.3ab	2.6a
8. VM + B	2.9a	2.6a	3.1abc	3.1ab	3.2abc
9. VM + B + WCM	4.4b	4.1cd	3.7c	3.6b	3.2abc

Numbers within a column followed by a common letter are not significantly different according to Tukey's honest significance test ($P = 0.05$).

Table 3. The influence of air spading (AS) and vertical mulching (VM) alone and in combination with a layer of woodchip mulch (WCM) and/or biochar (B) soil amendment on soil pH, vegetation ground cover (% VGC), cotton strip degradation (% CSD), and root dry mass (RDM) at year 5 after treatment.

Treatment	pH	% VGC	% CSD	RDM (mg/cm^3)
1. Control	6.2a	5.0a	12.1a	6.6a
2. WCM	6.6cd	65.0c	45.0c	11.7ab
3. AS	6.3ab	87.5d	49.2c	10.7ab
4. AS + WCM	6.5bc	97.5de	62.9de	11.8ab
5. AS + B	6.5bc	88.7d	57.1d	10.1ab
6. AS + B + WCM	6.7d	100.0e	67.9c	14.0b
7. VM	6.2a	15.0ab	13.8ab	8.3a
8. VM + B	6.3ab	18.8b	20.4b	8.8ab
9. VM + B + WCM	6.6cd	75.0c	47.5e	10.7ab

Numbers within a column followed by a common letter are not significantly different according to Tukey's honest significance test ($P = 0.05$).

combination with biochar and woodchip mulch (treatment 6, year 5), and vertical mulching with biochar amended backfill and woodchip mulch (treatment 9, year 5), where soil organic matter content was higher than the control but not significantly so.

pH (Table 3)

Irrespective of treatment, there was little significant effect on soil pH recorded throughout the 5-year study. For reasons of clarity, only data for year 5 is shown. Soil pH ranged from 6.2 (control) to 6.7 (treatment 6, air spading in combination with biochar and woodchip mulch). Results indicate that all soil decompaction and soil amendments resulted in a slight increase in soil pH towards alkalinity.

Vegetation Ground Cover and Cotton Strip Assay (Table 3)

At year 5, vegetation ground cover ranged from 5% (control) to 100% (treatment 6, air spading in combination with biochar and woodchip mulch), and the degree of cotton strip degradation ranged from 12.1% (control) to 67.9% (treatment 6, air spading in combination with biochar and woodchip mulch). The air spading treatments (3 to 6) had the greatest effect on vegetation ground cover and cotton strip degradation, which ranged from 87.5% to 100% and 49.2% to 67.9%, respectively. The order of which treatment had the greatest to least effect on both vegetation ground cover and cotton strip degradation was: air spading in combination with biochar and woodchip mulch (treatment 6); air spading in combination with woodchip mulch (treatment 4); air spading in combination with biochar (treatment 5); air spading alone (treatment 3); vertical mulching with biochar amended backfill and woodchip mulch (treatment 9); woodchip mulch alone (treatment 2); vertical mulching with biochar amended backfill (treatment 8); vertical mulching with native soil backfill (treatment 7); control.

Root Dry Mass (Table 3)

The treatments that had the greatest effect on root dry mass as measured in year 5 were: woodchip mulch alone (treatment 2), air spading in combination with woodchip mulch (treatment 4), and air spading in combination with biochar and woodchip mulch (treatment 6). These treatments resulted in an increase in root dry mass over the non-decompacted control soil that ranged from 77% to 112%. Vertical mulching with native soil backfill (treatment 7) had the lowest effect on root dry mass, with a non-significant increase of 26% over the control, and vertical mulching with biochar amended backfill (treatment 8) resulted in a slightly higher root dry mass (33% increase over the control), which was also non-significant. The only treatment which showed a significant increase in root dry mass when compared to the non-decompacted control soil was air spading in combination with biochar and woodchip mulch (treatment 6).

Earthworm Count (Table 4)

Air spading combination treatments (treatments 4 to 6), woodchip mulch alone (treatment 2), and vertical mulching with biochar amended backfill and woodchip mulch (treatment 9) had the largest positive effect on earthworm counts when counts were taken in years 3 and 5 (2019 and 2021, respectively). These treatments had an earthworm count that was 150% to 250% higher than the control in year 3 and 33% to 133% higher in year 5. These differences were significant ($P < 0.05$) with the exception of air spading in combination with woodchip mulch (treatment 4) in year 3, and woodchip mulch alone (treatment 2) and air spading in combination with biochar (treatment 5) in year 5. Although earthworm counts were higher than the control by 150%, 33%, and 67%, respectively, these differences were not significant. Air spading (treatment 3), vertical mulching with native soil backfill (treatment 7), and vertical mulching with biochar amended backfill (treatment 8) had no significant effect on worm counts compared to the non-decompacted control soil at years 3 and 5.

Table 4. The influence of air spading (AS) and vertical mulching (VM) alone and in combination with a layer of woodchip mulch (WCM) and/or biochar (B) soil amendment on earthworm counts at years 3 and 5 after treatment.

Treatment	Year 3	Year 5
1. Control	1.7a	2.5a
2. WCM	5.6c	4.2ab
3. AS	2.6ab	2.3a
4. AS + WCM	4.8bc	6.6b
5. AS + B	6.0c	4.9ab
6. AS + B + WCM	6.7c	6.1b
7. VM	2.7ab	2.9a
8. VM + B	2.0a	2.9a
9. VM + B + WCM	6.5c	6.6b

Numbers within a column followed by a common letter are not significantly different according to Tukey's honest significance test ($P = 0.05$).

DISCUSSION

Throughout the 5-year study, in most cases the greatest treatment effects on soil quality in terms of bulk density, soil organic matter, vegetation ground cover, cotton strip degradation, root dry mass, and earthworm counts were the result of air spading in combination with biochar and woodchip mulch applied across the treated surface area. Few published studies evaluating the short- and long-term effects of combining air spading, biochar, and woodchip mulch on soil quality exist. Of the research available, Fite et al. (2011) investigated the effects of air spading using an AirSpade® 2000, fertilizer, and mulch application singly and in combination at 4 urban sites located in Pennsylvania, South Carolina, Massachusetts, and Boston. Soil quality parameters measured included: bulk density, soil strength, soil organic matter, soil nutrient levels, and soil volumetric water content. They concluded that the air spading plus the incorporation of fertilizer and a woodchip mulch layer treatment was the most effective in improving soil quality, and that a multi-pronged approach to soil remediation provides arborists with an effective means to improve compacted soils under established trees. Similarly to the study of Fite et al. (2011), air spading in combination with biochar and a woodchip mulch layer was the most effective but time consuming and expensive treatment in this study. In contrast, application of woodchip mulch alone, which was the most inexpensive and least time-consuming treatment, also proved very effective in increasing vegetation ground cover, cotton strip degradation, root dry mass, earthworm count, and soil organic matter content. The benefits of a woodchip mulch layer on soil quality are well documented in the literature and include fertilization, organic matter enhancement, maintenance of soil temperature and moisture, and weed suppression (Chalker-Scott 2007; Scharenbroch 2009). Few studies have, however, evaluated the long-term (3 to 5 year) impacts of a woodchip mulch layer on soil quality and fertility. Of that available, 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 tree growth of *Acer rubrum* and *Betula nigra* in a compacted urban soil. Results here support the findings of Scharenbroch and Watson (2014) and Fite et al. (2011) in that a woodchip mulch layer provides a simple and relatively inexpensive method of long-term soil structure improvement, creating a soil environment optimal for root growth. In a related study, Sax et al. (2017) evaluated a Scoop & Dump (S&D) system, i.e., physical fracturing of compacted soils in combination with application of locally sourced compost and annual mulching. Benefits on soil quality over 12 years included reduced bulk density, increased active carbon, and potentially mineralized nitrogen, with the conclusion that the S&D system has potential for improving long-term quality of compacted soils using relatively straightforward methodology.

One of the functions of a woodchip mulch layer is to suppress competing vegetation growth. The increase in vegetation ground cover at year 5 in this study can be explained by the fact that by the end of year 3, most of the woodchip layer had decomposed, and the subsequent increase in soil fertility allowed for rapid establishment of vegetation (Watson 1988; Fite et al. 2011). Likewise, the increase in vegetation ground cover recorded at year 5 involving woodchip mulch (treatments 2, 4, 6, and 9) may be due to enhanced soil biological activity caused by mulch decomposition (Scharenbroch and Watson 2014). In support of this, a significantly higher worm count was recorded in woodchip-mulch-treated soils compared to a non-decompacted soil (control). Earthworms, through their burrowing activity, play a major role in the structural and functional heterogeneity of soils (AHDB 2019). Earthworm counts are also recognized as a useful proxy of soil health and biological activity (Riches et al. 2013; AHDB 2018). For example, application of earthworms to compacted agricultural soils has been shown to alleviate compacted soil and improve structure, resulting in enhanced crop yields (Riches et al. 2013; Thomsen et al. 2019). Likewise, the cotton strip assay is a quantitative assay for biological activity and is consequently used to assess ecosystem integrity, because this method provides a standardized measure of organic matter decomposition (Reid and Cox 2005). Higher rates of cotton strip degradation in woodchip-mulch-treated plots in this study indicate enhanced biological/microbial activity below ground (Reid and Cox 2005).

Although vertical mulching is recognized as a means of decompacting soils, results of this study found few significant effects on soil quality over a 5-year period following this treatment. One of the disadvantages of vertical mulching is that although this process ameliorates compaction in each hole, the bulk soil between the holes remains largely compacted (Morris et al. 2009). Even the addition of the soil amendment biochar in combination with vertical mulching had little influence on enhancing soil quality, as effects on soil quality were not, in many cases, significantly different from non-decompacted control soils at year 5 after treatment. Application of a woodchip mulch after vertical mulching and biochar soil amelioration, however, resulted in a significant increase in all soil quality measurements, again emphasizing the effectiveness of a woodchip-mulch treatment in ameliorating long-term soil compaction. Other researchers indicate vertical mulching to be more effective as a means of decompacting soil and improving soil microbial activity and plant quality when combined with fertilizer-based soil amendments, which was not undertaken in this study (Kuncheva 2015; Nandhini et al. 2021).

In agreement with other findings, air spading alone or in combination with biochar soil amendment and a woodchip mulch layer had the most immediate effect on significantly reducing bulk density (Morris et al. 2009; Fite et al. 2011). Differences in bulk density were also, in most cases, still significantly lower than the non-decompacted control soil by the end of the fifth year after treatment. There was, however, a gradual increase in bulk density values from year 1 to year

5, possibly as a result of long-term soil settling combined with light foot traffic caused by members of the public (Morris et al. 2009). Similarly, air spading alone or in combination with biochar soil amendment and a woodchip mulch layer had the greatest effects on vegetation ground cover at the end of year 5. Ground cover is widely used as an indirect indicator of soil quality; a soil lacking a cover of living plants is almost certainly indicative of poor soil quality (Zuazo and Pleguezuelo 2009). A lack of vegetation ground cover or smaller stunted plants is also associated with compacted soils (Ben-Dor et al. 2009). By year 5, 100% vegetation ground cover was recorded following air spading in combination with biochar and a woodchip mulch layer compared to 5% in non-decompacted control soils, indicating a significant improvement in soil quality. Vegetation ground cover observed at year 5 consisted mainly of grassland species (*Lolium perenne*, *Poa annua*) and a few weed species, including white clover (*Trifolium repens*), dandelion (*Taraxacum officinale*), nettle (*Urtica dioica*), and dock (*Rumex obtusifolius*). The percent composition of each species within each treatment was not quantified in this trial.

The application of biochar as a soil amendment has been shown to enhance transplant survival of young trees, improve root growth and health of mature established trees, reduce soil compaction, and reduce the severity of root pathogens such as *Armillaria* and *Phytophthora* (Scharenbroch et al. 2013; Schaffert and Percival 2016; Blanco-Canqui 2017; Yoo et al. 2020; Schaffert et al. 2022). Results of this study, however, show little improvement in soil quality when biochar was added via vertical mulching. Similar results, i.e., little root growth, have been obtained when using other soil amendments such as perlite, an amorphous volcanic glass, in combination with vertical mulching (Kalisz et al. 1994). Indeed, the work of Kalisz et al. (1994) concluded that perlite-filled vertical mulch channels were actively avoided by tree roots of *Acer saccharum*. In another study, tree growth responded as well to empty holes as it did those filled with fertilizer following vertical mulching (Smith 1978). Watson et al. (1996) found that replacement of soil within the root zone of mature *Quercus alba* via radial trenching improved fine root density by 320% and rooting depth by 68%. Although application of biochar in combination with air spading resulted in a significant improvement in soil quality, these improvements were, in most instances, not significantly greater than air spading alone. Consequently, results of this study indicate that biochar addition in combination with air spading and vertical mulching had limited effects on improving soil quality compared to air spading and vertical mulching alone.

CONCLUSIONS

A combined treatment of air spading, biochar, and woodchip mulch proved optimal in improving a suite of soil physical, chemical, and biological properties in a heavily compacted soil over a 5-year period. This treatment was also the most expensive and time consuming. A woodchip mulch layer was the most effective of the individual treatments and the most cost effective. Vertical mulching alone had little influence on soil quality. Air spading alone proved effective in improving soil quality over a 5-year period, and the long-term effects of air spading could be improved by the addition of a woodchip mulch layer. In agreement with Fite et al. (2011), results demonstrate effective long-term soil decompaction measures exist that provide arborists with a useful means to improve compacted soils within urban landscapes.

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Résumé. Le sol urbain est souvent compacté par les activités anthropogéniques, ce qui constitue un enjeu complexe pour la croissance des arbres. Deux techniques de décompactage des sols (bêchage pneumatique et paillage vertical) ont été évaluées individuellement et en combinaison avec un amendement de sol biochar et/ou un paillis de copeaux de bois. Les effets sur la qualité du sol (densité apparente, matière organique, couverture végétale, dégradation des bandes de coton, masse sèche des racines et nombre de vers de terre) ont été suivis pendant 5 ans. Un traitement combiné de bêchage pneumatique, de biochar et d'une couche de paillis de copeaux de bois s'est avéré optimal pour améliorer la qualité d'un sol fortement compacté sur une période de 5 ans. Ce traitement était cependant le plus onéreux et nécessitait le plus de temps. La pose d'un paillis de copeaux de bois a été le plus efficace des traitements individuels et le plus rentable. Le bêchage pneumatique, utilisé seul, s'est avéré raisonnablement efficace pour améliorer la qualité du sol au cours de la période d'étude de 5 ans. Les effets du bêchage pneumatique pourraient être améliorés par l'ajout d'un paillis de copeaux de bois. Le paillage vertical individuellement ou en combinaison avec le biochar a eu peu d'influence sur la qualité du sol sur une période de 5 ans. Les résultats démontrent qu'il existe des mesures efficaces de décompactage du sol à long terme permettant aux arboriculteurs d'améliorer les sols compactés.

Zusammenfassung. Städtische Böden werden häufig durch anthropogene Aktivitäten verdichtet, was ein schwieriges Substrat für das Wachstum von Bäumen darstellt. Zwei Techniken zur Dekompaktierung von Böden (Spatenstich und vertikales Mulchen) wurden allein und in Kombination mit der Bodenverbesserung Biokohle und/oder einem Holzschnitzelmulch bewertet. Die Auswirkungen auf die Bodenqualität (Schüttdichte, organische Substanz, Bodenbedeckung durch die Vegetation, Abbau der Baumwollstreifen, Wurzeltrockenmasse und Regenwurmzahl) wurden über einen Zeitraum von fünf Jahren beobachtet. Eine kombinierte Behandlung aus Luftspaten, Biokohle und einer Mulchschicht aus Holzschnitzeln erwies sich als optimal für die Verbesserung der Bodenqualität eines stark verdichteten Bodens über einen Zeitraum von fünf Jahren. Diese Behandlung war jedoch die teuerste und zeitaufwändigste. Eine Mulchschicht aus Holzschnitzeln war die wirksamste der einzelnen Behandlungen und die kostengünstigste. Die Luftumwälzung allein erwies sich bei der Verbesserung der Bodenqualität über den 5-Jahres-Zeitraum der Studie als recht wirksam. Die Wirkung des Luftstreichens konnte durch die Zugabe von Hackschnitzelmulch noch verbessert werden. Vertikales Mulchen allein oder in Kombination mit Biokohle hatte über einen Zeitraum von 5 Jahren kaum Einfluss auf die Bodenqualität. Die Ergebnisse zeigen, dass es für Baumpfleger wirksame Maßnahmen zur langfristigen Bodenverfestigung gibt, um verdichtete Böden zu verbessern.

Resumen. El suelo de Australia a menudo se compacta debido a las actividades antropogénicas, lo que hace un sustrato desafiante para el crecimiento de los árboles. Se evaluaron dos técnicas para descompactar suelos (pala de aire y acolchado vertical) solas y en combinación con el biochar de enmienda del suelo y/o un mantillo de astillas de madera. Los efectos sobre la calidad del suelo (densidad aparente, materia orgánica, cubierta vegetal del suelo, degradación de tiras de algodón, masa seca de raíces y recuentos de lombrices de tierra) se monitorearon durante 5 años. Un tratamiento combinado de pala de aire, biochar y una capa de mantillo de astillas de madera demostró ser óptimo para mejorar la calidad de un suelo muy compactado durante el período de 5 años. Este tratamiento fue, sin embargo, el más caro y lento. Un mantillo de astillas de madera fue el más efectivo de los tratamientos individuales y el más rentable. La pala de aire sola demostró ser razonablemente efectiva para mejorar la calidad del suelo durante el período de estudio de 5 años. Los efectos de la pala de aire podrían mejorarse mediante la adición de un

mantillo de astillas de madera. El acolchado vertical solo o en combinación con biochar tuvo poca influencia en la calidad del suelo durante 5 años. Los resultados demostraron que existen medidas efectivas de descompactación del suelo a largo plazo para que los arboristas mejoren los suelos compactados.

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