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The Differential Influence of Urban Soil Management Practices on Soil Properties, Tree Growth, and Ecosystem Services: A Review

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Abstract. Urban land development often leads to compacted and degraded soils, hindering urban tree establishment and growth and related ecosystem services. Thus, there is a growing interest in restoring degraded soils through various urban soil management practices (USMPs). However, the impact of different USMPs on soil properties, tree establishment and growth, and ecosystem services has not been comprehensively documented and evaluated. To address this knowledge gap, we conducted a literature review, and 41 peer-reviewed articles were selected from 5,913 articles for this analysis. The key response variables included soil bulk density, soil pH, tree growth, total soil carbon, and soil infiltration rates. Existing USMPs were grouped into 4 main categories: (1) organic matter amendments; (2) organic matter with tillage/subsoiling; (3) organic matter with vegetation; and (4) vegetation alone. Urban soil research is unevenly distributed globally, with more than half (53.7%) of studies in the United States, and most studies (82.8%) were short term (≤ 4 years). Generally, USMPs improved soil properties and enhanced tree growth and ecosystem services by reducing 28% to 51% soil bulk density and increasing nutrient availability, microbial activities, infiltration rates, tree growth, and total soil carbon. These findings provide valuable insights on restoring degraded urban soils, sustaining/increasing urban tree canopy cover, and enhancing urban sustainability for urban foresters/planners, policy- and decision-makers, and researchers.

Keywords. Carbon Sequestration; Soil Amendments; Soil Compaction; Stormwater Runoff Management; Urban Forests.

INTRODUCTION

By 2050, 68% of the global population are expected to live in urban areas (United Nations 2019). With accelerating urbanization and population growth, land-use change continues to reshape landscapes globally (Seto et al. 2011). Urban lands are projected to nearly triple from 3.1% in 2000 to 8.1% by 2050 in the United States (Nowak and Walton 2005). However, urban areas are highly vulnerable to a changing climate due to urban heat islands (UHI) and drought conditions intensified by impervious surfaces and built structures (Hunt and Watkiss 2011). Urban expansion driven by population growth has increasingly accelerated land degradation over the past several decades (Ferreira et al. 2018). In particular, urban roads and roadside pavements cover a vast area of soil in cities, creating widespread barren and lifeless zones despite the emergence of soil, microbial, and plant activities in overlooked pavement crevice soils (Manu et al. 2025; Manu and Li 2025). Increasing urban tree canopy is a widely recommended strategy to mitigate human operation and climate impacts (Brandt et al. 2016; Zhang and Brack 2021), providing benefits such as localized cooling (Bowler et al. 2010), carbon (C) storage (Davies et al. 2011; Ko 2018), and stormwater runoff mitigation (Bartens et al. 2008; Gonzalez-Sosa et al. 2017; Dowtin et al. 2023). Urban forests also improve environmental quality and overall human health and wellbeing (Nowak and Walton 2005; Wolf et al. 2020). While trees help cities adapt to a changing climate by regulating microclimate and mitigating UHI and heat waves (Zhao et al. 2020), they are themselves vulnerable to extreme heat, drought, and other environmental stresses—factors expected to intensify in the coming decades (Esperon-Rodriguez et al. 2022). Urban tree mortality is alarmingly high: in a study of 480 newly planted trees along a boulevard in Oakland, CA, USA, 34% of newly planted street trees were either dead or removed after the first 2 years, with an average annual mortality rate of 19% (Nowak et al. 1990). Similarly, a recent meta-analysis (Hilbert et al. 2019) reported that annual mortality ranged from 0.6% to 68.5% in newly planted trees, with the highest rate occurring within the first 5 years. One of the factors associated with tree mortality was site conditions. Site condition refers to physical and environmental characteristics, such as soil texture, compaction, drainage, slope, and management factors at a particular location shaped by both direct disturbances (e.g., grading, filling, pavement) and indirect environmental changes (Pouyat et al. 2010). Soil quality integrates physical, chemical, and biological components and processes and their interactions (Dexter 2004). Soil quality is also one of the limitations for urban tree survival and growth, prompting extensive research on soil degradation and compaction, as well as on management strategies such as application of soil organic amendments and soil rehabilitation techniques (Scharenbroch et al. 2005; Pouyat et al. 2007; Oldfield et al. 2014; Layman et al. 2016; Ward et al. 2021).

Urban land development practices, such as installing grey infrastructure, vegetation and topsoil removal, and heavy equipment use, often result in soil compaction and the degradation of soil structure and functions (Gregory et al. 2006; Olson et al. 2013; Kranz et al. 2022; Percival et al. 2023). Additional stressors, such as vehicular and site traffic during construction or nearby urban activities, can further compact soils. These disturbances alter soil physical, chemical, and biological properties (Craul 1994; Cogger 2005; Scharenbroch et al. 2005), impairing urban tree growth and canopy establishment (Chen et al. 2014) and ecosystem services such as C sequestration and storage and stormwater runoff mitigation (Cogger 2005; Sloan et al. 2012; Wiseman et al. 2012; Sax et al. 2017). Soil compaction reduces porosity, thereby limiting aeration, water infiltration, and moisture retention (Gregory et al. 2006; McGrath and Henry 2016; Somerville et al. 2020). Consequently, urban soils often exhibit poor structure, reduced porosity, high bulk density, low organic matter content, decreased water-holding capacity, and increased soil strength (Kozlowski 1999; Scharenbroch et al. 2005).

Given these significant disruptions, there is increasing interest in restoring degraded urban soils to improve site aesthetics, recreational value, and environmental quality (Carlson et al. 2015) and to improve the capacity of sites to support healthy urban trees and ecosystem services (Dowtin et al. 2023). In particular, soil, trees, and ecosystem services are interconnected in urban settings. For example, compost addition has shown positive impacts on growth rates of planted trees (Layman et al. 2016). Organic soil amendments decreased soil bulk density, increased infiltration rates, and soil C storage (Khaleel et al. 1981; Cogger 2005; Loper et al. 2010). Pouyat et al. (2010) suggested that several factors could result in soil C losses during and after soil construction activities by removing soil or physically disturbing soil aggregates. It is also documented that plant roots can penetrate compacted soils and may help improve soil conditions (Bartens et al. 2008). Bartens et al. (2008) demonstrated that tree roots can increase the average saturated hydraulic conductivity 27× compared to unplanted controls in a compacted site. Additionally, infiltration rates can also affect urban tree transpiration and rooting depths (Bartens et al. 2009).

A variety of urban soil management practices (USMPs), practices/interventions/techniques aiming to rehabilitate/restore degraded urban soils, have been developed and applied to improve soil properties, support vegetation establishment or growth, and enhance ecosystem services. Examples include tilling with compost amendments (Loper et al. 2010; Cellier et al. 2012; Olson et al. 2013; Chen et al. 2014; Oldfield et al. 2014; Ward et al. 2021; Kranz et al. 2022); mechanical decompaction with and without organic amendments (McGrath et al. 2020); Scoop and Dump (Sax et al. 2017); suburban subsoiling (Schwartz and Smith 2016, 2021); and Soil Profile Rebuilding (Layman et al. 2016). Additionally, there are innovative practices/techniques like structural soils (Bartens et al. 2009) that have been used to better support urban trees and related ecosystem services (e.g., stormwater runoff mitigation). Despite growing recognition of the importance of soils in urban forest management, a comprehensive analysis of the impact of different USMPs remains lacking. To address this research gap, this study asks: how do USMPs influence soil properties, tree establishment and growth, and ecosystem services (i.e., C sequestration and storage, stormwater runoff mitigation)? It is worth noting that this review includes both planted trees and existing urban forests managed under USMPs.

MATERIALS AND METHODS

We conducted a literature review using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 framework (Page et al. 2021). PRISMA framework was selected for this study because it is a standardized guideline that improves transparent, consistent, and reproducible reporting of systematic reviews, including literature selection (Knobloch et al. 2011). Specifically, we searched literature using the PRISMA method in Web of Science database with a total of 36 keywords and their combinations (Table S1); for example, “urban forest and soil rehabilitation”, “urban and compost amendments and soil compaction”, and “urban forest and soil restoration”. The search fields were limited to the field “Topic” and all articles published from any time to 2023 December 8 were included. Initially, a total of 5,913 articles were retrieved from the Web of Science (Figure 1). The total number of articles decreased to 3,202 after eliminating the duplicates. Then all the literature was screened using the following reasons: first, non-English literature was eliminated; second, books and conference papers were excluded; third, the articles not relevant to urban forestry and urban soils were eliminated. Specifically, articles were included if they assessed the effects of USMPs on at least one of the following: (1) soil physical, chemical, or biological properties; (2) tree establishment and growth; and (3) ecosystem services. Finally, a total of 41 peer-reviewed articles published from 2006 and 2023 (Table S2) were selected for this study for full-text review (Figure 1).

We reviewed each of the selected 41 studies and extracted the desired information to a structured table

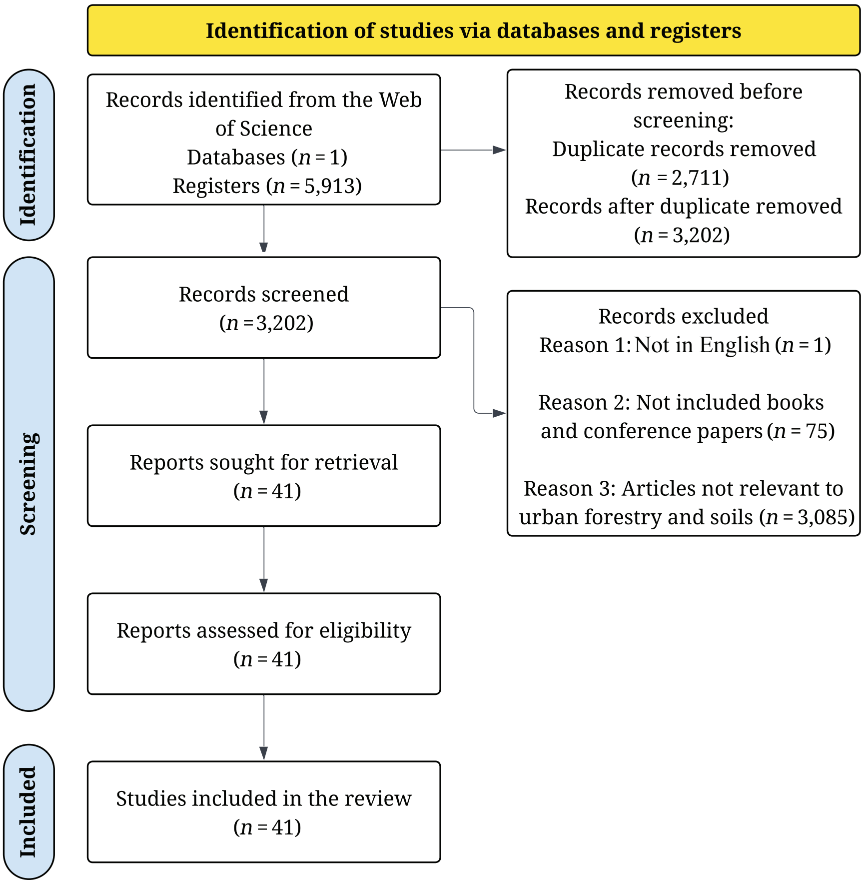

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) diagram.

regarding soil physical, chemical, and biological properties (e.g., soil bulk density, pH, and microbial biomass C); tree growth parameters (e.g., tree growth rates); and ecosystem services (i.e., C sequestration and storage and stormwater runoff mitigation), mainly based on qualitative parameters to assess the impacts of the application of USMPs. The quantitative impacts (e.g., % of soil bulk density reduction) were also recorded when data was available (e.g., % of increase/decrease). Specifically, all extracted information was organized for each parameter under respective categories (i.e., soil physical, chemical, and biological properties; tree growth parameters; and ecosystem services). The findings were then summarized to identify common trends, differences, and knowledge gaps. Additionally, we recorded and synthesized other study-related information such as publication year, study location, USMPs methods, and study duration.

To ensure rigor in data interpretation, we evaluated each study for basic methodological quality based on criteria. Studies were grouped according to 5 key response categories—soil physical, chemical, and biological properties; tree growth; and ecosystem services—to identify patterns and consistencies across USMPs. Because the included studies varied widely in scale, measurement techniques, reporting units, and study design (e.g., greenhouse vs. field; experimental vs. observational; research-led vs. municipal implementation), we synthesized findings qualitatively rather than conducting a meta-analysis. To address methodological heterogeneity, we extracted results as directional outcomes (i.e., increase, decrease, or no change) when numerical standardization was not possible while recording quantitative values when available. Study characteristics such as vegetation types, USMPs methods/approaches, and study duration were used to contextualize differences in outcomes.

RESULTS AND DISCUSSION

Geographical Distribution and Temporal Trends

In general, the selected 41 peer-reviewed articles were published from 2006 to 2023 (Figure 2). Interestingly, no article was found based on our review system (Figure 1) before 2006. There was a gradual

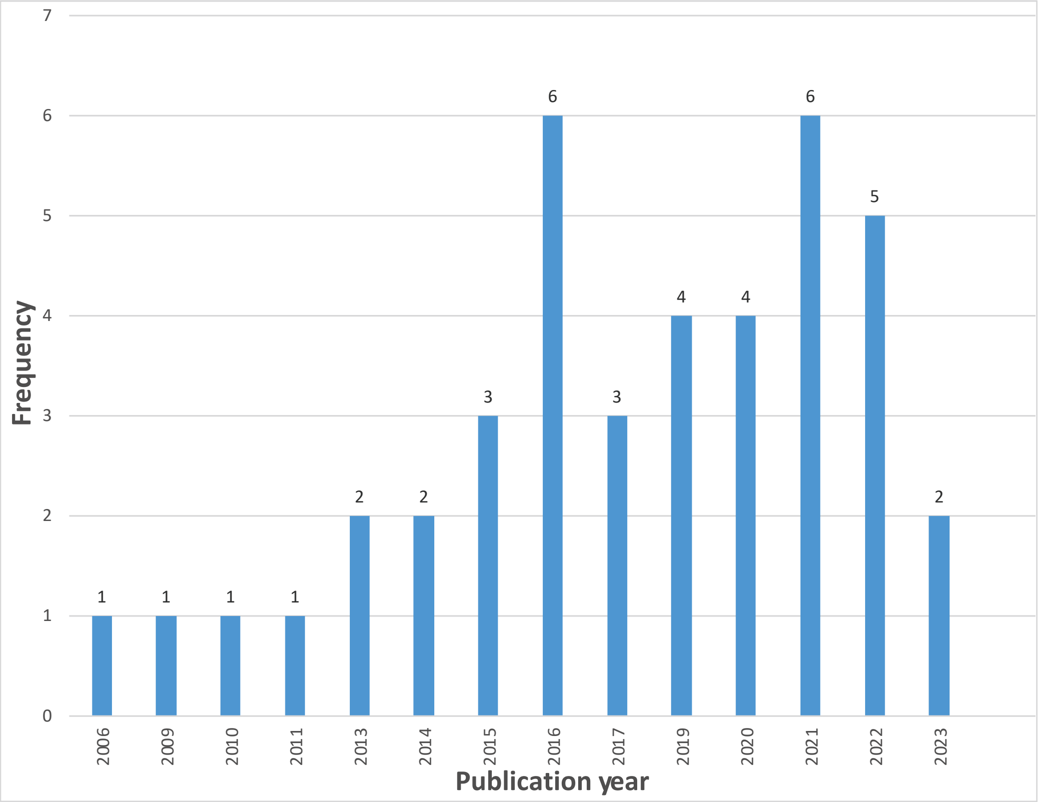

Figure 2. Number of peer-reviewed articles published by year (*n* = 41).

increase in publications since 2013 and an obvious increase in publications since 2016, reflecting increasing research interest in relevant topics. However, with an average of 2.28 articles per year, it also implies the urgent need for future research in this field. Based on the articles included in this review, the geographic distribution of studies was uneven (Figure 3). Among 41 reviewed articles spanning 7 countries, over half of them (22 articles; 53.7%) were conducted in the United States, followed by China (6 articles; 14.6%), Canada (5 articles; 12.2%), France (3 articles; 7.3%), Australia (3 articles; 7.3%), and Bulgaria and Spain (1 article; 2.4%, respectively). Additionally, most studies were conducted in temperate regions, while no studies were conducted in tropical regions. As a result, more research is needed in those understudied regions (e.g., Asia and Africa) to better assess USMPs' broader applicability across the region.

USMPs Categories, Amendment Application Depths, and Study Duration

Various USMPs were developed and applied aiming to rehabilitate degraded urban soils which can be categorized into 4 main categories (Table 1): (1) organic matter amendments (OM); (2) organic matter with tillage/subsoiling (OMTS); (3) organic matter with vegetation (OMV); and (4) vegetation alone (VA), intentionally managing degraded urban soils. Moreover, soil organic amendments were typically incorporated to the depth of 10 cm to 30 cm (Loper et al. 2010; Cellier et al. 2012; Oldfield et al. 2014; Bean and Dukes 2015; Carlson et al. 2015; Beniston et al. 2016; McGrath and Henry 2016; Obriot et al. 2016; Schwartz and Smith 2016; Schmid et al. 2017; McGrath et al. 2020; Rivers et al. 2021; Rojas et al. 2021; Sun et al. 2021; Ward et al. 2021; Kranz et al. 2022; Rojas et al. 2022), while they were applied to the greater depth of 45 cm to 60 cm using tilling or subsoiling techniques in some studies (Chen et al. 2013a; Chen et al. 2014; Layman et al. 2016; Sax et al. 2017; Somerville et al. 2020; Fikri et al. 2021). But the optimal depth for applying organic amendments remains undetermined and may depend on the purpose and/or needs of USMPs; for example, tree specific USMPs may differ from those that are focused on other types of vegetation in urban settings. In addition, most studies (29 articles, 82.8%) were short-term studies and conducted within 4 years, especially on newly planted trees. Only 6 studies (17.1%) were conducted for a long-term period of 5 years or more than 5 years. These studies include Layman et al. (2016) and Ward et al. (2021) for 6 years; McGrath et al. (2020) for 5 years; Sax et al. (2017) for 12 years; Obriot et al. (2016) for 14 years; and Paetsch et al. (2016) for 15 years. As a result, more long-term studies are needed in the future, especially comparing the effects on newly planted trees and more mature trees.

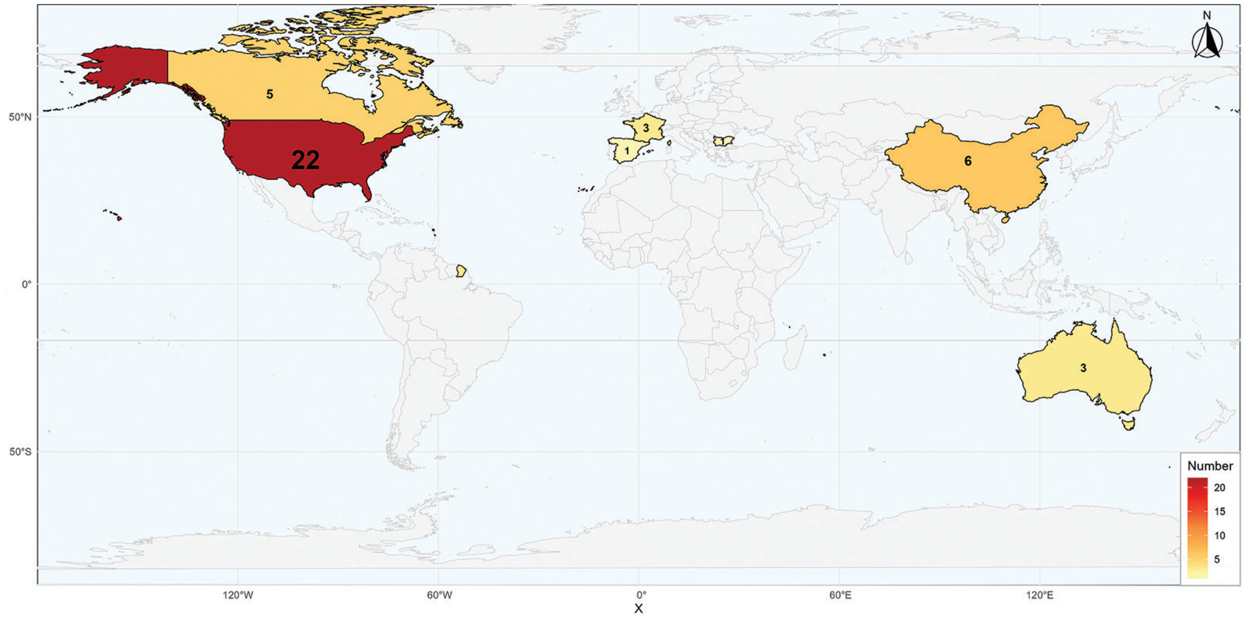

Figure 3. The geographical distribution map of reviewed peer-reviewed articles (*n* = 41).

Table 1. Four main categories of USMPs. USMPs (urban soil management practices); OM (organic matter amendments); OMTS (organic matter amendments with tillage/subsoiling); OMV (organic matter amendments with vegetation); and VA (vegetation alone).

S.N.	Categories	Descriptions and examples	Total number and percentages of articles	Sources
1	OM	Adding various organic matter amendments like compost, biochar, biosolids, other vegetative manures, vegetative yard wastes, green waste, and organic substances	15 (36.6%)	Gregory et al. 2006; Schneider et al. 2009; Carlson et al. 2015; Obriot et al. 2016; Paetsch et al. 2016; Yue et al. 2017; Badzmierowski et al. 2019; Brown and Beecher 2019; Somerville et al. 2019; McGrath et al. 2020; Fikri et al. 2021; Sun et al. 2021; Shiu et al. 2022; Sun et al. 2022; Sifton et al. 2023
2	OMTS	Combined organic matter amendments with tillage or subsoiling techniques like SPR to break compacted soil and integrate organic matter deeper into the soil	15 (36.6%)	Loper et al. 2010; Chen et al. 2013a; Olson et al. 2013; Chen et al. 2014; Bean and Dukes 2015; Layman et al. 2016; McGrath and Henry 2016; Schwartz and Smith 2016; Sax et al. 2017; Schmid et al. 2017; Somerville et al. 2020; Rivers et al. 2021; Schwartz and Smith 2021; Kranz et al. 2022; Rojas et al. 2022
3	OMV	Application of organic matter amendments along with vegetation such as shrubs, grasses, and trees, as well as turf grass and mulching with pine bark and green waste compost	6 (14.6%)	Oldfield et al. 2014; Beniston et al. 2016; Qu et al. 2019; Barredo et al. 2020; Rojas et al. 2021; Ward et al. 2021
4	VA	Using vegetation alone without the addition of organic matter amendments; Perennial ryegrass (*Lolium perenne* L.) and Tall fescue (*Festuca arundinacea* Schreb var. Albena) were used in urban lawns and green buffer patches	5 (12.2%)	Millward et al. 2011; Livesley et al. 2016; Berland et al. 2017; Petrova et al. 2022; Dowtin et al. 2023

Impacts of Urban Soil Management Practices (USMPs) on Soil Properties, Tree Establishment and Growth, and Ecosystem Services

We found that 25 (23.1%), 23 (21.3%), 18 (16.7%), 15 (13.9%), and 27 (25%) articles studied soil physical properties, soil chemical properties, soil biological properties, tree establishment and growth, and ecosystem services, respectively. It is to be noted that some studies have studied multiple properties. Then, the major response variables studied were identified for each area (Figure 4). For instance, soil bulk density, porosity, moisture, texture, aggregate stability, and soil strength were studied under soil physical properties, while soil pH, electrical conductivity, total soil nitrogen, phosphorus, potassium, calcium, magnesium, sodium, and other micronutrients like zinc, copper, and iron were studied for soil chemical properties. For biological properties, microbial biomass C, enzyme activities, microbial communities, and decomposition rates were studied. For tree establishment and growth, tree growth rates, tree survival rates, and other variables (e.g., root growth, chlorophyll content) were measured. For ecosystem services, soil infiltration rates and total soil C were studied. Notably, several peer-reviewed articles have studied more than one parameter. We found that most studied variables were soil bulk density (53%), soil pH (28%), microbial biomass C (42%), tree growth rates (63%), and total soil C (46%).

Influence of USMPs on Soil Properties

Physical Properties

In general, USMPs altered soil physical properties, and the impacts varied among different practices. Organic matter amendment-related USMPs usually

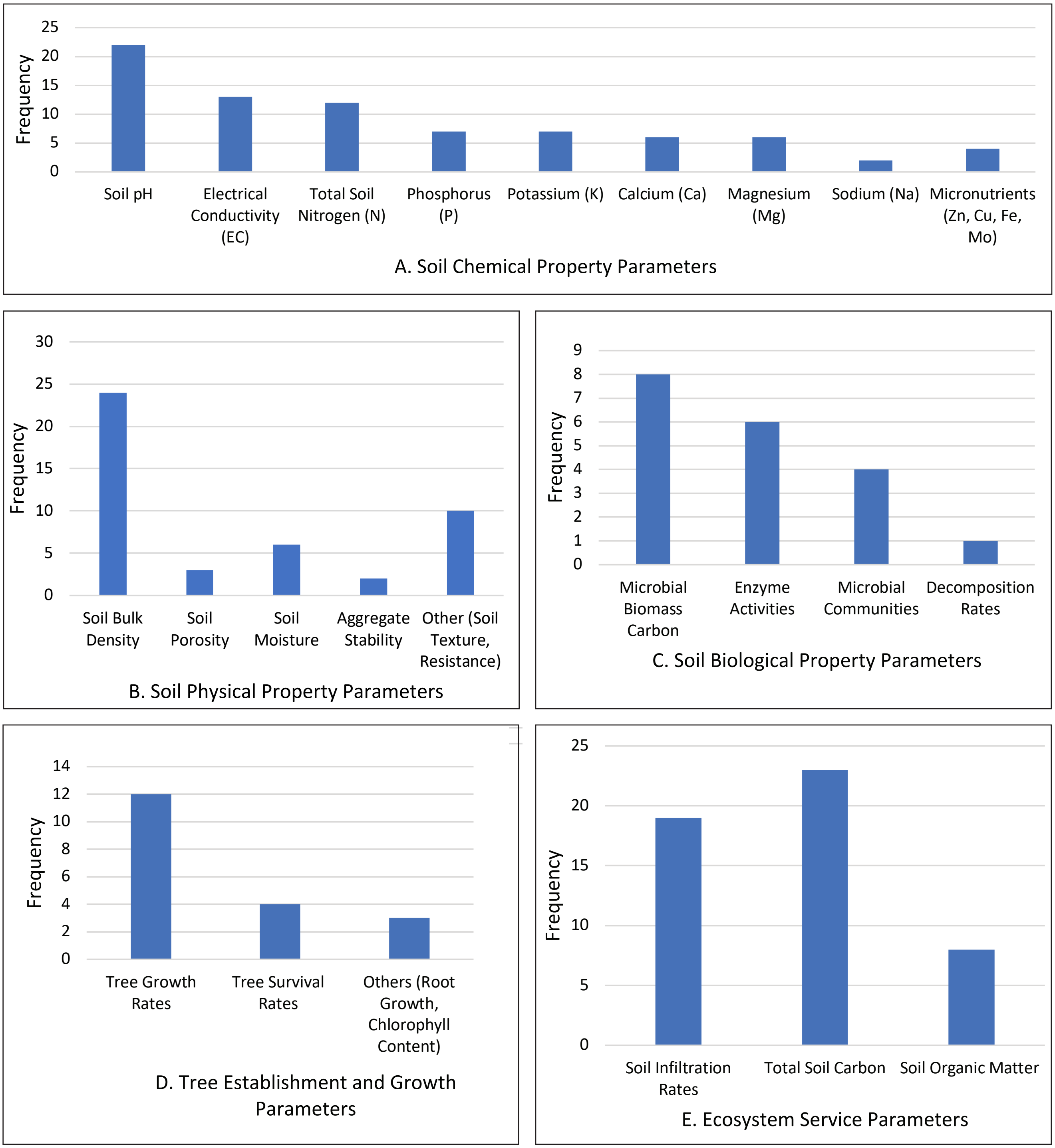

Figure 4. The total number of studies for various parameters studied within each area. (A) Soil chemical properties (*n* = 79); (B) soil physical properties (*n* = 45); (C) soil biological properties (*n* = 19); (D) tree establishment and growth (*n* = 19); and (E) ecosystem services (*n* = 50). Note: n represents the total number of response variables studied in 41 reviewed articles; some studies investigated more than one parameter.

performed better than tilling alone. However, different compositions of soil organic amendments may produce varying effects. For example, exogenous organic matter enhanced various soil parameters like soil biodiversity, biological activities, and soil physical properties compared to mineral fertilizer (Obriot et al. 2016). We found that soil bulk density was one of the most studied soil physical properties in the reviewed studies (Figure 4). Soil compaction is a key factor limiting soil functions and tree establishment and growth in urban environments; for example, soil compaction can restrict root growth when soil bulk density ranges between 1.5 Mg m^{-3} and 1.8 Mg m^{-3} (Beniston et al. 2016). The application of USMPs lowered soil bulk density ranging from 28% to 51% (Oldfield et al. 2014; Sax et al. 2017; Schwartz and Smith 2021). It's worth noting that the presence of trees can also lower soil bulk density compared to other ground covers. For instance, tree-planted areas had softer and less compacted soils compared to grassy areas (Livesley et al. 2016). The soil bulk density reduction occurred mainly in topsoils, and the most effective soil depth of reduction varied among different USMPs. For example, soil profile rebuilding had significant effects at 15cm to 30 cm soil depth (Layman et al. 2016) while a significant reduction of soil bulk density was observed at 0 cm to 20 cm soil depth after applying compost alone (McGrath et al. 2020) or using both tilling and compost (Bean and Dukes 2015). The application of yard wastes significantly reduced bulk density at 0 cm to 10 cm but not at 15 cm to 30 cm soil depth (Beniston et al. 2016). Tilling alone had a limited impact on soil bulk density (Bean and Dukes 2015). Additionally, when applying compost, compost application rates may also affect the impact on soil bulk density and other physical properties. A wide range of compost application rates (10% to 100% volume to volume) has been studied and showed the benefits of lowering soil bulk density to some degree (Rivenshield and Bassuk 2007; McGrath and Henry 2016; Rojas et al. 2021; Kranz et al. 2022). However, the recommended rates will be site-specific depending on site conditions, needs/purpose, compost types and quality, surrounding environment, and other management practices. Urban foresters need to consider those factors as well as tree related factors (e.g., species, age, health, condition).

The effects of organic amendments on soil aggregation and structural ability were also evident, with a high variation among different USMPs. Most studies found that the applications of compost, biochar-based compost, and farmyard manure/green sewage sludge improved soil aggregation/aggregate stability/structure, while biochar alone, tilling alone, or municipal waste application did not (Olson et al. 2013; Layman et al. 2016; Paetsch et al. 2016; Yue et al. 2017; Shiu et al. 2022). However, Loper et al. (2010) found that compost application did not affect soil size. Some USMPs like applying compost or compost combined with tilling can also buffer soil temperature (Olson et al. 2013; Layman et al. 2016), while others like using living mulches or biosolids, rather than synthetic fertilizers, can enhance water retention or soil moisture retention (Badzmierowski et al. 2019; Sun et al. 2022). But there was no significant difference in soil moisture among treatments, which consisted of a control (no amendment); decompaction only; 10%, 25%, and 50% volume-to-volume compost incorporation; and a combination of decompaction with 25% volume-to-volume compost over the 2-year study period (McGrath and Henry 2016). Additionally, certain types of USMPs (e.g., application of biosolids, soil organic amendments + perennial grasses, or mulches with pine bark and green waste compost) improved oxygen availability, aeration, or total porosity (Badzmierowski et al. 2019; Qu et al. 2019; Petrova et al. 2022). Increased pore spaces will consequently lower soil bulk density and increase infiltration and improve tree establishment and growth. This is an example to show the interconnections among soils, trees, and ecosystem services.

Chemical Properties

We found that the application of USMPs influenced soil chemical properties (e.g., soil nitrogen (N) content), and soil pH was one of the most studied variables (Figure 4). The application of compost, biochar, biowaste, farmyard manure, or organic matter amendments helped stabilize (increasing or decreasing) soil pH (Loper et al. 2010; Beniston et al. 2016; Obriot et al. 2016; Yue et al. 2017; Ward et al. 2021), which can create favorable conditions for nutrient availability. In terms of electrical conductivity, compost additions raised electrical conductivity, likely due to the presence of salts in the compost, but the initial rise in soil electrical conductivity levels caused by organic amendments could be stabilized over time (McGrath and Henry 2016; Schwartz and Smith 2016). Several studies have also demonstrated that the application of organic amendments increased soil N levels. For instance, the application of compost led to up to a 59% increase in N compared to unamended plots (Ward et al. 2021). An increase of 391% in potentially mineralizable N over 12 years was observed through the application of organic amendments (Sax et al. 2017). Vegetative compost and biosolids applications also resulted in increased N and phosphorus levels over the 2-year study period (Carlson et al. 2015). Additionally, mulching with organic materials such as pine bark and green waste compost increased soil mineral N content (Qu et al. 2019).

Likewise, phosphorus, potassium (K+), and magnesium (Mg^{2+}) levels significantly increased in soils associated with certain tree species following biochar-based compost applications (Shiu et al. 2022). Moreover, biochar application at a rate of 50% significantly increased available phosphorus and potassium by more than 1.5× to 5.6×. However, careful consideration for application is needed as excessive biochar application can lead to heavy metal accumulation, including zinc, copper, chromium, lead, and cesium (Yue et al. 2017). Furthermore, the use of compost and proper site preparation helped native tree and shrub species grow well in urban areas, but soil nutrients such as C, nitrogen, phosphorus, and potassium increased in the first year and then decreased (Rojas et al. 2021) due to plant uptake and nutrient leaching. Also, soil management strategies, such as periodic compost additions or mulching, might help sustain nutrient availability. However, these practices may also pose potential risks. For instance, Saha et al. (2024) reported that the presence of per- and polyfluoroalkyl substances (PFAS) in yard waste compost has the potential for these contaminants to leach into soils and water, posing potential environmental and health risks. Future studies should also evaluate these trade-offs while studying the effects on tree establishment and growth.

Biological Properties

Overall, USMPs improved soil biological properties by enhancing microbial biomass C, microbial activity, and enzyme activities (Figure 4). The application of organic amendments increased soil microbial C 4× and 20× in the studies of Oldfield et al. (2014) and Beniston et al. (2016), respectively. However, variations exist among different types of USMPs. For example, compared to biochar-based compost, biochar alone had no significant effects on microbial community structure and microbial properties, especially within the first year of application (Somerville et al. 2020; Shiu et al. 2022). The effective depths of UFMPs also varied. Soil Profile Rebuilding (SPR) with compost amendment and deep tillage increased soil microbial biomass C at 15 cm to 30 cm soil depth (Chen et al. 2013a). Additionally, the application of organic amendments promoted the microbial decomposition rate and nutrient cycling as they enriched soils with essential nutrients (Somerville et al. 2020).

The application of USMPs can influence microbial diversity and activities. For instance, the combined application of perennial grasses and green manures resulted in an increased number of fungi and heterotrophic bacteria, leading to increased microbial activity and diversity and promoted N fixation (Petrova et al. 2022). Green waste compost mulch led to enhanced biological activity at shallow depths due to higher organic matter (Sun et al. 2022). The application of farmyard manure and compost resulted in the highest microbial biomass, including bacteria and fungi and earthworm abundance (Chen et al. 2013a; Obriot et al. 2016). Additionally, enzymatic activities in soils were also studied. A direct correlation between enzymatic activities and the addition of organic mulch was observed, and the application of organic mulch—green waste compost—increased enzymatic activities in the rhizosphere through enhanced root activities compared to uncovered bare urban tree pits (Sun et al. 2022). Similarly, compost created from biosolids increased enzymatic activities and higher growth in certain functional bacteria (Carlson et al. 2015). Additionally, the application of exogenous organic matter amendments increased enzymatic activities like β-glucosidase, urease, and phosphatase (Obriot et al. 2016). Despite the observed increase in some soil microbial activities and some functional microbial groups in the first year following the amendment, Petrova et al. (2022) observed a decline in the following year, though their levels remained higher than those in the control. Thus, future research is needed to observe the long-term effects of these practices on soil microbial communities and other biological properties.

Influence of USMPs on Tree Establishment and Growth

As soils are critical for vegetation in urban settings (Gregory et al. 2006; Layman et al. 2016), we found that applying soil organic amendments enhances tree establishment and growth, with tree growth rates being one of the most studied variables (Figure 5). For example, site preparation can help improve soil conditions (e.g., reducing soil bulk density) for native tree saplings, consequently enhancing urban greening efforts (Oldfield et al. 2014). Compost application can enrich soil with nutrients and support tree establishment and growth (Bean and Dukes 2015). The 25% volume-to-volume compost application rate has resulted in increased survival rates, tree height, trunk diameter/trunk-cross-sectional area, growth rate, chlorophyll content, and shoot extension, compared to the control, indicating better tree health. When combined with mechanical soil decompaction, this treatment also enhanced tree germination compared to unmaintained sites (McGrath and Henry 2016; McGrath et al. 2020). Likewise, trees grown in SPR plots had higher growth rates, canopy expansion, higher photosynthesis rates, and a 77% increase in trunk-cross-sectional area at 15 cm, but no significant differences were observed at greater trunk heights of 30 cm and 1.30 m (Layman et al. 2016). In contrast, living mulches such as turfgrass and pine bark had no significant impact on tree trunk diameter and tree height (Qu et al. 2019), although they improved soil structure compared to nonliving mulch-like water-permeable brick. Along with the increased tree growth rates, the application of herbicides and compost also resulted in enhanced native tree growth, reduced non-native species, and improved vegetation cover (Rojas et al. 2021, 2022). However, Qu et al. (2019) found no significant effects on the growth of older trees. As a result, urban planners/foresters need to consider soil amendment types and application rates, tree species, tree ages, and other relevant factors in future tree planting.

Furthermore, along with enhanced growth rates, compost-amended soils led to increased root cross-sectional area, indicating enhanced root development in ornamental plants, though the responses were species-dependent (Loper et al. 2010). Likewise, compost-amended plots had 20% larger basal areas compared to unamended plots after 6 years (Ward et al. 2021). Moreover, the combined application of biochar with biofertilizers likely inactivated yeast, increased sapling biomass by up to 91% and tree height by 24% with larger leaf area compared to the control (Sifton et al. 2023). Additionally, along with the greater growth rates by 3× in diameter at breast height (DBH) and canopy growth, reduced water stress and negative leaf water potentials indicated better water availability in organic-amended soils compared to unamended or tillage plots (Somerville et al. 2020). More research is also needed to better understand the impacts of USMPs on different tree species to ensure the right USMP for the right tree and to explore the interplay between organic amendments and tree roots.

Influence of Various USMPs on Ecosystem Services

The impacts of USMPs on soils and trees presented above can consequently affect ecosystem services. Here, we present relevant findings regarding C sequestration and storage as well as stormwater runoff mitigation as examples.

Carbon Sequestration and Storage

Generally, we found that most USMPs (e.g., application of compost, biosolids, mulches) can enhance C sequestration (Badzmierowski et al. 2019; Brown and Beecher 2019; Sun et al. 2021; Ward et al. 2021). However, the impact and degree varied among different practices, application rates, and other factors. For example, a 17% increase in C stocks was observed in compost-amended soils compared to unamended plots (Ward et al. 2021) due to both the direct input of C through compost application and enhanced soil C sequestration associated with improved soil physical and biological properties in amended soils. Similarly, biochar amendments also increased soil C stocks and improved C sequestration (Schneider et al. 2009; Yue et al. 2017; Shiu et al. 2022). The organic C was increased by 1.8× to 45× in the biochar-amended soils (Yue et al. 2017). This wide range in data reflects differences in biochar application rates: higher application rates tended to produce a greater increase in soil C but also increased environmental risks, such as heavy metal accumulation. Additionally, the addition of organic mulch accelerated soil C and N cycling (Sun et al. 2021). Sun et al. (2022) reported that enzymatic activities had a stronger response to organic mulching and thus enhanced C cycling. Vegetation also played a role in C sequestration and storage. Forest soil had a higher C/N ratio compared to grassland soil (Livesley et al. 2016). Weissert et al. (2016) identified soil moisture and temperature as key drivers of carbon dioxide emissions, highlighting urban soils' role in C storage. It is worth noting that USMPs can affect both short-term and long-term C sequestration and storage. Several studies (Obriot et al. 2016; Paetsch et al. 2016; Sax et al. 2017) revealed that the application of soil amendments such as compost, organic waste, sewage sludge, farmyard manure, and biowaste increased soil C storage over 12 to 15 years. At the same time, the application of soil organic amendments increases carbon dioxide or greenhouse gas emissions due to higher soil organic matter, especially at the initial application stage. For example, Soil Profile Rebuilding enhanced C sequestration, but it also increased greenhouse gas emissions due to enhanced microbial activity (Chen et al. 2014). As a result, the whole C cycle (e.g., inputs, outputs, fluxes) and related C budget need to be considered, especially in urban areas typically possessing lower soil C storage and C sequestration (Chen et al. 2013b). Future research needs to explore the impacts of application rates and other integration strategies of USMPs on soil C. Additionally, interplanting with tree and shrub species requires further investigation since the effectiveness of interplanting varies with species selection and soil conditions. Since different tree species respond differently to organic amendments, a multispecies trial is necessary to understand their effects comprehensively.

Stormwater Runoff Mitigation

In general, organic matter-related USMPs (OM, OMTS, OMV) can mitigate urban stormwater runoff mainly through increasing infiltration rates, hydraulic conductivity, and water-holding capacity, which is consistent with previous studies (Pitt et al. 1999) that demonstrated compost amendment as an effective practice to increase infiltration rates in disturbed urban soils. While compacted urban soils usually have decreased (by up to 70% to 99%) infiltration rates due to higher bulk density (Gregory et al. 2006; Wang et al. 2018), the application of organic soil amendments increased infiltration rates (Khaleel et al. 1981; Cogger 2005; Loper et al. 2010). The application of compost also resulted in increased hydraulic conductivity and reduced runoff compared to control plots (Schneider et al. 2009; Olson et al. 2013). The tilling with compost addition was able to reduce runoff by 1.8× to 5.6× compared to control plots (Olson et al. 2013). Likewise, several other studies reported higher water holding capacity in amended soils (Sax et al. 2017; Rivers et al. 2021; Ward et al. 2021). However, some studies reported no significant differences in soil infiltration rates in compost-amended soil, although the rates tended to be higher (Bean and Dukes 2015; Rivers et al. 2021), with infiltration rates observed to be up to 6× greater than in tillage and control plots (Rivers et al. 2021). Similarly, tilling and compost application both increased infiltration rates compared to the control (Kranz et al. 2022). In contrast, though initial benefits were observed in tillage plots, no significant difference between unamended and tillage plots was observed after 2 years, and only organic matter amended plots had higher field-saturated hydraulic conductivity (Somerville et al. 2020); organic amendments also increased plant-available water (PAW) in sandy soils (Somerville et al. 2019). Infiltration rates were also enhanced by suburban subsoiling, as it improved the rooting depth from 20 cm to 30 cm of the restored soil (Schwartz and Smith 2021). Adding vegetation like turfgrass enhanced water storage and reduced runoff rates (Bean and Dukes 2015). Additionally, naturalization to urban parks over 6 years increased water infiltration and enhanced moisture retention (Millward et al. 2011). Somerville et al. (2020) and Chen et al. (2014) also observed increased saturated hydraulic conductivity in amended soils, and biochar and compost-treated plots had greater hydraulic conductivity than biochar alone. It may be due to the compost's larger pore sizes. These findings provide insights into how compost amendments improve soil infiltration rates. They also suggested a positive relationship between compost application and increased soil infiltration rates. Future research is needed to understand the long-term impacts of USMPs on water infiltration capacity. Additionally, the role of trees in reducing stormwater runoff in urban areas through canopy interception loss, transpiration, and infiltration has been well documented (Berland et al. 2017). Dowtin et al. (2023) demonstrated that specific tree traits, such as high leaf area index, high surface roughness, root architecture, as well as specific management practices, influenced stormwater runoff mitigation. These findings suggest that, in addition to soil management practices, careful selection of tree species could optimize stormwater mitigation. Thus, future research could identify optimal combinations of USMPs and trees for stormwater runoff management, especially in the long run.

Summary of USMPs Impacts

Overall, we found that different USMPs (OM, OMTS, OMV, and VA) improved soil properties (physical, chemical, and biological), tree establishment and growth, and ecosystem services (Figure 5). The application of OMTS and OMV led to a reduced soil bulk density by 28% to 51% over years (Rivenshield and Bassuk 2007; Oldfield et al. 2014; Beniston et al. 2016; Layman et al. 2016; McGrath and Henry 2016; Sax et al. 2017; McGrath et al. 2020; Schwartz and Smith 2021; Ward et al. 2021; Kranz et al. 2022). All 4 types of USMPs increased total soil C, but only OMV increased microbial biomass C (Chen et al. 2013a; Oldfield et al. 2014; Beniston et al. 2016; Ward et al. 2021). VA showed the least impacts compared to the other 3 USMPs (OM, OMTS, and OMV), especially in the areas of tree growth (Bean and Dukes 2015; Layman et al. 2016; McGrath et al. 2020; Ward et al. 2021; Rojas et al. 2022; Sifton et al. 2023), soil infiltration rates (Schneider et al. 2009; Olson et al. 2013; Bean and Dukes 2015; Sax et al. 2017; Rivers et al. 2021; Schwartz and Smith 2021; Ward et al. 2021), and total soil C (Schneider et al. 2009; Obriot et al. 2016; Paetsch et al. 2016; Sax et al. 2017; Yue et al. 2017; Badzmierowski et al. 2019; Ward et al. 2021). Furthermore, we found a significant interrelationship between enhanced soil properties and improved tree growth. In areas with degraded soils where USMPs were applied, not only soil properties were significantly enhanced, but tree growth was also notably improved compared to the control plots (Loper et al. 2010; Layman et al. 2016; McGrath and Henry 2016; Barredo et al. 2020; McGrath et al. 2020; Somerville et al. 2020; Sifton et al. 2023). This suggests a positive feedback loop, where the restoration of soil health directly promotes tree growth (Loper et al. 2010; Layman et al. 2016; McGrath and Henry 2016; McGrath et al. 2020; Somerville et al. 2020; Sifton et al. 2023). This aligns with the broader soil-ecological framework proposed by Heneghan et al. (2008), which emphasizes that physical, chemical, and biological components of the soil should be taken into consideration in an integrated, dynamic way for successful restoration.

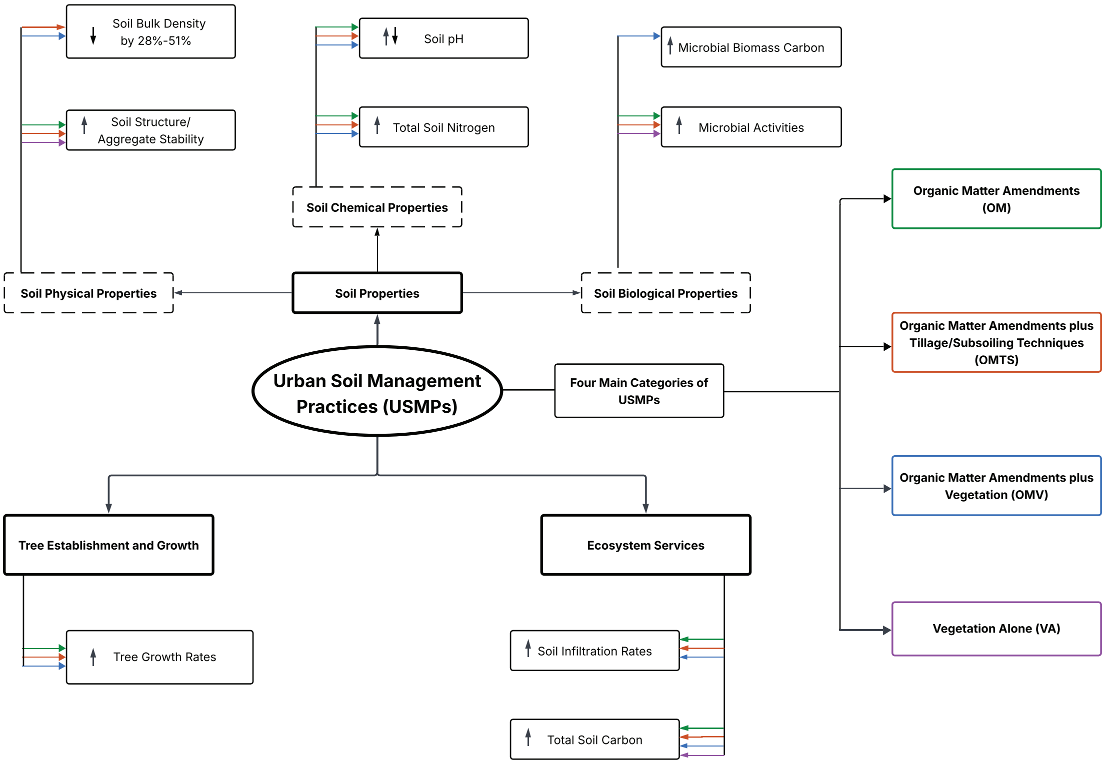

Figure 5. The effects of Urban Soil Management Practices (USMPs) on soil properties (i.e., physical, chemical, biological), tree establishment and growth, and ecosystem services (*n* = 41 peer-reviewed articles). Boxes are color-coded for 4 different USMPs. The different color boxes indicate the 4 different USMP categories for soil amendments. Colored arrows denote the impacts of different USMPs.

While we found that all studies primarily focused on soil-mediated effects, urban trees face a range of environmental stressors, including heat island effects, air and soil pollution, invasive species, and management techniques that may worsen stress in urban ecosystems (Pavao-Zuckerman 2008; Carreiro et al. 2009). Although the studies reviewed did not quantify these additional stressors, the consistent positive response of trees to USMPs suggests that improved soil conditions may have helped buffer the potential impacts of urban stresses under challenging conditions. The resilience and health of urban forests may be further improved by combining soil restoration with broader urban management strategies—such as mitigating heat stress, reducing pollutant exposure, and managing invasive species. Future research could aim to quantify how soil restoration interacts with other urban stressors to better inform urban planning and urban forest management strategies, especially from a holistic urban ecosystem approach.

IMPLICATIONS

To the best of our knowledge, this is the first review to comprehensively summarize existing USMPs and their effects on soil properties, tree growth, and ecosystem services. The findings provide a list of existing USMPs to practitioners (e.g., urban foresters, urban planners, landscape designers, master gardeners, and homeowners) as well as a science-based assessment of their potential. Our review indicated that organic matter-related USMPs were more frequently used and had more positive impacts on soil properties and tree growth. While single treatments such as tillage or biochar alone showed limited effects, combinations of treatments (e.g., compost with biochar or subsoiling) enhanced soil health more effectively. However, a variety of factors (e.g., site conditions, needs/purposes, application rates/depths/frequencies, tree species, tree age) need to be considered in decision-making, because there is no one-size-fits-all solution, and the selection of USMPs needs to be site-specific. The findings from this review highlighted the importance of belowground (soils) because soils are brown infrastructure in the city, as well as the interconnections between belowground (soils) and aboveground (trees). Moving forward, a holistic approach is needed that integrates green infrastructure with brown infrastructure in urban planning and urban forest management.

LIMITATIONS AND FUTURE DIRECTIONS

There are some limitations of this review including: (1) only English peer-reviewed articles were searched and included, which may limit the understanding of research published in non-English languages and/or non-peer-reviewed publications (e.g., books, conference papers, technical reports); (2) only Web of Science was used for the search, which may exclude studies in other databases; (3) small sample size, with a total of 41 studies and no distinguishing in scales, data collection methods, and study designs; and (4) only C sequestration and storage and stormwater runoff mitigation were included in ecosystem services. While the application of organic amendments demonstrated clear benefits, the specific impacts of different amendment types and the influence of depth incorporation remain unknown. Furthermore, long-term studies (5 to 10 years) are required to evaluate the sustained impacts of amendments such as biochar and compost on soil physical and chemical properties, particularly long-term ecosystem services like C sequestration and stormwater runoff mitigation. Thus, future research is needed in the following areas: (1) understudied regions like Asia and Africa; (2) long-term impacts of USMPs in various degraded urban soil types and conditions considering other urban ecosystem stressors; (3) additional databases with more targeted search criteria and expanded study parameters that have gained less attention and other ecosystem services related to growth and survival of urban trees; (4) the impacts of the application of different amendment types and their incorporation depths; and (5) non-peer-reviewed publications and cost-benefit analysis to help guide decision-making and/or large-scale implementation.

CONCLUSION

Urban soil degradation remains a major barrier to establishing and sustaining healthy urban forests. This systematic review demonstrates that a wide range of USMPs can meaningfully improve soil function and support tree growth, especially when these practices combine organic matter addition with structural soil rehabilitation. Collectively, these strategies contribute to more resilient soils that better support vegetation, water movement, and C sequestration and storage in the built environment. Beyond site-level outcomes, effective soil management underpins the broader ecological benefits that cities increasingly rely on—heat mitigation, stormwater mitigation, and long-term C sequestration and storage. Because urban forests are expected to shoulder a growing share of climate adaptation and quality-of-life goals, improving soil conditions is not simply a horticultural practice; it is a foundational investment in sustainable urban infrastructure. The evidence synthesized here highlights that prioritizing soil health accelerates returns on urban tree canopy investment by improving early survival and long-term ecosystem functions. Looking ahead, urban planners and urban foresters can strengthen green infrastructure by embedding soil restoration into design, budgeting, planting, and maintenance planning across land-use types. Cities that recognize soil as living, brown, strategic infrastructure will be better positioned to expand urban tree canopy, enhance environmental quality, and respond to climate stress. Urban soil management is therefore not an isolated technical intervention—it is a cornerstone of how cities can grow greener, healthier, and more resilient in the future.

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Appendix

Table S1. Keywords used in Web of Science. C (carbon).

No.	Keywords	No.	Keywords
1	urban forest and soil rehabilitation	19	urban forestry and soil health
2	urban forest and stormwater management	20	urban forestry and soil C storage
3	urban forest and tree canopy and soil management	21	urban forest soil management
4	urban forest management and tree canopy and soil management	22	urban forest and soil compaction
5	urban forest and soil profile rebuilding	23	urban forest and soil remediation
6	urban forest and street tree and soil management	24	urban forestry and stormwater mitigation
7	urban trees and tree canopy and soil management	25	urban tree canopy and soil improvement and C sequestration
8	urban forest and increase and tree canopy	26	urban forestry and soil management practices
9	urban tree canopy and increase and C sequestration	27	urban tree canopy and soil improvement
10	urban forest and tree canopy and C sequestration	28	C sequestration and urban soil and urban forest
11	urban forest and increase and tree canopy and C sequestration	29	soil fertility and urban greening
12	urban forest and tree canopy and soil restoration	30	urban forestry and C storage
13	urban forest and C sequestration	31	urban forest and soil enhancement
14	urban forest and tree canopy	32	urban tree canopy and C sequestration
15	urban forest and soil restoration	33	urban and organic amendments and soil compaction
16	urban forest and soil management	34	urban and soil profile rebuilding and compost
17	urban greening and urban soil restoration	35	urban and compost amendments and soil compaction
18	urban forestry and soil quality improvement	36	land development and compost and soil remediation

Table S2. List of studies included in the systematic review.

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