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Impacts of organic matter amendments on urban soil carbon and soil quality: A meta-analysis

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ABSTRACT

Organic matter amendment application is an important avenue of beneficial waste diversion and is used to improve soil quality in agricultural and urban settings. In urban regions, amendments are used to support local food production, maintain vegetation for landscaping and recreational use, and reclaim disturbed soils. Urban regions generate large quantities of wasted organic resources for potential application aiding in creating a circular nutrient economy. There is a growing interest in understanding the effects of amendments such as compost, biosolids, and biochar on soil properties in agricultural settings. Gaps remain, however, in assessing their effects in urban land uses. We conducted a literature review to assess the effects of compost, biochar, and biosolids on soil carbon and soil quality of urban soils managed for gardening, landscaping, recreation, and reclamation. Application of organic matter amendments led to an average increase of 3.6 units of soil organic matter% (SOM %). Compost and biochar improved SOM% the most, by 3.1 and 6.5 units of SOM%, respectively. Biosolids resulted in the smallest increase in SOM% but had greater nutrient benefits than other amendments. Parameters related to chemical and physical soil quality improved with the application of amendments. Gaps in the literature remain, such as assessing urban gardens, soil to depths greater than 30 cm, and the persistence of SOM in amended soils. This meta-analysis proposes that organic matter amendments are a powerful means to improve soil quality in urban regions, provide vital cobenefits to surrounding communities, and increase soil carbon storage.

1. Introduction

Many forms of organic matter amendments, such as compost, plant residues, animal manure, and biosolids, are used to improve soils (Pane et al., 2015; Anwar et al., 2015). The addition of organic matter amendments to soil is an established practice to improve soil health and support plant production. However, our understanding of the effects of amendments used in urban settings is lacking when compared to agricultural use (Fitzpatrick et al., 2005). While used in both settings, amendment use is dominated by agricultural settings due to focuses on production and large-scale soil health movements (Hargreaves et al., 2008). In agriculture three of the most common organic matter amendments are compost, biosolids, and biochar. Biochar is made from the pyrolysis of feedstocks, typically woody and plant based. Biochar is well positioned for increasing soil carbon and for reducing leaching of nutrients and pollutants in soils (Albert et al., 2021; J. Wang et al., 2016). However, biochar's high C:N can also lead to the immobilization of nutrients such as nitrogen (Nguyen et al., 2017). Biosolids are akin to a faster releasing fertilizer, typically made from treated municipal solid wastewater, and are very high in nutrients such as nitrogen and phosphorus. Biosolids often strongly increase soil nitrogen and phosphorus, but increase soil carbon to a lesser degree (Sharma et al., 2017; Wijesekara et al., 2021). Composts are a middle ground of the three amendments and they can be created from many organic materials. The carbon and nutrient soil gains of compost fall between biochar and biosolids by achieving moderate gains in both categories, and there are also often large improvements in microbial biomass and structure (Adugna, 2018; Kallenbach and Grandy, 2011; Siedt et al., 2021). All of these amendments are used to improved soil quality and health broadly, but which may be best is context dependent. Despite varying contexts, increases in soil quality factors such as nitrogen and phosphorus by 20–100% or more have been measured in agricultural meta-analyses

Abbreviations: BD, Bulk density; K, Potassium; N, Nitrogen; OM, Organic matter; P, Phosphorus.

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with organic matter amendments (Gravuer et al., 2019; Ma et al., 2021). When comparing these results to urban soils, similar impacts are often seen in individual studies, though there is far less study and specification, leading to uncertainty.

While much of the use of organic matter amendments is focused on soil fertility and plant production, there is recent movement to further organic matter amendments use to combat climate change specifically. From a climate perspective, organic matter amendments contribute to climate change mitigation by tightening the waste loop and sequestering carbon in the soil. Soils have a high capacity to store carbon – holding significantly more carbon than the atmosphere and terrestrial biomass combined (Scharlemann et al., 2014). In agriculture these amendments can have sizeable carbon benefits, biochar is technologically capable of 1 Pg CO_2eq per year globally and compost can regularly increases SOC by 45% or more (Aguilera et al., 2013; Griscom et al., 2017). However, these SOC increases are not permanent sinks and these estimates commonly only assess agricultural and natural soils, leaving urban soils out of the picture.

Specifically, urbans soils are an underutilized reservoir for organic matter amendments due to the sheer amount of organic waste generated in urban regions, the proximity of their end use, and the potential for large carbon gains. Urban soils have been degraded from the placement of impermeable surfaces, soil erosion during construction, and improper management (S. Brown et al., 2012). Due to this, urban soils often contain less carbon than natural spaces – though some urban soils are very well managed - but this gap could be closed with soil health management, such as applying organic matter amendments (Chien and Krumins, 2022; Pouyat et al., 2006). Use of amendments could help to provide healthier soils and better urban soil carbon storage, however, the extent to which urban soils could contribute to city, state, national, and international climate goals is not well constrained. These lands constitute a nontrivial area; the United Sates is over 3% urban and this figure is expected to rise to 8% by 2050, and 2–3% of land globally is urban (Z. Liu et al., 2014; Nowak and Walton, 2005). Illustrating the magnitude of carbon loss due to urbanization, approximately 0.21 Pg of the 1.72 Pg total soil carbon contained in current urban areas was lost in the southern United States from 1945 to 2007 due to rapid urbanization from in this region (Zhang et al., 2012). Losses like this could potentially be negated and turned into sinks with the application of organic matter amendments. Additional external losses of carbon could be mitigated by replacing non-sustainable amendments and horticulture products such as urban peat use with organic matter amendments generated from urban organic waste streams. Many commercial bagged amendments used in urban settings consist of this peat, which is an important carbon resource that is destructively harvested, but this could be displaced by organic matter amendments (Alexander et al., 2008; Fascella, 2015; Schmilewski, 2008). However, there has been recent shifts away from peat use, especially in areas of Europe that have focused on reductions in peat use and restoration of peatlands, to urban green waste composts instead (Andersen et al., 2017; Boldrin et al., 2010; Kazamias et al., 2017). These organic matter amendments are prime for urban use as large quantities of organic resources are generated by humans in urban areas - 20 kg of dry matter biosolids and 22 kg of dry matter food waste per capita annually – and could be transformed and applied directly as urban soil amendments (Kim et al., 2017; Parthiba Karthikeyan et al., 2018). Current research supports the benefits of organic matter amendments in urban systems, but estimates are not well constrained and studies are often limited to single amendment types or singular urban land-uses.

In addition to sequestering soil carbon, organic matter amendments can contribute to methane reduction from landfill avoidance and have important implications for circular resource economies. In California, landfilling is a common fate for organic wastes, which account for 41% of the state's human-generated waste (CalRecycle, 2015). As a result, landfills are the largest point-source of methane emissions in the state (Duren et al., 2019). Several recent and emerging policies target organic diversion from landfills as methane reduction strategy (CA SB 1383, 2016; Reynolds et al., 2020), and some of these policies include requirements for the procurement and use of compost in urban spaces (e.g. CA SB 1383, Statutes of 2016).

When diverted from landfills and recycled to the land, organic matter amendments give societal and environmental co-benefits that are not directly monetized, often making them less financially attractive compared to the immediate and traditional results of synthetic alternatives. The use of organic matter amendments in agricultural ecosystems have increased transportation costs and less immediate benefits compared to synthetic fertilizers, which can lead to financial barriers in using organic matter amendments, though some organic matter amendments are supported by subsidies to combat this (Harrison et al., 2020; Kan et al., 2010; H. Wang et al., 2008). However, when farmers invest in organic matter amendments they recoup increased upfront cost with long term soil health benefits and can aid in becoming organic farmers (Hijbeek et al., 2019; Horrocks et al., 2016; Viaene et al., 2016). In addition to organic matter amendment application to agricultural soils, application to urban soils may present an opportunity to further the use of organic matter and decrease costs. Organic matter amendment application to urban soils may also be more cost-effective and feasible due to the resources used to create amendments being generated in urban settings, even though processing of organic material may occur beyond the direct urban boundary (Lehec, 2020; Zurbrügg et al., 2004). However, processing outside this urban boundary can still result in efficient urban soil application, especially when the production of compost of biosolids is municipality based (McIvor et al., 2012). There are also instances of direct urban center processing such as the cost-efficient use of home composting or city park departments conducting their own composting processes (Morrow and Davies, 2022; Vázquez and Soto, 2017). By using a portion of organic matter amendments from urban waste resources for use in urban settings, regions can tighten nutrient cycles, decreasing transportation costs and emissions.

Urban organic matter amendments may also have additional societal benefits, such as affordable and local urban food production. Using organic matter amendments on preexisting urban garden soils can help increase food security through increased produce production (Barthel and Isendahl, 2013). Higher degrees of productivity can also be achieved when organic matter amendments are used to reclaim vacant and polluted urban soils for food production (Kumar and Hundal, 2016). However, there are concerns over contaminants for sites with dangerous prior uses, such as leaded gasoline and paint exposure (Imperato et al., 2003; Laidlaw et al., 2017). Remediation and monitoring of these lands using organic matter amendments could increase urban food production, lowering the need for imported foods and providing significant shares of the food needed in urban areas, particularly in lower-income communities and countries (Algert et al., 2014; Badami and Ramankutty, 2015). Thus, organic matter amendments used in urban agriculture will contribute to lower greenhouse gas emissions from imported food and increased food security in addition to their soil benefits (Kulak et al., 2013).

While much is known about organic matter amendments benefits in agricultural settings and their potential social impacts, the study of their use and impact on soils in urban settings is less developed, and there is a lack of a comprehensive meta-analysis. This meta-analysis synthesized current literature on organic amendment use in urban environments and quantitatively assesses the impacts of their use on soil properties. The questions this meta-analysis focused on are: **1.** To what degree do organic matter amendments affect urban soil carbon? Furthermore, which amendments are the most effective at increasing soil carbon stocks? **2.** To what degree do organic matter amendments improve urban soil quality indicators? Which amendments are the most effective at improving soil quality? **3.** What literature gaps remain in the study of these amendments in urban settings? In assessing these questions this paper quantitatively synthesizes the impacts of various organic matter amendments on soil properties, discusses the co-benefits for applying organic matter amendments, and highlights the knowledge gaps that require additional research focus.

2. Materials and methods

2.1. Data compilation and literature review

Data on soil responses to organic matter amendments in urban settings were compiled searching for peer-reviewed published works primarily via Google Scholar, Web of Science, African Journals Online, and Dialnet databases up until July 2023. Urban environments were defined as areas dominated by anthropogenic influences in urban and suburban spaces with relatively high population density and impervious surface cover, primarily excluding soil ecosystems such as rural agriculture and natural forests (Hobbie and Grimm, 2020). Keywords used in the literature search focused on urban soil + amendment type (Table S1) and forward and backward searches used these keywords as well. Studies were selected using the criteria below: **(1)** Included one or more organic matter amendment (compost, biosolids, biochar, or a combination); **(2)** Reported an urban environment or urban soil used for ex-situ studies; **(3)** Included data from one or more variables of interest, carbon (C), nitrogen (N), phosphorus (P), potassium (K), bulk density (BD), or pH (Table S2); and **(4)** Included a control urban soil in conjunction with amended soils within the study. Soil organic carbon was assessed (excluding inorganic carbon), and soil P and K data were classified as "extractable" and/or "available" while soil N was typically collected as total N. Additional properties such as soil microbial abundance, communities, and dynamics are important aspects of urban soil health that could be affected by organic matter amendments (Kranz et al., 2020; Oldfield et al., 2014; Sax et al., 2017). However, there was insufficient data on biological indicators of soil health to include in the meta-analysis and this is why we henceforth refer to overall changes in soil quality instead of changes in soil health.

2.2. Data organization and calculation

We found 50 studies in our literature assessment that fit our inclusion criteria, with a total of 322 reported sample values, 104 control and 218 treatment values. Studies had four to five treatments on average with most studies including a control and more than one treatment, varying based on amendment types, application amounts, soil textures, and/or settings. From this, studies on average held 3–8% of our study's total samples for each soil property overall. The exception is for potassium which had only 13 studies reported, leading to studies contributing greater than 8% of the total potassium data on average (Table S3). The share percentages presented in Table 1 represent the percent of the total sample pool that any one study contained. Thus, despite one study containing 29% of an interested property's data (Bulk density), there is still independence in measurements due to variations in treatments within larger studies.

For regression models, urban land-uses were placed into four categories: gardening, reclamation, recreation, and landscaping. Gardening consists of urban gardens, arboretums, and a horticulture center. Reclamation consists of roadside plots, vacant lands, and former industrial sites. Recreation consists of urban parks, while landscaping consists of managed areas adjacent to buildings, passive turfgrass fields not used for recreation, and pot trials using urban soil (Fig. 1B). Pot trials were placed in this category as these studies used soil from landscaping settings and aimed to use amendments in landscaping scenarios. These land-use categories were designated to help distinguish the impacts on unique soil systems with different baselines and management goals. In addition to land-use type, a geographic distribution of studies was assessed using ArcGIS (Fig. 1A).

Regression models were run on different amendment types, such as compost, biochar, biosolids, and combination to compare varying amendment impacts. The compost category was dominated by compost studies of green waste and also included composted biosolids. Biosolids include samples labeled as biosolids and sewage sludge, primarily from municipal wastewater treatment. Biochar is composed of woody waste with samples identified as biochar, fine char, and coarse char. The combination category included studies that looked at a combination of the above treatments, consisting of compost and biochar or compost with sewage sludge (Fig. 1C).

Table 1
ANOVA and regression results for models of soil properties by both urban land use and treatment. N refers to total data points across studies. Level of significant is: ns: $p > 0.05$, *: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$, ****: $p \leq 0.0001$.

Soil Property	Independent Variables	Sample Size	Study Size	Adjusted R^2	Significance
SOM%	Setting	223	38	0.15	****
	Amending	223	38	0.10	****
	Setting + Amending	223	38	0.26	****
N (g/kg)	Setting	189	31	0.0	p = 0.36
	Amending	189	31	0.04	**
	Setting + Amending	189	31	0.04	*
Total P (mg/kg)	Setting	142	24	0.0	p = 0.55
	Amending	142	24	0.06	**
	Setting + Amending	142	24	0.06	*
Total K (mg/kg)	Setting	51	13	0.01	p = 0.31
	Amending	51	13	0.18	**
	Setting + Amending	51	13	0.22	**
Bulk Density (g/cm^3)	Setting	149	21	0.22	****
	Amending	149	21	0.18	****
	Setting + Amending	149	21	0.41	****
pH	Setting	147	33	0.08	**
	Amending	147	33	0.0	p = 0.57
	Setting + Amending	147	33	0.07	**

Units used to report results were not consistent across all studies. Therefore, we converted to common units whenever possible. For example, conversions occurred if soil organic carbon percent (SOC%) was reported but not SOM%. SOM% was used in calculations due to its dominance in the respective literature and in its data availability. This conversion was done by multiplying SOC% by 1.72, which while not an exact conversion for all soils, can provide a baseline for the few studies that required conversion (Allison, 1965; Pribyl, 2010). In addition, soil carbon can vary based on measurement method, in our case elemental analysis was primarily used, but soil carbon can also be measured in other methods such as loss on ignition, which can cause discrepancies between studies, especially for biochars produced at high temperatures.

Calculations for estimating the technical potential for urban soil carbon sequestration at the global scale were made with several assumptions: **(1)** 8–26% of diverted organic wastes could be applied to urban lands in the United States (Harrison et al., 2020); **(2)** There are 146 million tons of municipal solid waste in the US and 51.4% is organic (US EPA, 2017). **(3)** Compost is assumed to be the organic matter amendment applied, at approximately 76 Mg/ha to increase SOM% by 1.2 and Mg/ha by 22.2 – the most efficient rate to increase SOM in our study when including associated bulk density changes (Fig. 4); **(4)** Approximately 30% of carbon is lost from municipal solid waste during composting (H. Guo et al., 2019); **(5)** Soil carbon changes from amendments are focused in the top 30 cm (no studies included this meta-analysis go beyond 50 cm, most stop at 20–30 cm); and **(7)** OM% is approximately 58% carbon (Allison, 1965).

2.3. Statistical analyses

R software was used for statistical analyses and visualization (R Core Team, 2020). Analysis of variance (ANOVA) and linear regressions were

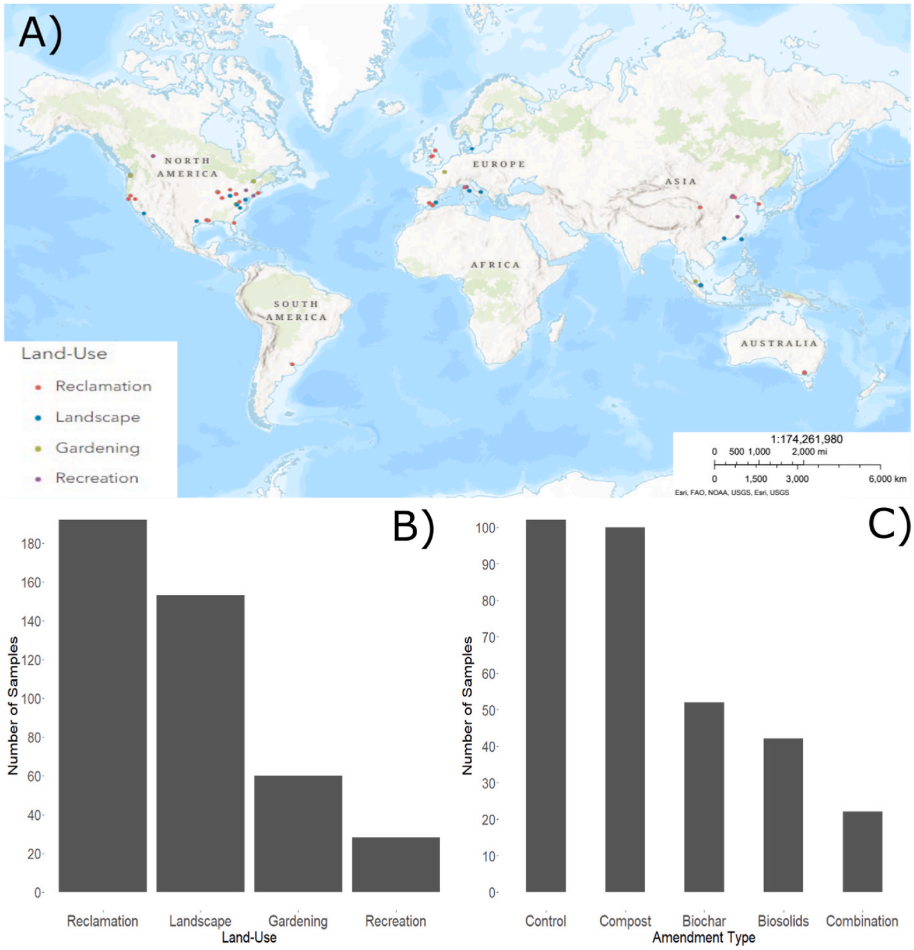

Fig. 1. **A)** Geographic distribution of the samples used in this study. **B)** List of the total number of reported sample values for each amendment type. **C)** Number of samples present in this meta-analysis based on land-use of urban site.

used to assess statistically significant relationships. Mean values are reported along with ±standard error. An alpha level of 0.05 was given for significance in ANOVA testing. Visualization was conducted in R using the "ggplot2" and "ggpubr" packages in R for plots (Kassambara, 2020; Wickman, 2016, p. 2). Effect sizes were calculated using the "metafor" package for calculating and presenting forest plots (Viechtbauer, 2010). The effect size used was the log ratio of the means of treatments and controls. Only studies that reported a standard error or standard deviation were included in this assessment, as a standard deviation is necessary for calculation. If only the standard error was reported, the standard deviation was calculated by multiplying the standard error by the square root of the sample size (Altman and Bland, 2005).

Partial dependence plots were created to evaluate the effects of application amount on soil properties. The "pdp" package was used to create the partial dependence plots shown in this paper. Partial dependence plots allowed the assessment of the marginal effect of prediction using the partial function. This function is useful for assessing how changes in organic matter amendment application amount influenced results. Application rate data in the literature were reported in both Mg/ha and as a percentage of the total soil profile with Mg/ha being used in this paper as it is a more standard metric. Percent amendment application conversions to Mg/ha were made when possible using measurements such as bulk density, soil area, and volume.

3. Results

3.1. *Sample overview*

Studies included in this analysis encompassed a wide range of amendment types, land-uses, and geographic locations. Compost was the most common amendment type followed by biosolids and biochar (Fig. 1C). These amendment types also varied in their C:N with an average value of 28, 10, and 108 for compost, biosolids, and biochar respectively (Table S4). The most common land use category was reclamation followed by landscaping. After this there is a sharp drop off in reported samples assigned to the remaining two categories: gardening and recreation (Fig. 1B). Studies were not uniformly distributed geographically; North America and Europe dominated reported studies with several studies present in Asia (Fig. 1A). International journals were searched for studies in Africa and South America but only one study were found to fit our inclusion criteria and/or to be fully available. Studies also varied by soil texture with sandy loam soils being the most common followed by loam, silt, and clay soils (Table S5). Overall, 79% of our samples had a reported soil texture (253 of 322).

Missing values in the dataset were reported to assess gaps in the literature data. To assess literature gaps, only rows that contained at least one of the following properties were included in this statical analysis: SOM%, total N, P, K, pH, or bulk density. SOM% was the most reported value in the literature, followed by the remaining factors except for soil K, which had a significantly higher missing percentage of data than the other soil properties reported (Fig. S1). In addition to missing reporting of some soil properties, missing depth assessment

(>30 cm) is present in the literature as well. The majority of studies used for analysis assess soils to 30 cm or less, with few going to 50 cm, and none deeper. Studies were limited temporally as well as studies on average lasted only two to three years and were concentrated in the last 10 years (Fig. S2).

3.2. Soil carbon

Soil carbon measurements were reported in a total of 38 studies. Prior to the addition of organic matter amendments, SOM% averaged 3.5% ± 0.4 (n = 67) across all land use categories, while SOM% averaged 7.1% ± 0.4 for amended samples (n = 156; $P < 0.05$). When amended, the effect size of SOM% was 0.7 ± 0.4 (study n = 19; Fig. 2). SOM% varied by both amendment type and the land use of application ($P < 0.05$). All amendment types increased SOM% with the largest shifts seen in compost and biochar ($P < 0.05$) with a smaller increase due to biosolids ($P > 0.05$; Table 2). Differing application amounts also caused variances in SOM% as well as by amendment type in studies. Increased application amount increased SOM% for all amendment types, until between 300 and 400 Mg/ha, after which SOM% begins to increase much more slowly (Fig. 4). Both biosolids and biochar have strong increases in SOM% with application amount, with biosolids plateauing before biochar and biochar starting from a higher SOM% baseline (Fig. 4). Land use category differences in SOM% are minimal in the control except for gardening, which has a higher baseline SOM% (Fig. 3). The largest increases in SOM% were observed in the landscape, recreation, and reclamation by land use category, with a smaller increase in gardening. (Fig. 3).

3.3. Soil total nitrogen

Soil total nitrogen measurements were reported in 31 studies. Soil total nitrogen in controls averaged 1.4 g/kg ± 0.2 (n = 56) and 3.1 g/kg ± 0.4 for amended samples (n = 133; $P < 0.05$). The effect size for nitrogen presents increasing nitrogen with amending with an effect size of 0.6 ± 0.3 (study n = 12; Fig. 2). Nitrogen varied by amending ($P < 0.05$) but not significantly by land use category overall ($P > 0.05$; Table 1). All amendment types increased total soil nitrogen, with larger shifts due to compost and biochar ($P < 0.05$; Table 2) compared to biosolids ($P >$ 0.05). Varying application amounts influenced nitrogen levels with increasing application amounts sharply increasing nitrogen for biosolids with smaller increases and a short plateau for compost and biochar (Fig. 4). Soil total nitrogen in controls were relatively similar across the land use categories landscaping, reclamation, and recreation (means = 1.0 g/kg, 0.9 g/kg, 1.7 g/kg, respectively). Organic matter amendments increased total soil nitrogen significantly in these land use categories (Fig. 5). In contrast, no significant differences in total soil nitrogen were observed within the gardening land use category, which had significantly higher soil total nitrogen in controls compared to other land use categories ($P > 0.05$, mean = 3.1 g/kg: Fig. 5).

Table 2
ANOVA relationships between amended and control plots for all soil properties reported. Sample size indicates amended and control samples of a treatment type. N refers to total data points across studies. Level of significant is: ns: p > 0.05, *: p≤0.05, **: p≤0.01, ***: p≤0.001, ****: p≤0.0001.

Soil Property	Amendment Type	Sample Size	Study Size	R	Significance
SOM%	Compost	129	31	3.05	***
	Biochar	58	12	6.49	***
	Biosolids	30	8	2.14	p = 0.29
N (*g* /*kg*)	Compost	90	23	2.45	*
	Biochar	56	8	1.72	*
	Biosolids	34	8	1.25	p = 0.13
Total P (*mg* /*kg*)	Compost	64	18	33.39	p = 0.22
	Biochar	52	7	44.13	p = 0.28
	Biosolids	22	7	403.61	**
Total K (*mg* /*kg*)	Compost	27	10	120.75	p = 0.09
	Biochar	14	4	127.59	p = 0.16
	Biosolids	3	1	193.50	p = 0.08
Bulk Density (g/cm^3)	Compost	88	19	−0.25	****
	Biochar	20	5	−0.33	****
	Biosolids	23	5	−0.24	p = 0.23
pH	Compost	92	28	−0.04	p = 0.82
	Biochar	26	8	0.60	p = 0.11
	Biosolids	22	7	−0.33	p = 0.32

3.4. Soil phosphorus

Soil phosphorus was reported in 24 studies. Prior to the addition of

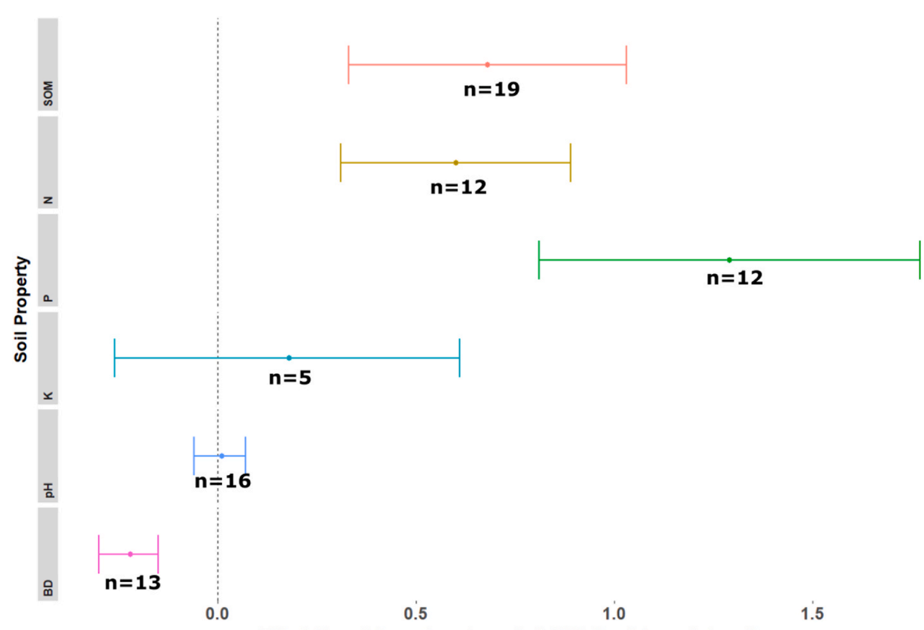

Fig. 2. Forest plot of log ratio effect size of amendments on different soil properties. Upper and lower bounds represent the 95% confidence interval. N represents the number of studies in the forest plot for that soil property.

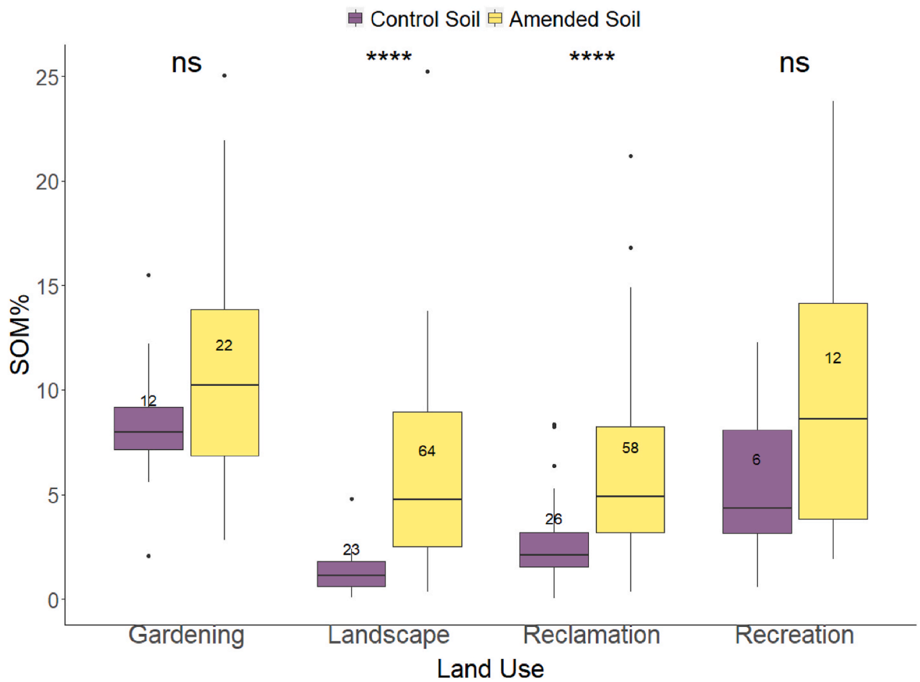

Fig. 3. Box plots of SOM% by land use category, with control in purple and amended sites in yellow. Number represent sample size. Level of significant is: ns: p > 0.05, *: p≤0.05, **: p≤0.01, ***: p≤0.001, ****: p≤0.0001. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

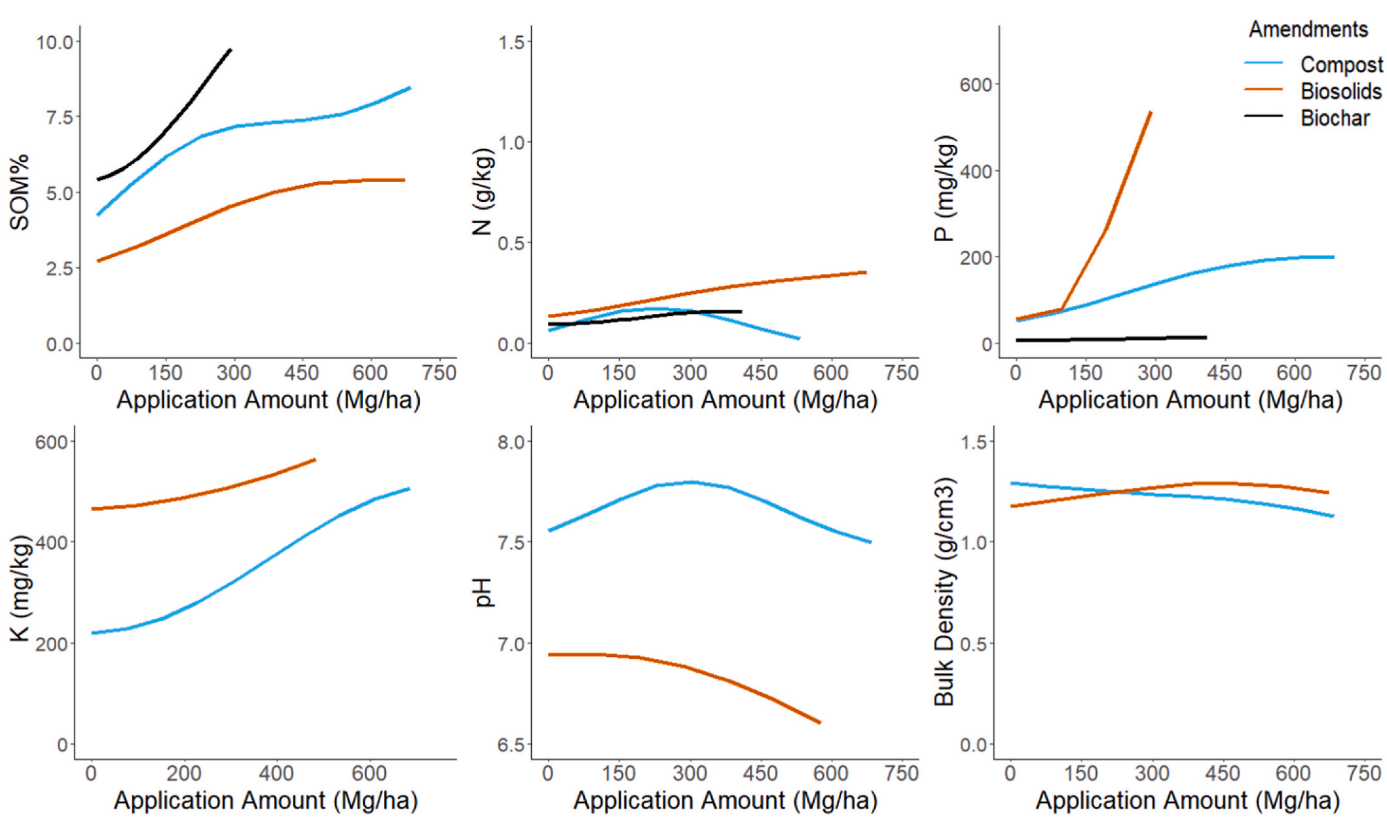

Fig. 4. Partial dependence plots of amendment type and application amount (Mg/ha) on soil properties.

organic matter amendments soil phosphorus averaged 49.4 $mg/kg \pm 12$ (n = 41) while it averaged 156 $mg/kg \pm 21$ for amended samples (n = 101; $P < 0.05$). The effect size for phosphorus showed increasing phosphorus with amending with an effect size of 1.3 ± 0.5 (study n = 12; Fig. 2). All amendments led to increases in phosphorus, with an order of magnitude increase in biosolids amended soils ($P < 0.05$; Table 2), compared to compost and biochar ($P > 0.05$). Application amount sharply increased soil phosphorus for biosolids with much

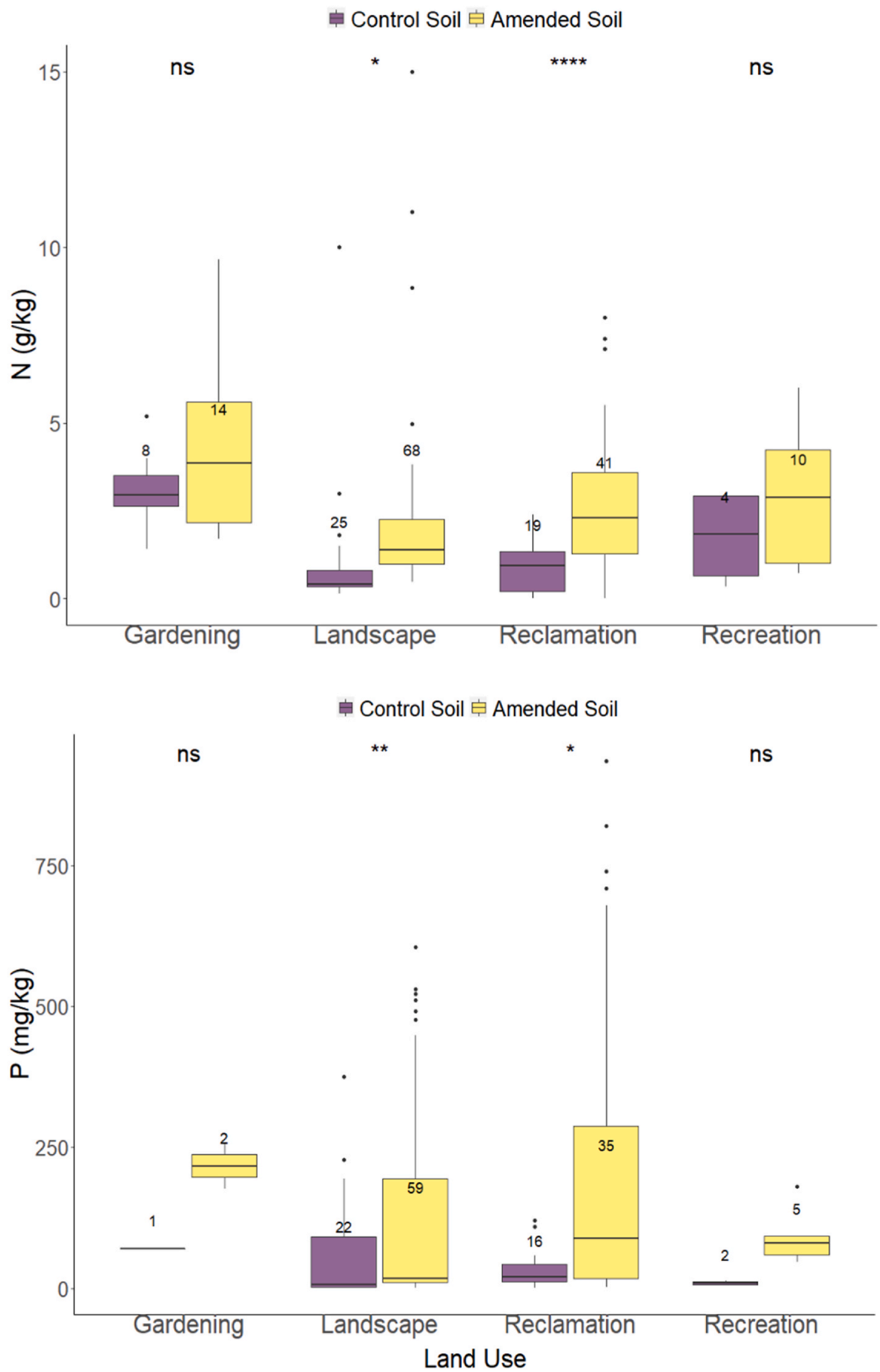

Fig. 5. Box plots of N (g /kg) and P (mg /kg) by setting with control in purple and amended in yellow. Number represent sample size. Level of significant is: ns: p > 0.05, *: p≤0.05, **: p≤0.01, ***: p≤0.001, ****: p≤0.0001. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

smaller increases for compost and little increase from biochar (Fig. 4). When amended, all land-uses saw sizeable increases in soil phosphorus, though only landscaping and reclamation sites were statistically significant (Fig. 5).

3.5. Soil potassium

Soil potassium was reported in 13 studies. Prior to the addition of organic matter amendments soil potassium averaged 130.6 $mg/\ kg \pm 32$ (n = 19) while it averaged 301.2 $mg/kg \pm 33$ for amended samples (n = 32; $P < 0.05$). The effect size for potassium concentration showed increasing potassium with amending with an effect size of 0.2 ± 0.4, but a study size of only five and wide range (Fig. 2). Potassium concentrations increased with amending ($P < 0.05$) but did not vary significantly by site type ($P > 0.05$; Table 1). All treatments increased potassium, with the largest increases in biosolids ($P > 0.05$) and compost ($P > 0.05$), compared to biochar ($P > 0.05$; Table 2). Application amount also influenced potassium concentration change, sharply increasing potassium for compost with smaller increases for biosolids (Fig. 4). Potassium concentrations increase in all reported sites, with reclamation having the largest increases (Fig. S4). While all potassium concentrations increase, it is important to note that potassium levels in soil can be very feedstock and ecosystem dependent due to its high solubility (Mikkelsen, 2007).

3.6. Soil bulk density

Bulk density was reported in 21 studies. Prior to the addition of organic matter amendments soil bulk density averaged 1.5 $g/\ cm^3 \pm 0.04$ (n = 55), while it averaged 1.2 $g/cm^3 \pm 0.03$ for amended samples (n = 94; $P < 0.05$). The effect size for bulk density was -0.2 ± 0.1, signaling decreasing density with amending (study n = 13; Fig. 2). In addition to amending, bulk density varied by setting ($P < 0.05$; Table 1). All amendments lower bulk density but only compost and biochar decreased bulk density significantly ($P < 0.05$; Table 2), with the largest decrease due to biochar. Bulk density steadily decreased with increasing application of compost with less change with application of biosolids (Fig. 4). When assessed by land use category, gardening had the lowest bulk density in both treatment and control, with all sites showing decreased bulk densities in the amended sites (Fig. 6).

3.7. Soil pH

Soil pH was reported in a total of 33 studies. It is important to note that pH was measured predominantly in a water solution but also in a $CaCl_2$ and potentially a KCl solution (as several studies did not mention pH methods), which could lead to variation in measurements between studies. For controls, soil pH averaged 7.2 ± 0.2 (n = 50), while it averaged 7.3 ± 0.1 for amended samples (n = 97; $P > 0.05$). The effect size for pH was minimal at 0.01 ± 0.1, consistent with the changes overall between control and amended pH (study n = 16; Fig. 2). This is due to contrasting effects of amendments such as compost and biosolids (Table 2); pH increased consistently by application amount of compost until around 400 Mg/ha while there was a consistent decrease when applied with biosolids (Fig. 4). pH varied strongly by site ($P < 0.05$), but weakly by amending overall ($P > 0.05$; Fig. S4).

4. Discussion

4.1. Urban soil carbon

Urban soils are understudied for carbon storage, especially compared to agricultural and natural ecosystems (Chien and Krumins, 2022). Natural and agricultural lands are commonly thought of in a carbon context, while this is not often true for urban soils (Lorenz and Lal, 2015; Vasenev et al., 2013). These soils, however, have the potential to store large quantities of carbon given proper management strategies (Brown et al., 2012; Pouyat et al., 2006). We found that organic matter amendments increase SOM% by an average of 3.6% SOM across a wide range of land uses, climates, and edaphic characteristics. While this represents a doubling of SOM concentration across amending, soil BD must be considered when assessing soil carbon change (Lee et al., 2009; VandenBygaart and Angers, 2006). When accounting for changes in both BD and SOM% from amending, we found that soil carbon storage increased by 60%. This effect represents a sizeable increase in urban soil carbon that could be used for climate change mitigation.

It is important to note that soil carbon increases varied by the applied amendment type applied. The greatest increases in soil carbon resulted from biochar applications, followed by compost, and then biosolids (Table 2). This finding is consistent with the nature of these materials as biosolids have lower carbon concentrations than both compost and biochar, and is a faster-releasing amendment than the two as well (Lima et al., 2009; Scharenbroch et al., 2013). Overall, having this explicate data from aggregated studies helps to properly assess which amendment is best to use based on the goals of application and to support prior assumptions of soil impacts from these amendment types.

Despite representing the largest impact on SOM, biochar may be more difficult to produce directly from urban settings. Biochar is often created with woody agricultural "waste" materials which are currently less utilized in urban settings – though this woody share currently constitutes 10% of the organic urban waste share (Zhao et al., 2019). However, biochar can also potentially be produced from sewage sludge treated with gasification or pyrolysis, a potentially plentiful feedstock for urban application (CalRecycle, 2015). A biochar conversion pathway

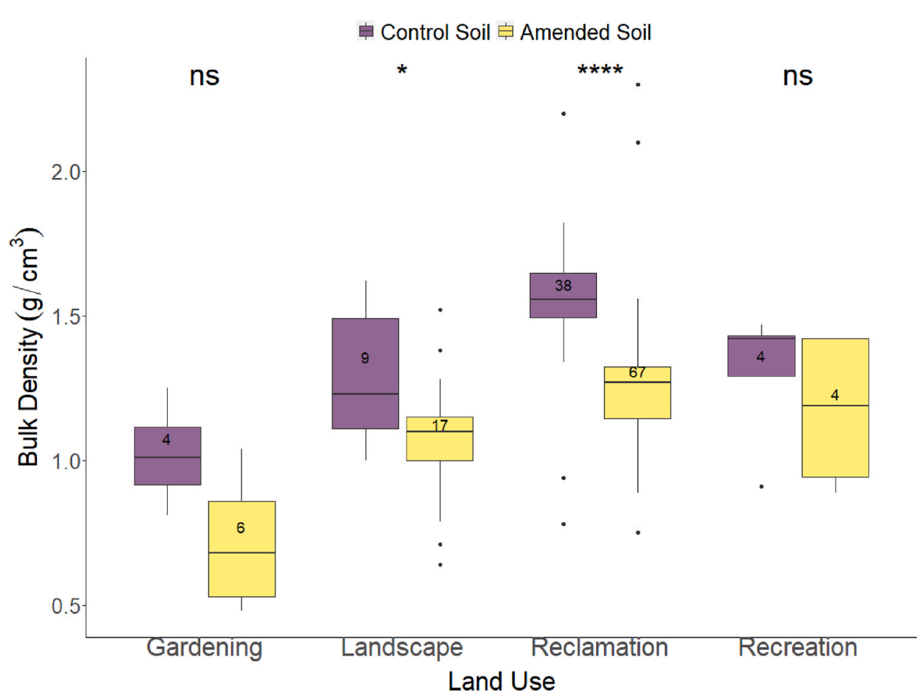

Fig. 6. Box plots of bulk density (g/cm^3) by setting with control in purple and amended in yellow. Numbers correspond to sample size. P-value level of significant is: ns: p > 0.05, *: p≤0.05, **: p≤0.01, ***: p≤0.001, ****: p≤0.0001. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for sewage sludge represents an emerging strategy to organic resource recovery and reuse that could benefit urban soils. In using urban materials directly, fractions of green waste and sewage sludge could be used to create biochar instead of compost, diversifying the organic matter amendment pool. Despite this, creation of biochar may prove difficult as large scale infrastructure for biochar production is currently nascent and compost may confer more soil quality benefits, specifically with available nitrogen and phosphorus, making compost more attractive (J. Liu et al., 2012; Sánchez-Monedero et al., 2019). Biochar may prove to be better for some urban sites that have high fertility and are focusing specifically on improving soil carbon or can simply act as a smaller portion of the urban waste conversion puzzle due to the logistics of composting versus biochar.

Materials to create compost are plentiful in urban regions as cities generate large amounts of green waste, food waste, and biosolids (CalRecycle, 2015; Gomez et al., 2008). With some regions focusing on increasing compost creation and use in agriculture, competition could arise between urban and rural users in using this waste resource to create compost. However, a recent study assessed the example of California's SB 1383 policy and found that at least 8–26% of California's diverted organic waste could then be applied to urban lands without compromising the ability for agriculture to substantially tap into this compost resource (Harrison et al., 2020). This leaves a sizeable portion of the total resource to apply in Californian urban regions — $6.3 * 10^5$ to $1.9 * 10^6$ metric tons of compost — which could be applied to urban Californian soils, despite the high demand for compost in the agriculturally intense state (Harrison et al., 2020). Less agriculturally intense states may have less of a need to distribute organic matter amendments to agricultural sites, leaving even higher shares of their region's organic waste available to be transformed into organic matter amendments for urban areas. Utilizing this share of urban waste as compost in urban areas specifically would help to increase soil carbon efficiently, reduce waste loads, and reduce harmful indirect emissions such as those from landfills and transportation (Adhikari et al., 2010; Keng et al., 2020). These benefits would be plentiful as large amounts of waste would be converted to compost and applied with large gains in SOM% up to 400 Mg/ha (Fig. 4). High amounts of carbon from composts are soaked up by these urban soils when applied reaping strong benefits - such as increased urban soil fertility, improved urban food production, and climate change mitigation.

Biosolids offer modest increases in SOM% but represent another common resource in urban systems. While their use as a carbon sequestration technique may be reduced compared to compost and biochar, they present an opportunity to reuse human waste and increase soil nutrients. Using and treating biosolids can also help to improve sanitation standards in many regions and improve the ecosystem services of amended locations (Trimmer et al., 2019, 2020). In addition to addressing important societal inequalities, land application of biosolids have the largest increases in soil phosphorus and potassium of any of the three major amendments in urban soil systems (Table 2). However, biosolids are often low in K and usually only garner improvements in soil N and P, so biosolid K gains could be an artifact of low urban biosolids K sample size (S. Brown et al., 2020). Nevertheless, by increasing nutrients, biosolids are useful in combination with other treatments or in soils limited by additional nutrients for carbon sequestration (Awasthi et al., 2017; Kirkby et al., 2014). In a goal to maximize SOM% while achieving some of the benefits of biosolids use, one could use composted biosolids which would add less available nitrogen but more carbon than uncomposted biosolids (Boen and Haraldsen, 2011; McIvor et al., 2012).

One important detail when assessing organic matter amendments influence on SOM% is that not all changes in SOM may come from the direct amendment itself, but through indirectly influencing other processes. Increases in plant productivity from amending may increase inputs to the soil and increase the SOM pool over time (Bolan et al., 2013; McClelland et al., 2022). In addition to this, other indirect mechanisms of organic matter amendment application can influence the SOM pool such as negative priming from biochar application reducing carbon mineralization rates (Jones et al., 2011; Reed et al., 2017). It is important to acknowledge that impacts to the soil from organic matter amendments are more complex than just the direct input of carbon and nutrients from the amendments themselves.

Among urban land-uses, the largest shifts in SOM% were seen in reclamation and landscaping, partially due to having the lowest baseline values (Fig. 3). Reclamation sites have the most to gain as they consist of degraded soils such as roadsides and vacant lands. Similarly, amendments in landscaping contexts increase carbon, potentially due to degraded lands nearby buildings and construction. Lower relative increases in carbon occur in gardening and recreation sites likely due to prior management strategies. For example, urban gardens are often sustainably managed for food production leading to higher baseline carbon levels, while recreation sites may be managed with nutrient and water additions to ensure parks remain green. Regardless, all sites improved soil carbon when organic matter amendments are applied.

Over all amendments and land-uses, the average reported increase in SOM% across studies was 3.6% in SOM%, with an average application of once over two to three years. To assess large scale changes in soil carbon more analysis is needed, however. In calculating these large scale changes in carbon storage we assumed 8–26% of urban municipal waste was transformed into an organic matter amendment and applied to urban soils annually (Harrison et al., 2020). This 8–26% would correspond to 22,191 to 72,125 ha of urban application when comparing to the application rate of the most efficient carbon increase, 76.2 Mg/ha for 1.2 SOM% increase, and the total US municipal solid waste load of 146 million tons, with it being 51.4% organic (US EPA, 2017). If amendments were to be widespread applied on urban soils this increase in carbon in the top 30 cm could represent an increase of $1.1 * 10^{-3}$ Pg C to $3.6 * 10^{-3}$ Pg C, in the United States, equivalent to 0.08%–0.26% of the United States' emissions in 2020 (US EPA, 2022). This would stem from an average increase of 22.2 Mg of carbon per hectare after 76.2 Mg/ha of amendment application. Globally, in addition to soil carbon sequestration, there is a large potential for avoided landfill emissions by transforming organic waste into organic matter amendments, as landfill emissions constitute up to 8–11% of global greenhouse gas forcing (Duren et al., 2019; Saunois et al., 2016). These numbers present untapped potential for carbon sequestration and carbon management in urban areas and policy measures should take this into account for regional and global carbon action plans. However, further study is needed on the longevity of the SOM increases due to these amendments in urban systems as most studies focus on short term single application of amendments. With focuses on short term application of amendments and the limit of 8–26% of urban municipal waste being used as an organic matter amendment, applying these amendments to urban regions would still be a multi-year project if we were to apply to all urban soils, leading to gains over time. Even if the same locations we reapplied annually or after several years there would be additional avoided landfill emissions, abated inorganic fertilizer emissions, and further soil carbon benefits, though reapplication may reduce the soil carbon increase due to carbon saturation limits (Stewart et al., 2007). However, these limits have largely not been reached as non-permafrost soils average holding 42% and 31% of their mineral carbon capacity in the top and subsoils respectively, with the highest carbon sequestration rates in soils at one-tenth of their carbon capacity (Feng et al., 2014; Georgiou et al., 2022). Thus, prioritizing the use of organic matter amendments for restoring and utilizing vacant and degraded urban land plots is the strongest path forward for increasing soil carbon.

While these urban lands in the United States represents only 3–5% of the country's total area, this figure will increase to 8% by 2050, and the potential C that could be stored in urban soils and the organic waste used to do so will continue to increase (Nowak and Walton, 2005). As the urban footprint grows it will be important to do so sustainability, such as by maintaining soil carbon and soil health and by utilizing organic resources such as food losses to create a circular economy. In addition to future sprawl, many current urban soils are degraded and could have substantial increases in carbon if organic matter amendments are applied, up to a doubling of SOM% in these soils (Table 1; Fig. 2). Carbon increases are one vital benefit in these soils when amendments are applied, but there can be social benefits as well, such as increased capacity to support urban food production and security.

4.2. Urban soil quality

The application of organic matter amendments improve soil properties such as soil nitrogen, phosphorus, potassium, and bulk density (Table 1; Salomon et al., 2020). These soil properties improve regardless of amendment type, but soil amendment type influences soil quality in distinct ways (Table 2). Biosolids have the most dramatic increases in soil nutrient levels for P and K, but when compared to compost's and biochar's improvements in N the changes are lackluster (Table 2). This is contrary to what one might expect, but the large difference between compost and biosolids is partially driven by composted biosolids being grouped with compost overall, thus increasing the compost applied nitrogen levels. There is still improvements in soil N with biosolids, though lower than expected with an average C:N of 10 (Table 3SI), and may be due to biosolids often being applied in lower amounts than compost. As for biochar, it is important to contextualize how biochar saw more increases than biosolids for N (Table 2). While studies have shown biochar to increase soil P, this large of an increase in soil N was unexpected (Gao et al., 2019). Approximately 1 g/kg of biochar's predicted 1.7 g/kg increase in soil N was driven by a study with pyrolyzed sewage sludge rather than woody material, Yue et al., (2017), which saw an increase of 0.8 g/kg to 10 and 20 g/kg, double the closest study. Even when including these pyrolyzed biosolids, biosolids alone are likely the favored amendment for high nutrient levels and faster mineralization compared to biochar and compost (Hagemann et al., 2017; Lu et al., 2012). Co-use of high nutrient biosolids with slower-releasing and higher-carbon compost or biochar could be used to effectively restore degraded urban soils, supplying carbon and nutrients, and could use further study (S. L. Brown et al., 2003).

Among land-uses, the largest improvements in nutrient levels are in reclamation and landscaping sites (Figs. 3, 5 and 6, S4). These land-uses likely see the largest gains as they have the lowest baseline values, allowing for the most potential improvement (Fig. 5). In comparison, only modest shifts are seen in gardening sites. This may be because urban garden sites are already managed for factors such as nitrogen and thus, do not have as much to gain as a vacant land site. However, garden sites may require more regular maintenance due to harvest and could be an effective location for continued nutrient-focused amendment application. Biosolids may then be appealing in gardening spaces where crop productivity is a main objective as these gardening spaces may not have as much room to grow in their SOM%, making them optimal locations for biosolids use to focus on improving soil nutrients instead (Fig. 3). All amendments types and land-uses see improved urban soil quality with amending, but as seen in gardening sites, aligning individual strengths to specific application and land-use goals will allow for the greatest potential benefit.

4.3. Societal Co-benefits

Organic matter amendments can also provide broad societal benefits to urban populations. Increased greenery can improve mental health, and the productivity of green spaces can be improved with soil amendments (South et al., 2018). Organic amendments are also important components of urban gardening, which improves local food security and provides a location for communities to learn and recreate (Barthel and Isendahl, 2013; Diekmann et al., 2020; Langemeyer et al., 2018). Encouraging organic matter amendment use in these areas could also lower the need for gardening peat, a destructively harvested carbon resource (Alexander et al., 2008; Schmilewski, 2008). However, a potential barrier to widespread use of some organic matter amendments in urban environments are the real or perceived risks of contaminants. However, the use of these amendments has actually been found to reduce the bioavailability of harmful compounds such as lead and arsenic in both soil and in plant tissue (Yang et al., 2018; Yue et al., 2017). In addition, plant concentrations of helpful nutrient such as nitrogen and phosphorus can increase, potentially making urban garden plants improved for human consumption with amendment application (Antonious et al., 2014; Una et al., 2022).

In addition to these benefits, compost application can reduce NOx emissions of soils by 80% (Meijide et al., 2007). Using California as an example, this could decrease total NOx emissions by approximately 7% as California soils emit 30% of state NOx emissions, with 30% of those emissions coming from developed land soils, leading to improvements in urban air quality (Almaraz et al., 2018; L. Guo et al., 2020). Therefore, additional science and outreach should be prioritized to reduce perceptions of risk and emphasize these potential public health benefits from adding organic matter amendments (Beecher et al., 2005; Whitehouse et al., 2022).

4.4. Literature gaps and future research

Based on our findings, we recommend seven priority focuses for future research in urban soil systems. First, future studies should further assess the effects of biochar and biosolids as the current literature is dominated by compost studies, despite the fact that feedstocks for biochar and particular biosolids are prevalent in urban systems. Second, future studies should assess recreation and gardening land-uses as they are underreported in the literature, are likely managed with fertilizer that could be supplemented by organic matter amendments, and provide many societal benefits. Third, future research should assess carbon to depth as reporting is done almost exclusively above 30 cm in urban systems with few observations to 50 cm or 1 m, potentially missing large stocks of carbon (Edmondson et al., 2012; Kranz et al., 2020). Fourth, studies should investigate the changes in soil carbon persistence to understand how changes in urban soil carbon stocks from organic matter amendments may last. Fifth, future research should evaluate how organic matter amendments influence urban soil greenhouse gas emissions. Several studies have found increases in CO_2 fluxes in urban soil systems but changes in nitrous oxide and methane soil emissions from organic matter amendment application – generally finding reduced fluxes - have overwhelmingly been assessed solely in agricultural contexts and without a systems perspective (Beesley, 2014; Pierre et al., 2016). Sixth, additional research should identify how urban soil microbial communities adapt to organic matter inputs, particularly as they are unique and highly diverse compared to other soil microbiomes (Guilland et al., 2018; Muth, 2021). Lastly, there is a need for longer term study as the vast majority of literature in this field is conducted on a one to three year timescale. Incorporating the recommendations above will allow for a more wholistic and long-term understanding of the urban soil carbon implications after the application of organic matter amendments.

5. Conclusion

Results from this study indicate the ability of organic matter amendments to strongly increase urban soil carbon, with SOM% doubling in amended sites. All urban land use types showed increases in SOM%, a finding that was consistent regardless of amendment type. Biochar and compost produced the largest increase in SOM%, while biosolids led to more pronounced increases in soil nutrients. Additional soil properties improve with amendments such as soil nitrogen and decreased bulk density. In addition to improving soil quality, amending presents many co-benefits. Urban planners and policy makers should prioritize the use of these urban organic matter amendments to reduce municipal waste loads, improve public health, and improve regional carbon planning. Organic matter amendments in urban settings hold untapped potential to help improve waste streams, improve urban soil quality, and increase soil carbon storage.

CRediT authorship contribution statement

Zachary Malone: Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Data curation, Visualization, Software. **Asmeret Asefaw Berhe:** Writing – review & editing, Supervision. **Rebecca Ryals:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Asmeret Asefaw Berhe is the current Director of the Office of Science at the US Department of Energy.

Other authors declare no additional competing interests.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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