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Research article

Improving stormwater infiltration and retention in compacted urban soils at impervious/pervious surface disconnections with biochar

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ABSTRACT

Urban development often results in compacted soils, impairing soil structure and reducing the infiltration and retention of stormwater runoff from impervious features. Biochar is a promising organic soil amendment to improve infiltration and retention of stormwater runoff. Soil at the disconnection between impervious and pervious surfaces represents a critical biochar application point for stormwater management from urban impervious features. This study tested the hypothesis that biochar would significantly improve water retention and transmission at four sites, where varying percentages (0%, 2%, and 4% w/w) of biochar were amended to soils between impervious pavement, and pervious grassed slopes. Field-saturated hydraulic conductivity (K_{sat}) and easily drainable water storage capacity were monitored at these sites for five months (two sites) and 15 months (two sites). At the end of the monitoring periods, the physical, chemical, and biological properties of each site's soil were assessed to understand the impact of biochar on soil aggregation, which is critical for improved soil structure and water infiltration. Results indicated that the field K_{sat}, drainable water storage capacity, and plant available water content (*AWC*) were 7.1 ± 3.6 SE, 2.0 ± 0.3 SE, and 2.1 ± 0.3 SE times higher in soils amended with 4% biochar, respectively, compared to the undisturbed soil. Factor analysis elucidated that biochar amendment increased the organic matter content, aggregate mean weight diameter, organo-mineral content, and fungal hyphal length while decreasing the bulk density. Across the 12 biochar/soil combinations, the multiple linear regression models derived from factor analysis described the changes in K_{sat} and *AWC* reasonably well with R^2 values of 0.51 and 0.71, respectively. Using soil and biochar properties measured before biochar addition, two recent models, developed from laboratory investigations, were found helpful as screening tools to predict biochar's effect on K_{sat} and *AWC* at the four field sites. Overall, the findings illustrate that biochar amendment to compacted urban soils can significantly improve soil structure and hydraulic function at impervious/pervious surface disconnections, and screening models help to predict biochar's effectiveness in this context.

1. Introduction

The conversion of natural pervious lands (grasslands, forests) into developed urban areas alters soil structure through the removal of vegetation and topsoil and extensive regrading and compaction, which increases soil bulk density, disrupts aggregation, and reduces porosity (Chen et al., 2014; Olson et al., 2013; Pitt et al., 2009). These changes in soil structure adversely impact soil hydraulic properties, reducing infiltration and water retention and increasing stormwater runoff (Ahmed et al., 2015; Chen et al., 2014; Rivers et al., 2021). To improve stormwater runoff reduction from the soil, soil amendments at the interfaces between impervious pavement and pervious soil – impervious/pervious surface disconnections are recommended (Voter and Loheide, 2018, 2020). Organic soil amendments are proposed as a cost-effective approach to meet increasingly stringent stormwater regulations since they improve the physical and hydraulic properties of

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existing compact urban soils and avoid the more costly construction of new stormwater best management practices (Imhoff and Nakhli, 2017; Ouedraogo et al., 2023).

Several studies have shown that amending urban roadway soils with compost improves soil physical properties, enhances stormwater infiltration, and reduces roadway stormwater runoff (Chen et al., 2014; Kranz et al., 2023; Olson et al., 2013; Rivers et al., 2021). While compost is a promising soil amendment in these locations, the potential release of nutrients from compost often makes it counterproductive for stormwater quality control (Stephanie et al., 2017; Taguchi et al., 2020). The longevity of compost after one application is also an open question since the compost decomposition rate is high resulting in a short half-life (Bolan et al., 2012). As an alternative to compost, biochar amendment may provide longer-lasting improvements since biochar is more recalcitrant with significantly longer half-life (3520 days) compared to compost (155 days) produced from similar feedstock (Bolan et al., 2012), and is thus more effective in sequestering carbon (Smith, 2016; Wang et al., 2023) with an estimated carbon sequestration factor of 80% compared to only 8% for compost after 100 years (Oldfield et al., 2018).

Biochar can potentially improve soil physical properties such as bulk density, particle size distribution, and porosity, directly affecting soil hydraulic properties such as saturated hydraulic conductivity (K_{sat}). However, based on meta-analyses of biochar amendment to primarily agricultural soils, the impact of biochar on soil physical and hydraulic properties is highly variable depending on the type of biochar and soil (Edeh et al., 2020; Omondi et al., 2016; Rabbi et al., 2021; Razzaghi et al., 2020). In addition, most studies reported immediate or short-term effects of biochar, which might be explained by biochar's influence on the intra- and inter-porosities of the soil matrix that govern water movement (Lim et al., 2016; Liu et al., 2017). However, with extended exposure to the environment, biochar pores may fill with soil minerals and microbes, triggering soil aggregation that changes soil water dynamics (Joseph et al., 2010; Juriga and Šimanský, 2018; Masiello et al., 2015; Wang et al., 2020). Thus, biochar amendment may enhance soil aggregation that improves soil structure, which then alters water retention and transmission critical for stormwater runoff management (Blanco-Canqui, 2017; Gul et al., 2015; Islam et al., 2021; Nkoh et al., 2021; Obia et al., 2016; Zhang et al., 2021). Moreover, a recent cost comparison between biochar amendment and 25 other best management practices for stormwater in the Chesapeake Bay Watershed found that to treat one acre (0.4 ha) of impervious surface, biochar amendment is less expensive than 21 other practices (Nakhli et al., 2021). Therefore, biochar amendment to urban roadway soil may be a viable stormwater management approach.

Despite the recognized benefits of biochar amendments, the long-term efficacy of biochar on urban roadway soil properties and stormwater infiltration is less explored, especially at impervious/pervious disconnections where soil may receive more water inflow from pavement runoff compared to urban soils in nearby locations. In addition, turfgrass, the prevalent plant in urban roadway soils, alters soil structure and hydraulic properties differently than agricultural crops (Lu et al., 2020). Therefore, this study aims to evaluate the hydrologic improvements resulting from biochar amendment at impervious/pervious disconnections before widespread biochar application for stormwater runoff reduction.

The primary objective of this study is to determine the significance of wood biochar amendment to compacted urban soils on water retention, vital for plant growth (Yoo et al., 2020), and saturated hydraulic conductivity (K_{sat}), critical for stormwater runoff reduction (García-Serrana et al., 2018; Voter and Loheide, 2020). Additionally, we assess the role of biochar in altering soil properties. We hypothesize that wood biochar amended to compacted urban soil increases soil aggregation due to increased organo-mineral content and fungal hyphal length. The organo-mineral content increases soil binding, while fungal hyphae improve the binding of microaggregates into macroaggregates (Bronick and Lal, 2005; Tisdall and OADES, 1982).

Finally, given the variable impact of biochar on soil, influenced by both the soil and biochar characteristics (Blanco-Canqui, 2017; Edeh et al., 2020; Omondi et al., 2016), predicting biochar's effect on K_{sat} and water retention is challenging; we are unaware of any model to predict biochar's effect on K_{sat} or water retention that has been validated with field data. This study tested the hypothesis that two recently developed models, despite their limitations, may provide reasonable estimates of biochar's effects on K_{sat} (Yan et al., 2021) and water retention (Yi et al., 2020) in compacted urban soils at impervious/pervious disconnections. To test these hypotheses, biochar was applied to urban soils at four sites at three different loadings and monitored up to 15 months.

2. Methods

2.1. Study site locations and characterization of soil and biochar

Four sites adjacent to roadways (Plaza and Ramp sites) and parking lots (Slack and Church sites), identified as critical points for stormwater management at impervious/pervious disconnections (NCDEQ, 2020), were selected. The Plaza and Ramp sites are managed by the Maryland Transportation Authority, which seeks cost-effective and long-lasting methods to alter roadway greenway soils to enhance stormwater infiltration. The Plaza site is located near the former Tydings Bridge toll plaza on northbound Interstate-95 (I-95) (39°35′ 14.1″N, 76°04′25.5″W), and the Ramp site is located at the southbound I-95 exit ramp to northbound MD 279 (39°38′29.6″N, 75°47′55.9″W). The Plaza and Ramp sites receive stormwater runoff from 58 m to 10 m wide concrete and asphalt roadways, respectively.

The Slack and Church sites are in Ellicott City, MD, known for devastating storms in 2016 and 2018 that led to severe short term flooding, property damage, and loss of human life (Doheny and Nealen, 2021). Within the Ellicott City watersheds, property owners and local government are in pursuit of cost-effective soil amendments to infiltrate stormwater at impervious/pervious surface disconnections (Wang et al., 2019). The Slack site is adjacent to Slack Funeral Home (39°15′51.3″N, 76°48′12.4″W), and the Church site is adjacent to St. Peters Episcopal Church (39°16′11.6″N, 76°48′34.4″W). The Slack and Church sites receive stormwater runoff from 27 m to 18 m wide asphalt parking lots, respectively, and are representative of impervious/pervious disconnections in the watershed.

Rogue Biochar (Oregon Biochar Solutions, White City, OR, USA), produced by pyrolyzing the top limbs of Douglas fir and Ponderosa pine at 950 °C, was selected for this study based on evidence that wood biochar, pyrolyzed at high temperatures (>600 °C) significantly improve soil aggregation and saturated hydraulic conductivity (Islam et al., 2021). Moreover, a local biochar distributor had access to a sufficient quantity required for this project. The Rogue Biochar was applied in the test sections at 2% and 4% by mass, since these application rates enhance soil aggregation and K_{sat} in bioretention mixtures (Akpinar et al., 2023). Considering that the top 20–30 cm surface soil of roadside swales is typically compacted (García-Serrana et al., 2017) yet responsible for infiltrating rainfall events $\leq$5 cmh^{-1} (Bharati et al., 2002), biochar amendments were targeted for 0–30 cm soil depth.

To evaluate the site soil bulk density and determine the required volume of biochar to achieve desired biochar mass amendments, undisturbed soil cores (2.25 cm diameter, 10–20 cm depth) were initially collected from each site at multiple locations. Because the Rogue Biochar had a particle envelop density of 0.44 g/cm^3, the 2% and 4% by mass biochar application was equivalent to 9% and 17% by volume. During the construction of test sections, a bulk sample of homogenously mixed tilled soil (0–30 cm depth) and a composite sample of biochar from 1.53 cubic-meter (2 cubic-yard) super sacks used for the construction were collected from each site to characterize the physical-chemical properties. These properties include particle size distribution, particle skeletal and envelop densities, intrapore volume (biochar), surface area, organic matter, cation exchange capacity, and extractable nutrients. The methods used for measuring these properties are described in Supporting Information (SI).

2.2. Construction of study sites

Test sections at each of the four sites were constructed in parallel and adjacent to impervious surfaces (within 0.30 m) to achieve maximum hydrologic benefit (Voter and Loheide, 2020). The test sections of the Plaza (total test area is 55.8 m^2) and Ramp (69.3 m^2) sites were constructed in June 2020 and consisted of a single section of a) Undisturbed (3 m × 3 m), b) Tilled with 0% (w/w) biochar (3 m x 4.5–6.1 m), c) Tilled with 2% (w/w) biochar (3 m x 4.5–6.1 m), and d) Tilled with 4% (w/w) biochar (3 m x 4.5–6.1 m), spaced 0.60 m apart (Fig. 1a). The Slack site (5.25 m^2) and Church site (5.25 m^2) test sections were constructed in March 2019 and consisted of single section of a) Tilled with 0% (w/w) biochar (1.5 m × 1.5 m), b) Tilled with 4% (w/w) biochar (1.5 m × 1.5 m), and c) Undisturbed (monitored after 15 months) test sections (Fig. 1b). Site construction involved turfgrass and topsoil removal for subsoil exposure, tilling and mixing soil for homogeneity, biochar addition, and seeding and mowing. The detailed construction procedures are provided in the SI.

2.3. Measurement of soil hydraulic properties

2.3.1. Field saturated hydraulic conductivity

Modified Phillip-Dunne (MPD) infiltrometers (Upstream Technologies, New Brighton, MN) were used to monitor K_{sat} during mid-late summer (July–September) and late fall (November) at different ages of the study sites (Table S1). For the Plaza and Ramp sites, K_{sat} was measured at two- and five-months following biochar amendment to capture the early effect of biochar, while for Slack and Church sites, measurements were conducted at five, seven-, and 15-months following biochar amendment to evaluate the prolonged-effect. The MPD infiltrometer measures infiltration from the ground surface to 10–25 cm depth by infiltrating ~3.5 L water (Ahmed et al., 2014; ASTM, 2018) and has been used to estimate K_{sat} in the field, which is an effective K_{sat} if air entrapment is significant (Ahmed et al., 2015; Alakayleh et al., 2019; Garza et al., 2017).

Given the expected spatial variability of K_{sat} because of natural variations in soil texture, porosity, and vegetation cover, multiple single-point K_{sat} measurements were performed during each test period to capture K_{sat} variability and determine a representative geometric mean K_{sat} for each section (Ahmed et al., 2015; Weiss and Gulliver, 2015). Five to 10 measurements were performed randomly at multiple points to determine the mean K_{sat} of each test section at the Slack and Church sites (Fig. S1). In the larger Plaza and Ramp sites, depending on the size of the treatment section, four to nine single-point K_{sat} measurements were performed following a regular grid pattern (1.5 m × 1.5 m) (Fig. S1). For simultaneous K_{sat} measurements at different site sections, 6 to 9 MPDs were used with a crew of two people. The K_{sat} measurement also required the initial volumetric water content (*VWC*) (cm^3/cm^3) before infiltration and the final *VWC* after measurement. Water content reflectometry was used to measure *VWC*, and was calibrated for each soil/biochar combination. Further methodological details on the K_{sat} and *VWC* measurements are provided in SI.

2.3.2. Water retention

At the beginning and end of each K_{sat} measurement, the *VWC* of the surface soils (0–5 cm depth) was measured. The *VWCs* were averaged across all sampling points for each monitoring period to determine an average initial and final (before and after K_{sat} measurement) *VWCs* for each test section. The final *VWCs* under each K_{sat} sampling point, indicative of near water-saturated conditions, are representative measures of the field-saturated *VWC*. The difference between the average field-saturated and initial *VWC* is defined here as the field water storage capacity of the topsoil – the *VWC* that might retain water from a storm event at the time of K_{sat} measurement.

During the last monitoring period at each site, undisturbed soil cores (Type 1:8 cm diameter and 5 cm height) were collected at 5–10 cm depth from three locations within each test section corresponding to the lowest, highest, and intermediate K_{sat} values (Fig. S1) to measure *VWC* at the field capacity (*FC*) and permanent wilting point (*PWP*). These measurements were performed using a pressure plate extractor (Soil Moisture Equipment Corp., Santa Barbara, CA USA) following standard procedures (Leong et al., 2004). Subsequent analyses on these cores included selected soil physical-chemical-biological properties to comprehensively assess the soil conditions following biochar amendment.

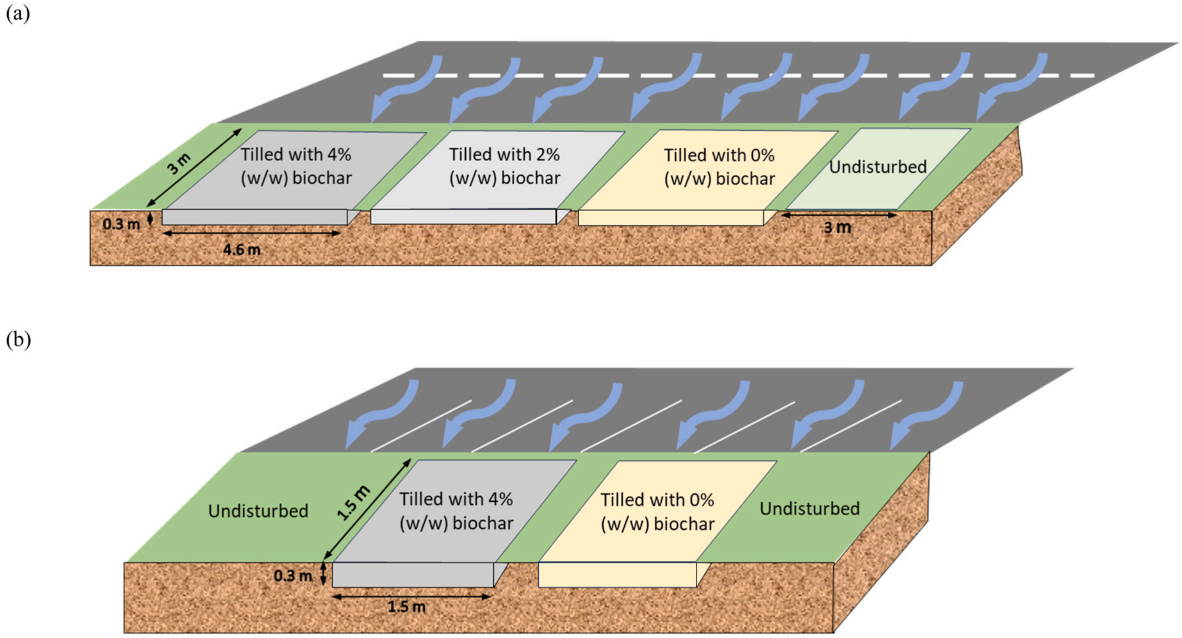

Fig. 1. Design of treatment sections at (a) Plaza site and (b) Church site as representative of the large-scale and small-scale sites, respectively.

2.4. Measurement of soil physical, chemical, and biological properties

2.4.1. Biochar content, median particle size, and pH

For the amended sections, biochar was intended to be applied at 2% (w/w) or 4% (w/w). To ascertain the actual biochar contents at the end of the last monitoring period (five months for Plaza and Ramp sites, 15 months for Slack and Church sites) soil cores (Type 2:2.86 diameter and 10 cm height), were collected in 10-cm increments from 0 to 30 cm, using an AMS compact slide hammer (Model 400.96, AMS, Inc., American Falls, ID). The biochar content in each sample was quantified using a two-temperature loss on ignition (LOI) method (Nakhli et al., 2019) and LOI profiles for native soil and biochar (Fig. S2). The median particle size of native and biochar-amended soil was determined based on the field biochar content and mass-based particle size distribution of soil and biochar separately. The pH was measured in 0.01 M $CaCl_2$ with a Hanna HI98194 pH meter (Hanna Instruments, Woonsocket, RI, USA) in a solid-solution ratio of 1:2.5 for soil and biochar-amended soil and 1:10 for biochar.

2.4.2. Soil compaction, bulk density, total porosity, and turfgrass

Soil compaction was measured at the Plaza and Ramp sites during the last monitoring period using a static cone penetrometer (Model H-4201 A, Humboldt Mfg. Co., Elgin, IL, USA). Four measurements were performed at the corners of a 30 cm × 30 cm square centered at each K_{sat} sampling point. The mean compaction pressure was recorded for each 10-cm depth interval, and the average of the four measurements was calculated. Due to space limitations at the smaller Church and Slack sites, compaction measurements were not performed to avoid interference in K_{sat} measurements.

Dry bulk density was determined using the Type 1 soil cores collected during the last monitoring period for water retention measurements. The total porosity of the undisturbed samples was calculated based on the dry bulk density, field biochar content, and envelop densities of biochar and soil particles (Table S2).

The impact of turfgrass on stormwater infiltration at the Plaza and Ramp sites was evaluated two months post amendment (August 2020). Turfgrass coverage was measured over a 30 cm × 30 cm square centered at each K_{sat} sampling point from a digital nadir photograph taken from ~1 m height. The digital images were analyzed to determine the percent green cover, a measure of vegetation density, using TurfAnalyzer (Green Research Services, LLC, Fayetteville, AR, USA) following established procedures. (Karcher et al., 2017; Karcher and Richardson, 2005; Russell et al., 2019). However, due to turfgrass dormancy, vegetation density measurements were not collected during the last monitoring period in late winter at the Plaza and Ramp sites. At the Church and Slack sites, in addition to the percentage of turfgrass cover, the grass species percentages were determined during the last monitoring period (15 months) due to notable differences in grass species, a phenomenon not observed at the other sites. Further details on the grass species measurement techniques are provided in SI.

2.4.3. Water stable aggregates

Water stable aggregates have been linked to the creation of macropores that transmit water at high rates in biochar-amended soils. Type 1 soil cores were collected during the last monitoring period to determine the large macroaggregate (5 mm), small macroaggregate (1.125 mm), and microaggregate (0.122 mm) fractions and the mean weight diameter (*MWD*) of aggregates. The measurement methodology is described in SI.

2.4.4. Factors affecting aggregation

After wet sieving, the remaining soil from Type 1 cores at each site was mixed and homogenized for each treatment section and then analyzed for organo-mineral associated content and fungal hyphal length, two critical parameters previously associated with the formation of water stable aggregates from the addition of wood biochar (Akpinar et al., 2023a; Nakhli, 2020). Organo-mineral association is a critical early step in the formation of microaggregates, while fungal hyphae stabilize and enlarge aggregates by enmeshing particles and microaggregates to form macroaggregates (Bronick and Lal, 2005; Tisdall and Oades, 1982). We postulate that biochar enhances the formation of water stable aggregates because it increases organo-mineral associated content and fungal hyphal length. Methods for measuring organo-mineral associated content and fungal hyphal length are described in SI.

2.5. Statistical analysis

One-way analysis of variance (ANOVA), post-hoc comparison of means test, correlation analysis, common factor analysis, and multiple linear regression were used to analyze and model field data. Details of these methods are discussed in SI.

3. Results and discussion

3.1. Biochar's effect on soil hydraulic properties

3.1.1. Field saturated hydraulic conductivity

Throughout the study, the effect of biochar amendment on K_{sat} was influenced by amendment age, season, site soil characteristics (soil and biochar characterization results are discussed in SI), and field conditions such as compaction, slope, and turfgrass. Early measurements (two months post amendment) revealed a significant increase ($p < 0.05$) in K_{sat} in all amended soils with subsequent decrease over time. Initially, at the Plaza site the geometric mean K_{sat} for 2% and 4% biochar-amended soil was 8.7 and 9.6 times higher, respectively, than undisturbed soil, but decreased over time (Fig. 2a, Table S3). A similar trend was observed at the Ramp site, with significantly higher mean K_{sat} ($p < 0.05$) in amended soils at two months post amendment (Fig. 2b). By five months, although K_{sat} of amended soil decreased, it remained significantly higher ($p < 0.05$) than that of undisturbed soil ($K_{sat} < 0.3$ cm/h), with ratios of 6.2 and 17.6 for 2% and 4% amended soil respectively. This decrease in K_{sat} over time is attributed to the soil's settling post-construction and seasonal changes from late summer to late fall. The cooler temperatures in the late fall monitoring period (50.1 °F in November versus 78.4 °F in August) increase water viscosity and surface tension potentially leading to soil structural changes and more air entrapment, which in turn can lower soil infiltration rate by 40–56% (Balstad et al., 2017; Ebrahimian et al., 2020).

In addition to the age of amendment and seasonal effects, the variation in K_{sat} at the Ramp site (Table S4 and Fig. S4) was affected by the site's topography: the Ramp site was notably steeper than other sites with a ground slope of 27 ± 2 SE% compared to 8.3 ± 0.7 SE%, 3.1 ± 0.9 SE%, and 9.2 ± 1 SE% at Plaza, Church, and Slack sites, respectively. The Ramp site's slope led to distinct differences in K_{sat} between the upslope and downslope regions (dividing the 3.0 m wide treatment section into 1.5-m wide Upslope and Downslope regions, Fig. S1). Initially, the mean K_{sat} of the downslope areas was, on average, 8.4 times higher than the upslope areas for both 2% and 4% biochar-amended soils (Table S4). At five months post amendment, this disparity lessened for the 2% biochar amendment but increased dramatically for the 4% amendment from a factor of 7.4 (two months post-amendment) to 47.9 (five months). The substantial increase in K_{sat} in downslope soils at the Ramp site is attributed to the erosion of biochar from upslope areas (Blanco-Canqui, 2017; Fu et al., 2021) and accumulation in downslope regions, which was supported by the higher biochar content in the surface soil of downslope versus upslope areas (discussed in 3.2.1).

Since biochar amendment involves tilling soil to a depth of 30 cm, comparing the biochar-amended soils with undisturbed soil does not isolate the impact of biochar from tillage. At the Plaza and Ramp site, measurements of K_{sat} in 0% amended soil (tilled, without biochar) were impractical due to extensive surface desiccation cracking post

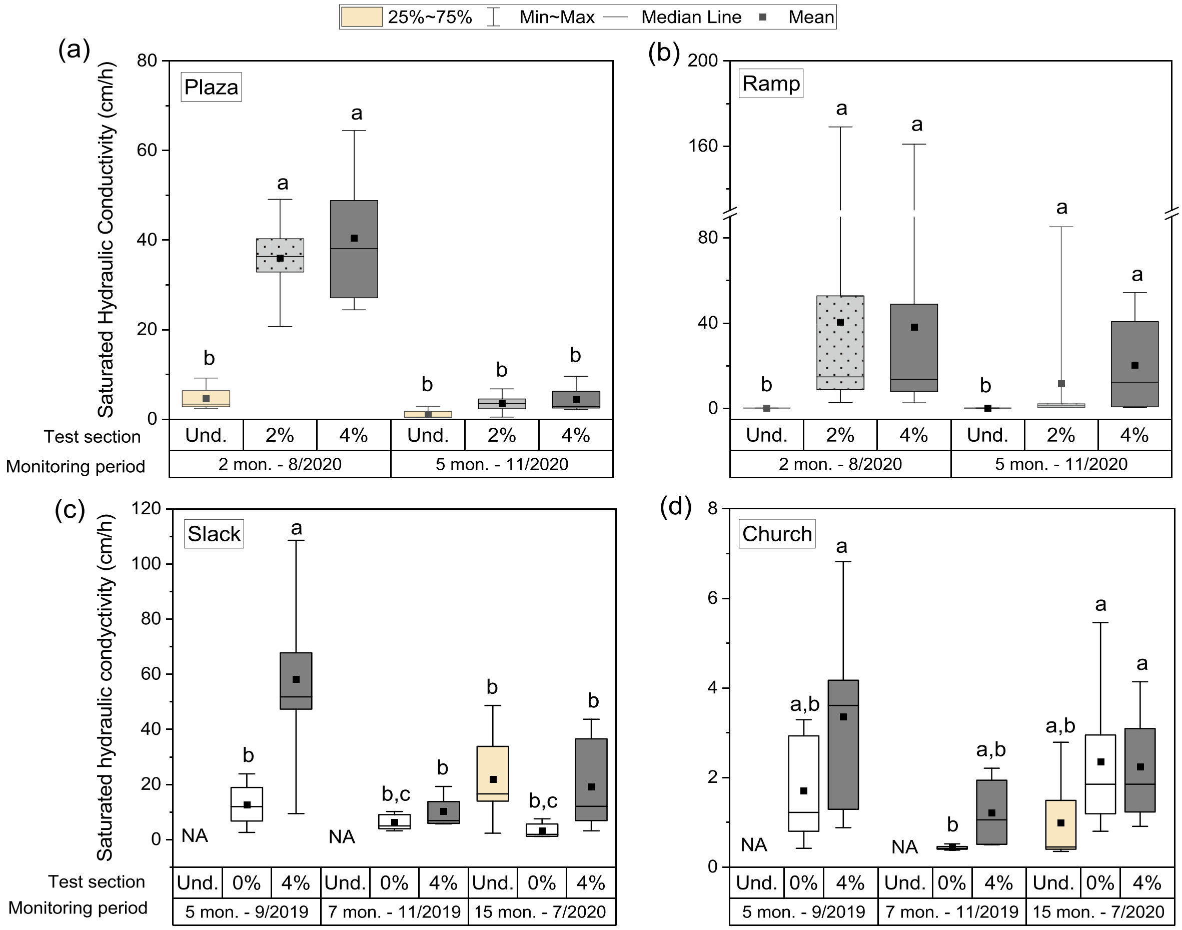

Fig. 2. Box plot showing the field saturated hydraulic conductivity (cm/h) for different test sections and monitoring periods at (a) Plaza site, (b) Ramp site, (c) Slack site, and (d) Church site. NA = data not available. Letters (a, b, c) represent statistical groupings based on Tukey's honestly significant difference in mean at the level of significance, α = 0.05. Groups sharing a letter do not differ significantly while those with different letters indicate significant difference in mean with hierarchical order a>b > c.

construction that led to preferential flow during infiltration tests (Fig. S3), which disrupted the homogeneity of soil permeability required for accurate MPD analysis (Ahmed et al., 2014). The cracks were likely caused by topsoil and turfgrass removal and subsequent hot and dry condition of late summer. In contrast, biochar's water retention and plant growth benefits (Yoo et al., 2020), discussed in 3.1.2, prevented such cracking in the biochar-amended sections.

The effect of biochar amendment over tillage could be assessed at the Slack and Church sites where the mean K_{sat} in 4% amended soil was 4.6 times and 1.9 times higher, respectively, than tilled soil (0% amendment) after five months (September 2019; Table S3). Although by late fall (November 2019) K_{sat} decreased in all sections, mirroring trends at the Plaza and Ramps sites, K_{sat} rebounded at both sites 15 months post-amendment (July 2020). At the Slack site, the mean K_{sat} in 4% amended soil was 5.3 times higher than tilled soil 15 months post-amendment. But K_{sat} in the tilled soil was lower than in the undisturbed soil, likely due to the undisturbed soil's 25% gravel content (Table S2) aiding water movement - a feature lost in the amended areas due to gravel removal during test site construction. For the Church site at 15 months post-amendment, the K_{sat} increase in 4% amended soil was modest (1.3 times) compared to tilled soil, but 4.9 times higher than undisturbed soil (Table S3). The unexpectedly high K_{sat} for the 0% amended and the adjacent undisturbed soil could be linked to the beneficial effects of tree shading on these regions that caused differences in turfgrass density and species in contrast to the 4% amendment. Tree shading only occurred for the 0% and undisturbed test sections, and its effect on turfgrass density and species is discussed in SI.

Despite the variable influences of soil type, age of amendment, season, and other field factors, by the end of monitoring period, combining data from all four sites, the mean K_{sat} increased by an average factor of 7.1 ± 3.6 SE over undisturbed soil with 4% by mass or 17% by volume biochar application. For comparison, a 50% by volume compost application increased K_{sat} by 27.1–76.3% for sandy or silty loam soil (Kranz et al., 2022) with porosity ranges (0.4–0.55 m^3/m^3) similar to porosities of the undisturbed soil in this study. The effect of biochar on mean K_{sat} for urban loam soil in this study is consistent with a meta-analysis of biochar's effects on soil water properties reported elsewhere (Edeh et al., 2020). The enhanced K_{sat} could potentially double the infiltration of runoff from impervious surfaces (García-Serrana et al., 2018), thereby improving stormwater management at impervious/pervious disconnections.

3.1.2. *Water retention*

Biochar amendment significantly enhanced the water retention of top soil (0–5 cm) as observed from the initial and final *VWCs* measured before and after K_{sat} measurements (Fig. 3a). Averaged across all sites, the 4% biochar-amended soils retained significantly ($p < 0.05$) more water at initial and saturated field conditions - by 80 ± 39% and 83 ± 34%, respectively - compared to undisturbed soil. As a result, the field water storage capacity (difference between the initial and final *VWCs*) in 4% amended soil was 2.0 ± 0.3 SE times greater than that for undisturbed soil. This enhancement demonstrates biochar's potential to improve soil water retention, boosting soil's capacity to hold water after a storm. Furthermore, plant available water content (*AWC*) of the 5–10

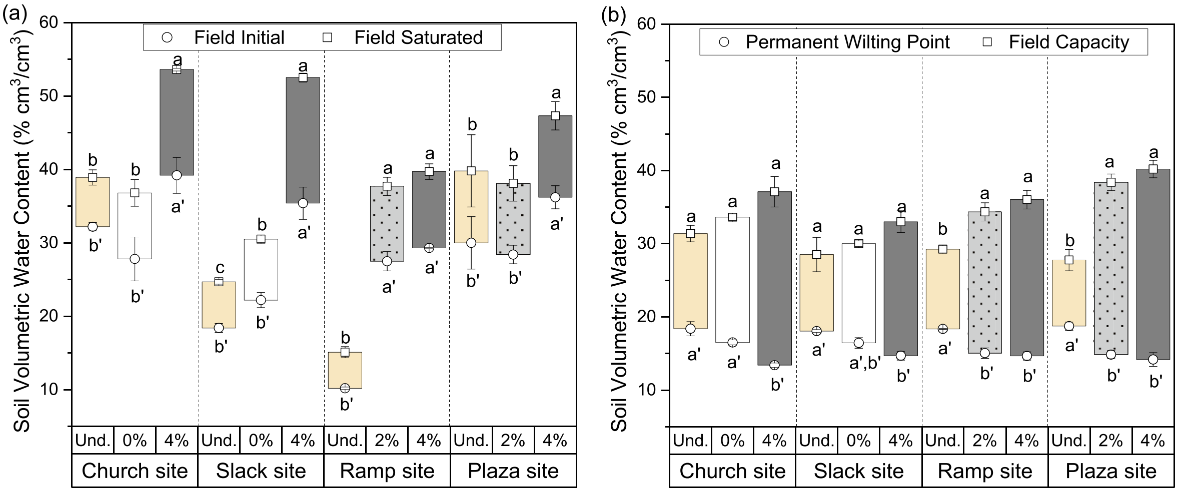

Fig. 3. (a) Water retention capacity (difference between the mean field initial and mean field saturated soil volumetric content over the whole monitoring period) of top 0–5 cm soil, (b) Plant available water content (difference between the mean field capacity and mean permanent wilting point of undisturbed field samples collected at the last monitoring period of each site). Letters (a, b, c) represent statistical groupings based on Tukey's honestly significant difference in mean at the level of significance, α = 0.05. Groups sharing a letter do not differ significantly while those with different letters indicate significant difference in mean with hierarchical order a>b > c.

cm soil layer was 2.1 ± 0.3 SE times greater in 4% (17% by volume) biochar amended soil compared to undisturbed soil, while the plant available water contents in soils amended with 10–30% by volume compost saw no improvement (Kranz et al., 2022). The increase in plant available water was accompanied by a higher field capacity (*FC*) and lower permanent wilting point (*PWP*), with on average, *FC* being 25 ± 6 % higher and *PWP* 22 ± 2 % lower in biochar amended soil compared to undisturbed soils (Fig. 3b). Similar but smaller field water storage capacity improvements were found for 2% amendment (Fig. 3b).

The enhanced water retention of biochar-amended soil, consistent with biochar's effect on other medium-textured soils (Razzaghi et al., 2020), is attributed to the added intra-porosity of biochar, increased interparticle porosity because of the large and irregularly shaped biochar particles, and the improved soil aggregation induced by biochar (discussed in 3.2.3) (Blanco-Canqui, 2017; Edeh et al., 2020; Hussain et al., 2021; Zhang et al., 2021). Additionally, biochar's larger particle size typically results in fewer micropores, contributing to a lower *PWP* than soil (Blanco-Canqui, 2017). This reduction in *PWP* coupled with an increase in *FC* is advantageous for turfgrass growth in compacted urban soil: it ensures more water available for plant uptake, thus minimizing the risk of plant wilting by maintaining higher water levels within the soil (Razzaghi et al., 2020).

3.2. Biochar's effect on soil physical, chemical, and biological properties

3.2.1. Biochar content, median particle size, and pH

Despite the initial aim to mix biochar at 2 or 4% dry mass fractions uniformly over the 30-cm depth treatment regions, imprecise measurements during biochar addition in the field, nonuniform tilling during field construction, and erosion resulted in smaller biochar contents than designed. Five- or 15-months post-amendment, a slight reduction in biochar content with soil depth was observed at Church, Slack, and Plaza sites (Fig. S5a). For the 4% amended soil, the field biochar content decreased from an average of 3.87 ± 0.83 SE % at the surface (0–10 cm depth) to 3.24 ± 1.06 SE % at deeper soils (20–30 cm depth). At the Ramp site, characterized by a steeper slope, biochar content was higher in downslope areas than in upslope regions (Fig. S5b): for example, biochar content at the downslope surface was 2.6 times higher than the 4% Upslope soil.

Low biochar contents in the upslope regions and enrichment at the downslope sections at the Ramp site are attributed to the erosional loss of biochar particles with stormwater flow across sloping soils (Blanco-Canqui, 2017). Moreover, the Rogue Biochar manufacturer reported a 34.9% retention rate (measured by Ball pen hardness test following AWWA B604-12), indicating the tendency of the biochar to break into smaller particles during tilling that might have contributed to the erosional losses. While the significance of this process was not quantified here, the smaller biochar particles might integrate more easily with the soil matrix and improve soil aggregation. Biochar amendment increased mean particle size (D50) at all sites but had mixed effects on soil pH, which varied with the age of amendment. These results are discussed in SI.

3.2.2. Soil compaction, bulk density, total porosity, and turfgrass

Biochar amendment at the Plaza and Ramp sites significantly decreased the mean compaction pressure at 0–20 cm depth after five months, without a notable differrence between 2% and 4% amendment (Fig. S6). Specifically, 4% amendment decreased the mean compaction from 10 ± 3 SE to 2 ± 1 (kg/cm^2) at 0–10 cm depth and from 20 ± 2 (kg/cm^2) to 6 ± 2 (kg/cm^2) at 10–20 cm depth. This amendment also significantly decreased the mean dry bulk density by 28 ± 1 SE% compared to undisturbed soil (Fig. S7a), a trend that persisted 15 months post amendment at Slack and Church sites with 18 ± 6 SE % reduction (Fig. S7b). The total porosity of the 4% amended soil increased by 19 ± 1 SE % at Plaza/Ramp after five months and 17 ± 7 SE % at Slack/Church sites after 15 months (Fig. S8). These changes are consistent with other research (Blanco-Canqui, 2017, 2021) and have been attributed to the lower particle density and higher porosity of biochar and biochar's enhancement of soil aggregation (Blanco-Canqui, 2017; Lim et al., 2016; Razzaghi et al., 2020).

Turfgrass coverage assessment at two months (Plaza and Ramp sites) and 15 months (Slack and Church sites) post amendment revealed that turfgrass density and species influenced K_{sat}. At the Plaza and Ramp sites, K_{sat} was strongly correlated ($r = 0.73$) with the grass coverage: as turfgrass cover density increased from 5-8% to 50–60%, K_{sat} rose from 2 to 10 to 40–60 cm/h for K_{sat} measurements in 2 and 4% biochar sections (Fig. S9). At the Church site, where the 4% amendment resulted in only a 30% increase in mean K_{sat} compared to 0% amended soil at 15 months post-amendment (Fig. 2d), this difference was attributed to denser turfgrass coverage under the shade of a nearby oak tree that favored the growth of deep-rooting grass species (details in SI). These findings highlight the need to explore biochar's effect on turfgrass, a potential area for future research.

3.2.3. *Water stable aggregates*

We postulate that a key mechanism by which biochar enhances water infiltration is through the formation of stable water aggregates that create macropores that transmit water and gas effectively (Mangalassery et al., 2013). To test this hypothesis, water stable aggregates, divided into microaggregates (0.053–0.25 mm), small macroaggregates (0.25–2 mm), and large macroaggregates (>2 mm), were measured in samples fro Type 1 soil cores collected at the last monitoring period. Averaged across all sites, 4% biochar amendment significantly increased the total water stable aggregate fraction by 41 ± 10 % and the mean weight diameter (*MWD*) of these aggregates by 62 ± 25 % compared to the undisturbed soil (Fig. 4). The positive effect of Rogue Biochar on soil aggregation varied with site soil characteristics and amendment age. For example, at the Plaza site (Fig. 4a), characterzied by the highest organic matter content among the site soils (6.76%, Table S2), 4% biochar amendment increased the water stable aggregate fraction by 19.3% than undisturbed soil after five months. Contrastingly, at the Church site with the lowest organic matter content (3.13%), the water stable aggregate fraction in 4% amended soil was 69.5% higher than undisturbed soil at 15 months post amendment, with *MWD* being 2.2 times larger while it was only 1.2 times larger at the Plaza site (Fig. 4d). These findings indicate that biochar's effect on wet aggregate stability is more pronounced in urban soils with lower organic matter content over time, consistent with other field studies (Islam et al., 2021; Wu et al., 2022). Additionally, it highlights biochar's critical role in improving soil aggregation and structural stability, thereby enhancing the capacity for water infiltration.

3.2.4. *Factors affecting aggregation*

Bicohar's role in increasing water stable aggregates can be further linked to the enhanced formation of organo-mineral complexes – essential building blocks of stable aggregate formation (Islam et al., 2021; Mukherjee and Lal, 2013; Pronk et al., 2012), and growth of fungal hyphae - a stabilizing factor of macroaggregates during water infiltration (Jien and Wang, 2013; Rahman et al., 2017; Zheng et al., 2018). Averaged across all sites, the 4% biochar amendment increased the organo-mineral content by a factor of 2.8 ± 0.8 SE (Fig. S11) and fungal hyphal length by a factor of 1.4 ± 0.1 SE (Fig. S12) compared to the undisturbed soils. These results are consistnet with wood biochar's impact on these properties in greenhouse investigations of biochar-amended biorentention media (Akpinar et al., 2023a) and a sandy loam soil (Akpinar, 2023b; Nakhli, 2020). The effect of biochar on increasing the organo-mineral content and fungal hyphal length was more significant for the Church/Slack site soil (analyzed after 15 months of amendment), where biochar resulted in more and larger water stable aggregates than undisturbed soil compared to the Ramp/Plaza soils (analyzed after five months of amendment).

The enhanced organo-mineral complex formation in biochar amended soil likely occurs via biochar serving as a formation nucleus, where biochar acts as a particulate organic matter (0.25–2 mm) and releases soluble organic matter, or as a precipitation nucleus, where biochar surface binds organic and mineral phases from soil (Mukherjee and Lal, 2013; Yang et al., 2016). These processes are intially facilitated by biochar's alkalinity which promotes the precipation of various mineral

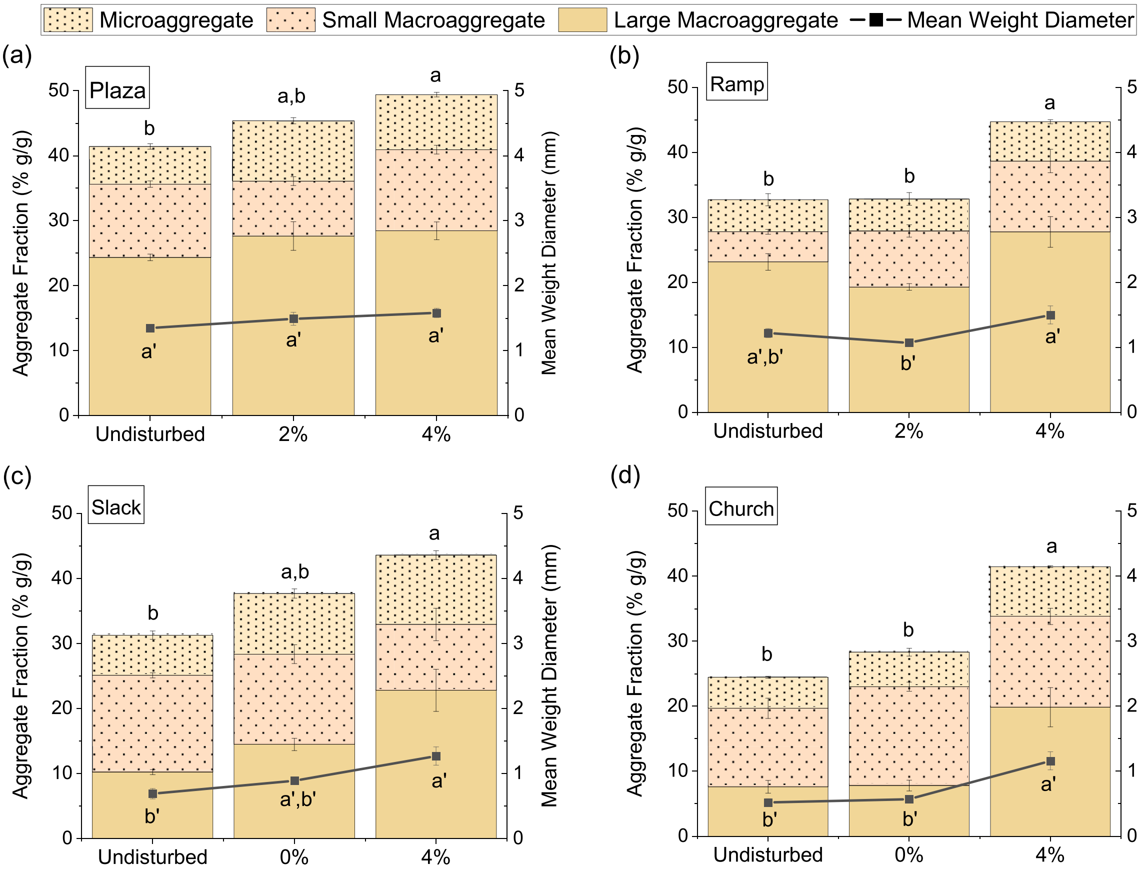

Fig. 4. Mean fraction (% g/g) of particle-corrected large macroaggregate (>2 mm), small macroaggregate (0.25–2 mm), and microaggregate (0.053–0.25 mm) and mean weight diameter (mm) of soil samples collected from (a) Plaza and (b) Ramp sites after five months of biochar amendment, and (c) Slack and (d) Church sites after 15 months of biochar amendment. Error bars depict the standard error of the means (n = 3 for all treatments). Letters (a, b, c) represent statistical groupings based on Tukey's Honestly significant difference in mean at the level of significance, α = 0.05. Groups sharing a letter do not differ significantly while those with different letters indicate significant difference in mean with hierarchical order a>b > c.

phases. As biochar ages, it's increased oxygen-containing surface functional groups favor the solubility of polyvalent cations and adsorption of mineral and organic matter (Joseph et al., 2010; Pignatello et al., 2015; Regelink et al., 2015).

The increase in fungal hyphal length in biochar-amended soil may be attributed to the high surface area and porous nature of biochar that promote fungi colonization and extension of hyphae to extract water and nutrients stored in internal biochar pores (Gul et al., 2015; Hammer et al., 2014; Jaafar et al., 2014). This fungal hyphae growth is further encouraged with biochar aging as the bicohar surfaces oxidizes and pH declines (Dai et al., 2021; Wang et al., 2020). These biochar enhanced soil aggreagation mechanisms underscore biochar's complex role in improving soil hydraulic properties over time.

3.3. Assessing correlations between biochar and soil properties

To understand the relationships between biochar amendment and soil properties and, with this understanding predict changes in K_{sat} and *AWC*, factor analysis was performed followed by multiple linear regression of factor analysis results (Finch, 2019) (details in SI). Initially, factor analysis used only soil physical properties and the two factors resulting from this analysis explained 83.6% of the total variance across seven soil physical parameters (Fig. 5a). Soil physical properties with strong positive loading (>0.75) with Factor 1 (interpret loadings like correlation coefficients) were biochar content, organic matter content, aggregate *MWD*, and total porosity, whereas the bulk density was strongly negatively loaded. D50 had the highest positive loading with Factor 2, and tillage had an intermediate loading with both Factors. Factor 1 is named "Biochar" in this analysis since biochar content and parameters strongly correlated with biochar content load highly onto it (see Table S5 for Pearson correlation coefficients). In contrast, Factor 2 is named "Particle Diameter" since D50 loads highly onto this factor. Although biochar amendment increased D50 at all four sites (Table S2), D50 was weakly loaded onto the Biochar factor (0.25 < |loading| < 0.5). This weak loading is attributed to the high sand (Church site) or gravel (Slack site) content at two of the four sites, which resulted in D50's for biochar-free media at these sites that exceeded D50's for biochar-amended Ramp and Plaza soils (Table S2).

Multiple linear regression, using these two Factors as predictors, described variations in *AWC* across all sites well ($R^2 = 0.76$) but was a weak predictor of K_{sat} ($R^2 = 0.38$) (Table 1). The factor analysis was extended to include soil pH, organo-mineral content, and fungal hyphal length (Fig. 5b). Organo-mineral content and fungal hyphal length loaded highly onto the Biochar factor with strong positive loadings (>0.75), while pH had a weak negative loading with the Biochar factor but moderate positive loading with Particle Diameter. Including organo-mineral content, fungal hyphal length, and pH, multiple linear regression improved the prediction for K_{sat} ($R^2 = 0.51$) while slightly reducing it for *AWC* ($R^2 = 0.72$). These results lead to two key insights. First, biochar amendment significantly influences several soil properties such as organic matter content, aggregate *MWD*, porosity, organo-mineral content, and fungal hyphal length positively while negatively impacting bulk density across all sites. Second, the models using the Biochar and Particle Diameter factors predict *AWC* well but are less precise for K_{sat}, suggesting the need for additional parameters like turfgrass root density for better prediction of K_{sat}.

Table 1
The multiple linear regression analysis results to describe variation in saturated hydraulic conductivity (K_{sat}) and available water content (*AWC*) using factors shown in Fig. 5. ± values are standard errors of the best-fit parameters.

Properties considered in Factors	Parameter	Regression equation	R^2
Physical properties (Shown in Fig. 4a)	K_{sat}	K_{sat} (cm/h) = (−0.437 ± 1.300) × Factor1 + (3.030 ± 1.300) × Factor2 + 4.186 ± 1.244	0.381
	AWC	AWC = (0.047 ± 0.009) × Factor1 + (0.017 ± 0.009) × Factor2 + 0.171 ± 0.009	0.757
Physical-chemical-biological properties (Shown in Fig. 4b)	K_{sat}	K_{sat} (cm/h) = (−0.837 ± 1.152) × Factor1 + (3.453 ± 1.152) × Factor2 + 4.186 ± 1.103	0.514
	AWC	AWC = (0.044 ± 0.010) × Factor1 + 0.020 ± 0.010) × Factor2 + 0.171 ± 0.010	0.713

3.4. Predicting biochar's effect on soil hydraulic properties

The statistical modeling discussed above illuminates the effect of biochar on soil properties, yet falls short of quantitatively predicting biochar's effect on K_{sat} and *AWC*, two parameters of particular interest to stormwater hydrologists We postulate that two recent models developed for K_{sat} (Yan et al., 2021) and *AWC* (Yi et al., 2020) may guide

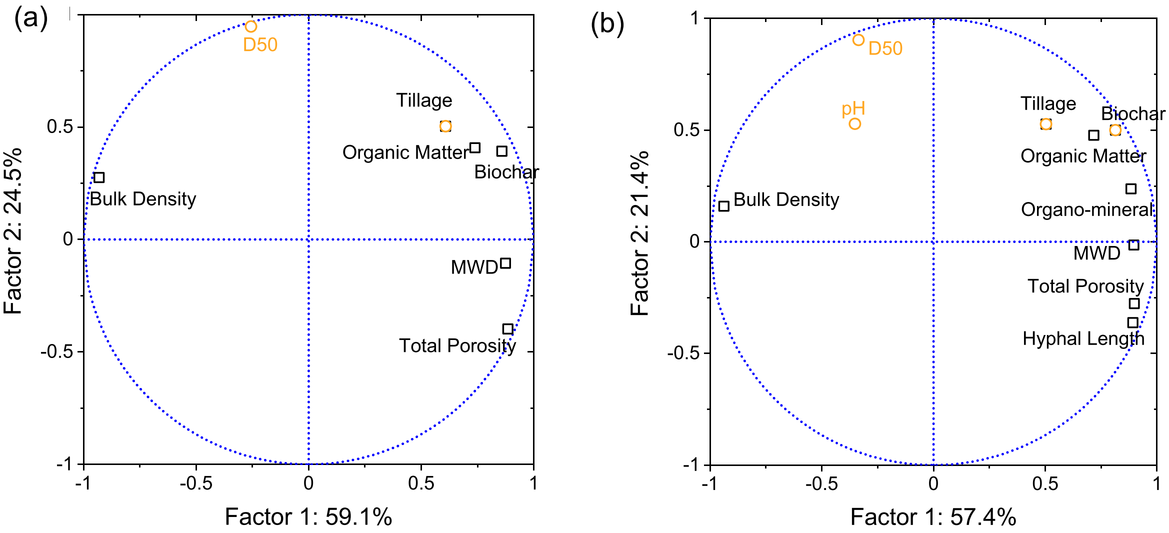

Fig. 5. Factor analysis of selected soil (a) physical properties and (b) physical-chemical-biological properties important for soil hydraulic properties - saturated hydraulic conductivity, K_{sat}, and available water content, *AWC*. Properties that are of identical color, black or brown, are strongly correlated with each other and Factor 1 (black) or Factor 2 (brown) with |loading| > 0.75; those with mixed color, black text and brown symbol (i.e., tillage), have loadings (|loading| > 0.5) with both factors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

biochar applications to achieve desired hydraulic properties, even if they do not predict K_{sat} and AWC precisely. When applied to our field dataset (modeling steps, required input data, and necessary measurement devices summarized in Table S6), the KC-OPT model (Yan et al., 2021), which is the Kozeny-Carmen model (Chapuis, 2012) optimized for wood biochar, accurately predicted biochar's positive effect in most of our soil/biochar mixtures, with a consistent underestimation of the magnitude of effect (Table S7). Across all six soil/biochar combinations, the KC-OPT model underpredicted the K_{sat} response factor ($K_{sat\text{-}bicohar}/K_{sat\text{-}undisturbed}$) by an average of 57 ± 11 SE % (Fig. 6). The Yi model (Yi et al., 2020) was modifed for this study to account for nonuniform biochar particles (model modifications described in SI). The Yi model was applied to our dataset (modeling steps, required input data, and necessary measurement devices summarized in Table S6) and successfully predicted an increase in AWC for all soil/biochar combinations (Fig. S15), albeit with an underprediction of the AWC response factor ($AWC_{bicohar}/AWC_{undisturbed}$) by 35 ± 6 SE %, on average (Fig. 6). The models' underprediction is due to the inability to incorporate dynamic changes like soil aggregation and turfgrass growth, which are induced by biochar leading to increased soil macroporosity and saturated water flow.

4. Summary and conclusions

This study added a commercial wood biochar to urban soils, specifically loam, and sandy loam, at varying percentages (0%, 2%, and 4% w/w) at four sites located between impervious pavement and pervious grassed slopes to improve the infiltration and retention of stormwater runoff. At the end of the monitoring periods, significant improvements were observed in the 4% biochar-amended soils compared to the undisturbed soil. Notably, the field-saturated hydraulic conductivity (K_{sat}) and easily drainable water storage capacity were on average 7.1 ± 3.6 SE and 2.0 ± 0.3 SE times higher in 4% biochar compared to undisturbed soils, suggesting that more numerous macropores were created in 4% biochar amendment, resulting in larger K_{sat}. Similarly, on average, the plant available water content (AWC) was 2.1 ± 0.3 SE times larger in 4% biochar than in undisturbed soils.

The study tested and confirmed two hypotheses. First, commercial wood biochar increases organo-mineral content and fungal hyphal length, which are correlated with more and larger water stable aggregates and improved water retention (AWC) and transmission (K_{sat}). This highlights the potential of biochar to mitigate the adverse effect of urban development on soil quality and stormwater management. Second, despite limitations, two recent laboratory-derived models correctly predicted the impact of biochar amendment on K_{sat} and AWC in field settings, i.e., if biochar would improve or degrade these properties, illustrating their utility as screening tools for informed decision-making of biochar amendments in specific urban locations to control stormwater runoff. The findings from this study underscore the importance of biochar's effect on organo-mineral association and fungal hyphae in improving hydraulic properties. Further exploration of biochar properties influencing organo-mineral association and fungal hyphae is recommended for a more comprehensive understanding of its effect. Overall, this study indicates that biochar amendment of compacted urban soils at impervious/pervious surface disconnections can significantly improve soil structure and hydraulic functions, which is imperative for stormwater runoff management from urban impervious features.

CRediT authorship contribution statement

Sraboni Chowdhury: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Derya Akpinar:** Investigation, Formal analysis. **Seyyed Ali Akbar Nakhli:** Formal analysis. **Marcus Bowser:** Investigation. **Elizabeth Imhoff:** Investigation. **Susan C. Yi:** Formal analysis. **Paul T. Imhoff:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

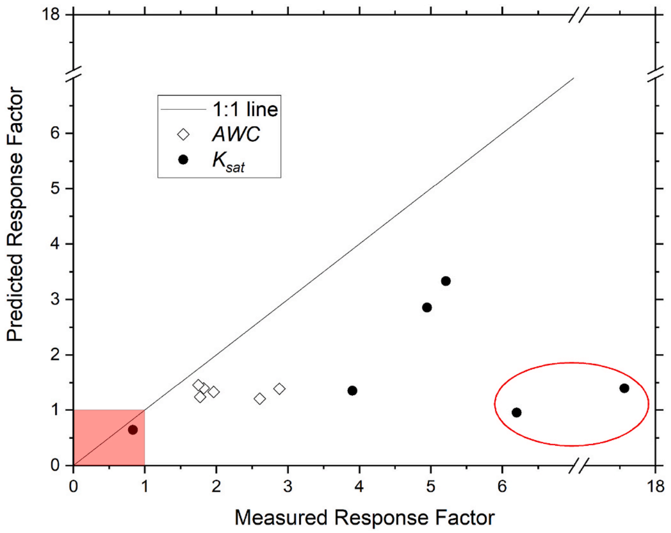

Fig. 6. Measured and model-predicted response factors (property with biochar/property without biochar) for saturated hydraulic conductivity, K_{sat}, and available water content, AWC. Models correctly predicted if improvements occurred but underestimated their magnitude. The shaded region is a response factor <1. Circled data are from the Ramp site, where vertical gradients in biochar content were significant due to erosion (Fig. S5) and likely affected K_{sat}.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used Grammarly to check grammar and condense the writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.121032.

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