The responses of topsoil organic carbon stocks in urban greenspaces to climate change and the urban heat island effect

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This thesis is submitted for the degree of *M.Sc. by Research* in Environmental Science at the University of Lancaster.

Lancaster Environment Centre, Lancaster University

September 2025

Abstract

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Urban greenspaces are increasingly recognised as important soil organic carbon (SOC) stores, yet their future dynamics remain uncertain due to unique interactions between climate change, management, and local urban drivers. The N14CP process-based nutrient cycling model, extended to represent urban parkland management, was applied to simulate SOC trajectories in 12 temperate and boreal urban greenspace sites from 2023 to 2100 under four SSP-based temperature scenarios, three nitrogen deposition trajectories, and three levels of urban heat island (UHI) intensity (+0, +1, +2.5 °C). Across sites, the model projected that SOC stocks declined by 6.5% on average under SSP2-4.5 with medium nitrogen deposition, with losses amplified by an additional ~2.5% per +1 °C UHI increment. Nitrogen deposition partially offset declines, but gains were modest and occurred only under low-to-moderate warming in a minority of sites. Site trajectories were heterogeneous, with some sites continuing to accumulate SOC under moderate warming, while others exhibited consistent decline, however, no sites exhibited resilience to warming, and SOC stock sensitivity to warming was consistently negative. The findings of this study also highlight that UHI effects could be of comparable magnitude to differences between global climate scenarios, underscoring the importance of urban cooling strategies to limit SOC stock loss in urban greenspaces. While nitrogen inputs can buffer declines, limited sequestration potential under continued warming and falling nitrogen deposition suggests that urban greenspaces should not be regarded primarily as a mitigation lever but rather integrated into wider carbon budgets and adaptation planning with explicit attention to site history, management, and local thermal regimes.

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Acknowledgements

I would like to express my sincere gratitude to my lead supervisor, Professor Jess Davies, whose guidance, support, and encouragement continually put me back on the right track whenever I strayed. Her thoughtful feedback and clear direction were invaluable throughout this project. I am also deeply grateful to Professor John Quinton, who has guided and nurtured my passion for this field over the past few years. His mentorship has been a constant source of inspiration and motivation, and I would not have reached this stage without his influence.

Declaration

In submitting this document, I declare that this submission is my own work. I have not submitted it in substantially the same form towards the award of a higher degree or other qualification. It has not been written or composed by any other person, and all sources have been appropriately referenced or acknowledged. Ethical approval was confirmed as not being necessary for the research presented.

Word count – 12178

Introduction

Soil organic carbon (SOC) is a cornerstone of the global carbon cycle: it constitutes the largest terrestrial carbon pool, mediates exchanges of CO_2 with the atmosphere, and is sensitive to disturbance and environmental change (O'Rourke et al., 2015; Ramesh et al., 2019; Rocci et al., 2021; Wiesmeier et al., 2019). Even modest fractional shifts in SOC therefore have outsized implications for climate change and mitigation strategies. Contemporary assessments emphasise both the magnitude of the global SOC pool and the persistent uncertainty around its response to warming, moisture change and land use change (Beillouin et al., 2022; Friedlingstein et al., 2022; Rumpel et al., 2020; Smith et al., 2008). Against this backdrop, SOC stocks have become a central focus for their potential to either sequester or release large quantities of carbon, for example, underpinning initiatives such as the 4 per 1000 strategy, which argues that annual increases in global soil carbon stocks of 0.4% could offset a substantial fraction of anthropogenic greenhouse gas emissions (Minasny et al., 2017; Rumpel et al., 2018).

Urban land area and populations continue to expand, with projections indicating that 68% of the global population will reside in cities by 2050 and, despite regional differences in urbanisation, urban greenspace area is expanding across both more and less developed regions (UN, 2019; Wu et al., 2023). Within urban planning, greenspaces remain central not only for recreation and public health but also for biodiversity conservation, stormwater regulation, and mitigation of urban heat extremes (Lin & Li, 2025; Wang et al., 2024; Wang & Lan, 2019). The size and distribution of SOC stocks in urban greenspaces have only recently begun to be characterised. The first global estimate of urban greenspace SOC stocks (1.46 Gt C) suggests that while these soils represent only ~0.2% of the global topsoil pool, they constitute an increasingly consequential component of terrestrial carbon storage, particularly in the context of climate change and urbanisation (Edmondson et al., 2012; Guo et al., 2024a).

Current understanding of the drivers of urban SOC dynamics is limited, but evidence from both urban and non-urban systems highlights the influence of climate change, atmospheric nitrogen deposition, nutrient inputs, biomass removal, and legacies of historical land use (Bai et al., 2015; Livesley et al., 2016; Strohbach et al., 2012). Urban greenspace soils are strongly shaped by anthropogenic histories and management regimes that have no close analogue in many non-urban systems. Cultural layers defined by anthropogenic materials and black carbon from historic combustion can contribute materially to stocks, while long-term nutrient additions and organic amendments leave persistent anthropogenic signals in soil profiles (Alexandrovskaya & Alexandrovskiy, 2000; Burke et al., 2024; Vasenev & Kuzyakov, 2018). Chronosequence, city and global-scale studies suggest that long-established parks in cities with earlier urbanisation dates often contain greater SOC stocks than recently created greenspaces, reflecting cumulative inputs and soil development under relatively stable conditions (Cambou et al., 2021; Delbecque et al., 2022; Guo et al., 2024a; Suratt et al., 2024). Contemporary management practices including mowing, irrigation, fertilisation, and organic amendments as well as nutrient inputs from pet waste modify litter inputs, nutrient cycling and soil structure, often with positive effects on SOC stocks that vary across vegetation types and intensities of use (De Frenne et al., 2022; Edmondson et al., 2014a; Thompson & Kao-Kniffin, 2019; Townsend-Small & Czimczik, 2010).

In non-urban ecosystems, moderate nitrogen enrichment can raise plant productivity and litter inputs, promoting organic matter formation, whereas high loads can alter microbial processes and constrain sequestration, yielding context-dependent net effects on SOC (Luo et al., 2019a; Yang et al., 2025). Cities often receive greater atmospheric nitrogen inputs than surrounding rural areas. This difference may be shrinking across European cities along with a general downward trend of atmospheric nitrogen deposition, however the effects this may have on urban greenspace carbon dynamics has not yet been investigated (Decina et al., 2020; Macdonald et al., 2021).

In general, rising temperatures as a result of climate change also exert strong control on SOC stocks, accelerating microbial respiration and decomposition, reducing SOC residence times and increasing the likelihood of long-term carbon losses (Liang et al., 2024; Poeplau & Dechow, 2023; Wang et al., 2022b). Large-scale syntheses and modelling studies also confirm a latitudinal gradient in SOC, with higher stocks in higher latitude, cooler climates, a pattern that is also evident in urban datasets (Georgiou et al., 2022; Guo et al., 2024a; Tian et al., 2015).

Temperature dynamics that may affect carbon storage in urban greenspace soils are not just limited to climate change but also the urban heat island (UHI) effect, which arises because cities replace natural land surfaces with impervious materials such as asphalt and concrete that absorb and retain heat, while reducing vegetation cover and evapotranspiration (Mohajerani et al., 2017; Rizwan et al., 2008). As a result, urban areas often experience systematically higher near-surface temperatures than their rural surroundings, resulting in the warming of surface soils and accelerated litter decomposition rates (De Pauw et al., 2024; Vasenev et al., 2021).

Although urban soils are increasingly recognised as relevant to the terrestrial carbon cycle and understanding of the key drivers of their change is increasing, they remain largely invisible in regional and global projections. Most long-term scenario frameworks and carbon inventories, such as the UK greenhouse gas inventory, either exclude urban soils altogether or aggregate them into broader categories that do not consider their unique drivers (Brown et al., 2023). As a result, there is still little quantitative understanding of how urban greenspace SOC may respond to future warming, changing nitrogen deposition, or local microclimates such as the urban heat island.

Process-based modelling provides a means to address this gap by integrating multiple biogeochemical drivers together with site histories and greenspace management practices within a consistent framework. For example, the N14CP model, which couples carbon, nitrogen, and phosphorus cycles across natural and managed ecosystems, has been widely applied to assess the impacts of land-use change, climate change, and nitrogen deposition on soil carbon at regional and national scales, in natural and agricultural environments (Janes-Bassett et al., 2021a; Janes-Bassett et al., 2021b; Toth et al., 2025; Yumashev et al., 2022).

This study aims to address this gap by tackling two key questions: (1) How may urban greenspace SOC stocks respond to future climate warming and nitrogen deposition, and how sensitive are they to these factors? (2) How does the UHI effect combined with climate change influence urban greenspace SOC stocks? To answer these questions, the N14CP process-based nutrient cycling model is applied to parkland urban greenspaces across 12 temperate city greenspaces, simulating long-term SOC dynamics to 2100. The model is extended to include an urban parkland-specific land-use type, reflecting contemporary greenspace management, and incorporates historical climate, nitrogen deposition, and land-use transition data. SOC dynamics are evaluated under four shared socioeconomic pathway (SSP) based temperature scenarios, three nitrogen deposition scenarios, and three UHI index levels. This study is the first application of a long-term biogeochemical model to urban greenspaces, providing new insights into their SOC dynamics and potential vulnerability under future environmental change.

Literature review

The importance of urban soil organic carbon in the global carbon cycle

Soil organic carbon (SOC) is increasingly recognised as amongst the most critical components of the global carbon cycle and therefore of great importance in climate regulation (O'Rourke et al., 2015; Wiesmeier et al., 2019). Although estimates of the global SOC pool vary based on the maximum depth and types of soils considered, the most exhaustive estimates reach a value of around 3000 Gt C, greater than the atmospheric (875Gt C) and vegetation (450 Gt C) pools combined (Friedlingstein et al., 2022; Köchy et al., 2015b). Therefore, even small perturbations in the global SOC stock through carbon emission or sequestration have the potential to both accelerate or decelerate increasing atmospheric CO_2 concentrations and the consequent climate change (Amelung et al., 2020; Rumpel et al., 2020).

The continued growth of urban land use globally will alter patterns of carbon storage and cycling, giving increasing importance to SOC contained within urban greenspaces (Edmondson et al., 2012). Global urban land area is projected to grow by a factor of approximately 2.7 by 2100 with a corresponding increase in the global urban population of 2.5 billion by 2050 (Gao & O'Neill, 2020; UN, 2019). However, this pattern is not uniform, and more developed regions show a much slower relative growth in urban populations than less developed regions (UNDESA, 2018). Despite these disparities, an increase in average urban greenspace coverage has been recorded across both Global North and Global South cities since 2011 (Wu et al., 2023).

The size of urban soil organic carbon stocks

Guo et al. (2024a) provides the only estimate to date for the size of the global topsoil SOC stock contained within urban greenspaces of 1.46 Gt C. Although this accounts for only approximately 0.2% of global topsoil SOC, the growing nature of urban soils globally raises the question – how do urban SOC stocks compare to their non-urban counterparts? The research on urban vs non-urban SOC stocks has reported conflicting trends at both global and local scales. For instance, Chien and Krumins (2022) found that globally, natural ecosystems stored significantly more SOC on average (98 Mg ha^{-1}) than urban green spaces (55 Mg ha^{-1}) whereas a similar global meta-analysis by Vasenev and Kuzyakov (2018) found that urban SOC stocks to be around double their natural counterparts.

Although this appears to present a contradiction in the literature, these findings cannot be directly compared as Chien and Krumins (2022) considered SOC at a depth of 30cm in urban greenspaces, limited to land uses like parks and gardens, while Vasenev and Kuzyakov (2018) considered SOC at beyond 100cm in a broader selection of urban land uses. When comparing the findings for urban SOC stocks at a 30cm depth, the result from Vasenev and Kuzyakov (2018) (60-70 Mg ha^{-1}) is well within one standard deviation of the equivalent result from Chien and Krumins (2022) (54.61 ± 22.02 Mg ha^{-1}). This is expected, given that both studies rely on an urban soil carbon dataset with large overlap.

However, while Chien and Krumins (2022) sources its natural environment SOC data from direct measurements of many sites across many studies, Vasenev and Kuzyakov (2018) extracted natural environment SOC data from points nearby cities in global soil maps, resulting in lower estimation of the average SOC stocks in natural environments. Despite both studies explicitly aiming to address the question of the difference in urban and natural SOC stocks, neither produce a consistent methodology for their selection of soil carbon data in natural environments or attempt to ensure that this data is representative of the global distribution of natural land cover and climate types. They therefore provide little value in understanding how urban and natural soil carbon stocks differ on a global scale and demonstrate that depending on the selection criteria of soil carbon data, completely opposite results may be obtained.

A selection of results from studies analysing the differences between urban and non-urban soil carbon stocks is shown in Table 1. Although carbon stored in urban soils clearly often differs from non-urban soils, the direction and magnitude of this difference appears to be highly specific to the individual urban area. There is evidence that the carbon stocks in urban soils are relatively uniform compared to corresponding natural soils, indicating that the impacts of urbanisation may serve to enrich carbon poor soils and degrade carbon rich soils (Chien & Krumins, 2022; Pouyat et al., 2006).

Table 1: Urban vs non-urban soil organic carbon (SOC) stocks from global meta-analyses and a selection of individual studies

Study	Location	Land uses	SOC stock findings (urban/non-urban)
Vasenev and Kuzyakov (2018)	Global meta-analysis	Urban soils vs natural soils nearby urban areas (0-100cm)	~ 2
Chien & Krumins (2022)	Global meta-analysis	Urban greenspace soils vs natural soils (0-30cm)	0.56
Cambou et al. (2018)	New York City	Urban soils vs agricultural soils (0-30cm)	2.10
Cambou et al. (2018)	Paris	Urban soils vs agricultural soils (0-30cm)	1.45
Canedoli et al. (2020)	Milan	Urban parks vs arable land and non-urban grassland (0-40cm)	No significant difference
Pouyat et al. (2006)	Boston	Urban soils vs pre-urban native soils (0-100cm)	0.36
Pouyat et al. (2006)	Chicago	Urban soils vs pre-urban native soils (0-100cm)	1.06
Raciti et al. (2011)	Maryland	Residential urban soils vs forested soils (0-100cm)	1.28

Trends in urban greenspace soil organic carbon and their drivers

Land-use

A comprehensive understanding of the magnitude, trends, and underlying drivers of urban SOC necessitates a consistent definition of urban land use. Conflicting definitions of urban land use between studies limit comparisons and confidence in wider trends of urban SOC as they may lead to large variations in urban SOC stock estimates (Raciti et al., 2012). It is especially important that consistent definitions are used so that meta-analyses have directly comparable data, however, in the absence of such consistency, analyses must include robust, albeit arbitrary, definitions of urban land use for consistent inclusion criteria. Guo et al. (2024a), the most comprehensive meta-analysis and model of global urban greenspace SOC stocks, defines urban extents as areas with either a population density greater than 1500 inhabitants per square kilometre or greater than 50% artificial impervious surface area whereas other meta-analyses of global urban SOC stocks such as Chien and Krumins (2022) simply rely on keywords within a literature search. The latter methodology is especially unsuitable as the individual studies from which such data is drawn commonly have no definition of urban besides location within city or town boundaries (Bekier et al., 2023; Canedoli et al., 2020; Tresch et al., 2018).

Although urban greenspace may fall under a single classification for the purposes of much research, there is wide variation in land-use and vegetation type within urban greenspaces, as in non-urban greenspaces, which may challenge the generic grouping of urban greenspace. This stresses the importance of specific urban land-uses as drivers of SOC trends, rather than urban land use itself. Guo et al. (2024b) completed a global analysis of carbon stocks contained within different urban greenspace types and found that urban wetlands have the greatest SOC stocks, followed by urban forest and then urban turfgrass.

However, this pattern is a global average and when SOC stocks are compared between urban greenspace land-uses within the same urban area, the results are highly variable. While the results of some studies such as Bae and Ryu (2015), of an urban park in Seoul, Livesley et al. (2016), of golf courses in Melbourne, and Setälä et al. (2016), of parks in Finland, conform to the results of Guo et al. (2024b), finding the greatest SOC stocks in wetlands followed by forest and then grassland, others, such as Weissert et al. (2016) of urban greenspaces in Aukland, New Zealand, find urban parks contain greater SOC stocks than urban forests and some such as Canedoli et al. (2020) of urban greenspaces in Milan, Italy, find no significant difference in SOC stocks between urban greenspace land-use types. This stresses the importance of considering other factors, such as climate, land-use history, and soil types, in determining the relationship between urban greenspace land-use and SOC stocks. Additionally, attempts to study urban land-use effects on SOC stocks may benefit from considering vegetation taxa and functional classes present as there is strong evidence that vegetation influence on urban SOC is highly dependent on vegetation type and function and is highly genus specific (Edmondson et al., 2014b; Kortleve et al., 2023; Setälä et al., 2016). The results of studies analysing SOC stock differences between urban land-uses are summarised in Table 2 along with some suggested mechanisms driving these differences.

Table 2: Soil organic carbon (SOC) stock differences between urban land-use types and suggested mechanisms from a selection of studies.

Study	Location	SOC stock differences	Suggested mechanisms
Guo et al. (2024b)	Global meta-analysis	Urban wetlands > urban forest > urban turfgrass	Anoxic conditions in wetlands preventing organic matter decomposition. Cooler, wetter conditions in urban forests promote organic matter accumulation
Bae & Ryu (2015)	Seoul, South Korea	Urban wetlands > urban forest > urban lawn	Carbon rich anthropogenic cultural layer beneath urban wetlands. Soil carbon is more evenly distributed throughout soil horizons in forest compared to lawn soil
Weissert et al. (2016)	Auckland, New Zealand	Parkland soils > urban forest soils	Study assessed topsoil (0-10cm). Greater topsoil bulk density in urban parkland soils compared to forest soils
Canedoli et al. (2020)	Milan, Italy	No significant differences	Dominant anthropogenic factors including black carbon deposition and presence of construction and industrial waste in soil horizons have a greater influence on SOC stocks than land-use specific factors
Setälä et al. (2016)	Finland	Evergreen forests > lawn	Acidic conditions beneath evergreen trees slow organic matter decomposition
Livesley et al. (2016)	Melbourne, Australia	Beneath tree canopy > grassland	Greater organic matter inputs and reduced litter removal in forested areas compared to grassy areas

This demonstrates the importance of land-use type in classifying urban greenspaces, however, difficulties exist in accurately measuring the extent of urban greenspace land-use types or total extent of urban greenspaces altogether. The high heterogeneity and fragmentation of urban greenspaces present a problem in quantifying citywide, nationwide, or global urban greenspace SOC stocks. While most studies, including Guo et al. (2024a), utilise medium resolution imagery (e.g. 30m LANDSAT TM), this has been shown to greatly underestimate urban greenspace extent and fail to capture temporal changes in urban greenspace dynamics (Qian et al., 2015). While low and medium resolution imagery may be generally suitable for estimating extents of natural land types on regional and global scales, urban greenspace research may particularly benefit from use of recent, high resolution (e.g. 2.5m) imagery.

Geographical trends

Estimating the size of global and regional urban greenspace SOC stocks and therefore global geographical trends has only recently become viable due to increased data available on urban greenspace soils. This development is especially significant as accounting and modelling of current urban greenspace SOC stocks presents the first barrier to inclusion within wider climate research. Guo et al. (2024a) attempts the most comprehensive analysis of the patterns and distributions of global urban greenspace SOC stocks through collection of a large observational dataset and random forest analysis. This research provides a useful baseline for global-scale urban greenspace SOC modelling and identifies several important trends in the global urban greenspace SOC distribution. In particular, higher urban greenspace SOC densities appear to be associated with higher latitudes, lower mean annual temperatures and weaker temperature and precipitation seasonality. These findings mirror those of other urban soil meta-analyses and wider non-urban SOC stock models, which also generally show peaks in high latitude regions and negative relationships between SOC and mean annual temperature (Chien & Krumins, 2022; Georgiou et al., 2022; Tian et al., 2015; Vasenev & Kuzyakov, 2018). This strongly suggests that the mechanisms which result in high levels of SOC accumulation in non-urban soils in high-latitude regions, namely positive feedbacks between cool soil temperatures, higher water tables, slowed microbial decomposition, and SOC accumulation, also persist in urban areas (Grosse et al., 2011; Mori et al., 2012).

Urban greenspace age

The trend of urban greenspaces of greater age, in older areas within cities, or within older cities themselves tending to contain greater SOC stocks is perhaps the most wellreplicated finding in the urban SOC literature across diverse geographical regions in local, regional, and global studies (Cambou et al., 2021; Guo et al., 2024a; Lindén et al., 2020; Livesley et al., 2016; Luo et al., 2014; Raciti et al., 2011; Setälä et al., 2016; Trammell et al., 2020; Vasenev & Kuzyakov, 2018).

Although sufficient research has not been completed to explain the mechanisms that cause this pattern, it is likely that historical black carbon deposition from industrial and domestic coal burning and combustion engines in the centres of older cities within developed countries has resulted in significantly greater levels of topsoil SOC accumulation. Global meta-analysis reveals that around a quarter of organic carbon in urban soils is composed of black carbon and that this figure reaches as high as 39% in the historic industrial areas of North-East England (Burke et al., 2024; Edmondson et al., 2015).

There is also strong evidence that SOC stocks in urban soils, particularly in older cities, are dominated by deep cultural layers of anthropogenic origin consisting of manures, ashes and biochars, wooden remains, human and animal remains, and agricultural waste (Alexandrovskaya & Alexandrovskiy, 2000; Bae & Ryu, 2020; Mazurek et al., 2016). Vasenev and Kuzyakov (2018) presented the most detailed analysis of carbon stocks present in the cultural layers of urban soils and found that around half of urban soil carbon stocks are contained within cultural layers below 100cm and that carbon accumulation in cultural layers is positively associated with the age of the city.

Research on chronosequences of urban soils has demonstrated that newly created urban soils tend to show low soil carbon and organic matter content as a result of the clearance of prior vegetation but that the accumulation of soil carbon and development of more mature vegetation results in consistent increases in soil carbon content with time (Delbecque et al., 2022; Howard & Olszewska, 2011; Suratt et al., 2024). Together with positive global urbanisation trends, this may be expected to cause steady increases in global SOC stocks contained in urban ecosystems, further increasing the importance of urban greenspace SOC to the global carbon cycle. Understanding the dynamics of SOC stocks and cycles in urban soils will become an important part of our wider understanding of the global carbon cycle and its climate change responses and feedbacks. A summary of direct anthropogenic drivers of urban SOC stocks is presented in Table 3.

Table 3: Anthropogenic drivers and their effects on urban soil organic carbon (SOC) stocks (adapted from Vasenev and Kuzyakov (2018)). Positive and negative effects are represented by + and – respectively, with a greater number of signs indicating a stronger effect.

Drivers of SOC stock change	Direction of change
Soil sealing	--
Removal of topsoil	---
Imported topsoil	+++
Pruning and cutting	++
Fertilisation and irrigation	++
Combustion of wood and fossil fuels	+
Waste management	+++
Overcompaction	++
Accumulation of cultural layers	+++

Climate change

Due to the increasingly recognised importance of urban soils in the global carbon cycle, urban soils research has not only academic importance but forms an essential aspect of national climate strategies and greenhouse gas accounting.

Understanding the impact of climate change on the global SOC pool is of great importance due to its large size relative to other carbon pools and the large uncertainties associated with its response to climate change (Bradford et al., 2016). Although uncertainties remain large, studies have found that net soil carbon losses are likely to occur with increasing temperatures due to accelerated soil carbon turnover, while the effects of changing precipitation patterns depend strongly on existing regional climatic conditions (Chen et al., 2023; Varney et al., 2020; Wang et al., 2021).

However, these patterns strongly depend on future land-use changes. For example, modelling suggests that under low-emission scenarios, with restoration of grasslands and afforestation, soil carbon stocks in the UK may be maintained but that high emission scenarios result in soil carbon losses regardless of land management strategies (Yumashev et al., 2022).

Urban areas are uniquely impacted by climate change due to the urban heat island (UHI) effect. The UHI effect is known to result in significant warming of surface soils in urban areas compared rural areas, with magnitudes of around 2°C soil warming measured in both Moscow, Russia and Nanjing, China (Shi et al., 2012; Vasenev et al., 2021). Not only does the UHI effect result in increases of peak temperatures during the day but studies modelling the impact of climate change on the UHI effect suggest that the greatest increases will be seen in nighttime temperatures, resulting in less diurnal temperature variation (Andrade et al., 2023; Mccarthy et al., 2010). Although this effect may stimulate increase vegetation growth, it has also been shown to act to increase the rate of litter decomposition accelerate soil microbial respiration by up to 25%, increasing the turnover rates of the topsoil C stock (De Pauw et al., 2024; Vasenev et al., 2021).

Nitrogen deposition

Urban areas across the globe also average nitrogen deposition rates of twice nearby rural areas (Conrad-Rooney et al., 2023; Decina et al., 2020). The impacts of elevated rates of nitrogen deposition on SOC in urban greenspaces are also uncertain are unstudied. There is strong evidence that increased levels of nitrogen deposition may stimulate growth of plant biomass, increasing rates of carbon fixation and growing the size of SOC stocks, particularly in forests, however this relationship appears to reverse at high levels of nitrogen deposition after which SOC stocks fall (Fang et al., 2014; Lu et al., 2021; Thomas et al., 2010). Further study is necessary to understand the specific impacts of high levels of urban nitrogen deposition on carbon cycling in urban soils, but it is likely that the impacts strongly depend on the vegetation types present, as they do in non-urban environments (Hu et al., 2024).

Exclusion of urban soils from models and inventories

Despite improvements in the availability of urban SOC data and numerous studies producing estimates of the impact of climate change on SOC stocks and terrestrial carbon sequestration at both regional and global scales, urban greenspace soils and changes associated with urbanisation have been consistently unaccounted for due to exclusion in the land use classifications of models or effective exclusion due to lack of SOC data availability in urban greenspaces (Beillouin et al., 2023; Rojas et al., 2018; Wang et al., 2022a; Yigini & Panagos, 2016; Yumashev et al., 2022). The relatively new state of urban greenspace SOC research and the many difficulties associated with estimating existing urban greenspace SOC stocks mean that inclusion within global or regional climate-SOC predictions is not yet attainable.

Without improved data on urban greenspace soils and better understanding of their carbon stocks, integration into models may produce inaccurate results. For example, the UK Greenhouse Gas Inventory (UKGGI) considers changes in soil carbon stocks the dominant emissions factor of the settlement land-use and claims to have produced estimates of these changes using a tier 3 dynamic soil model (Brown et al., 2023). However, closer inspection of the dynamic soil model used, described in Annex 3.4.6, reveals that the model input data is sourced from Milne and Brown (1997) and Bradley et al. (2005), both which assume SOC values of 0 for all urban areas. Under current IPCC greenhouse gas inventory guidelines described in IPCC (2006), a tier 3 approach for estimating changes in the carbon stock of inorganic soils requires a careful isolation and analysis of the specific land-uses. The most recent UKGGI has evidently not met this requirement for urban soils and, due to the assumption that urban soils contain no organic carbon, may inaccurately estimate carbon emissions associated with urban land-use change.

Conclusion

This review has provided an overview of the significance of urban SOC in the global carbon cycle, how urban SOC stocks compare to natural SOC stocks, the drivers and associated mechanisms that control urban greenspace SOC stocks, and the drivers that are likely to influence urban greenspace SOC stocks in the future.

It has highlighted critical gaps in the understanding of how urban SOC stocks will change in response to climate change and nitrogen deposition. While studies have explored urban SOC stocks in present-day conditions and how SOC stocks in general may change under climate scenarios, none have yet attempted to quantify future trajectories of urban greenspace SOC stocks using predictive modelling approaches. Given that urban greenspaces undergo continuous management interventions, high levels of nitrogen deposition, and unique climate shifts, their SOC stocks may be expected to react differently to SOC stocks in non-urban environments. However, the timescales and magnitudes of these changes remain unknown.

This research project will address these gaps by using a process-based modelling approach to analyse how SOC stocks in a selection of city sites may change under future temperature and nitrogen deposition scenarios. The following key research questions will be explored:

- How will urban greenspace SOC stocks change under projected climate warming, UHI levels, and nitrogen deposition scenarios?
- How sensitive are urban greenspace SOC stocks to these factors?
- How do SOC stock trajectories differ across urban greenspaces with varying land-use histories and climates?
- What are the dominant mechanisms driving SOC accumulation or loss in urban greenspaces under future environmental conditions?
- How can process-based modelling improve the inclusion of urban greenspaces in global carbon cycle predictions?

Methods

Model description

The N14CP model is a process-based biogeochemical model that simulates cycling of carbon (C), nitrogen (N), and phosphorus (P) in terrestrial ecosystems at a quarterly time step. (Davies et al., 2016; Janes-Bassett et al., 2020). The model tracks the flow of C, N, and P between vegetation, litter, and soil organic matter pools separated between the topsoil layer (0-15cm) and the subsoil layer (>15cm). The major processes represented include primary production, litterfall, decomposition, mineralisation, immobilisation, denitrification, leaching, and phosphorus weathering. Vegetation growth is determined by climate conditions and nutrient availability, with realised productivity constrained by Liebig's law of the minimum across temperature, precipitation, and the supply of N and P (Davies et al., 2016). Soil organic matter is represented by three pools in the topsoil (fast, slow, and passive), which span turnover times from years to millennia. Decomposition is modelled with pool-specific rate constants and a temperature sensitivity governed by a Q10 formulation.

The N14CP model has been applied to temperate and boreal forest, grassland, and agricultural ecosystems, where it has been used to quantify long-term trajectories of soil carbon and nutrient dynamics under historical and contemporary variation in climate and atmospheric nitrogen deposition (Ndep) (Davies et al., 2016; Janes-Bassett et al., 2021a; Janes-Bassett et al., 2021b; Janes-Bassett et al., 2020; Tipping et al., 2017). It has further been employed in scenario analysis extending to 2100, integrating projected changes in climate, nitrogen deposition, and land use to assess potential future trajectories of soil carbon stocks (Yumashev et al., 2022). These applications demonstrate the model's capacity to evaluate carbon-climate-nutrient interactions across ecosystems and time, providing the basis for its novel application here to urban greenspaces.

The N14CP model was extended to incorporate an urban greenspace land-use type, representing typical biomass removal and nutrient inputs. For urban grassland spaces, an above ground biomass of 80 gm^{-2} is maintained by a cut on each quarter where the above ground biomass exceeds this value, with cuttings returned to the litter pool. This value is typical of urban turfgrasses with contemporary management practices (Golubiewski, 2006; Jo & Mcpherson, 1995; Ng et al., 2015; Raciti et al., 2008). Nutrient inputs of 1.1 g N m^{-2} yr^{-1} and 0.5 g P m^{-2} yr^{-1} were applied to urban greenspace land-use based on field measurements of annual nutrient inputs to urban greenspaces from dog excreta in European peri-urban reserves (De Frenne et al., 2022).

Site data

Site selection was undertaken to identify representative urban greenspaces suitable for modelling long-term soil carbon dynamics. Urban greenspace sites were selected from a global database compiled by Guo et al. (2024a) consisting of 420 individual observations of urban greenspace soil organic carbon (SOC) stocks from 257 cities. Inclusion criteria for selection included temperate or boreal climate, sample depths of between 10 and 20 cm inclusive, parkland land use, and lawn/turfgrass vegetation. This produced a list of 24 observations, of which 12 were excluded due to lack of data availability, incorrect land use classification, unsuitable climate, or clear evidence of recent fertiliser or herbicide application. The final set comprised of 12 study sites distributed across Europe and North America. The locations of the 12 sites are shown in Figure 1, and their mean annual temperature (MAT) and rates of atmospheric nitrogen deposition are shown in Table 4.

Figure 1. Location of urban greenspace sites.

Table 4. Mean annual temperature (MAT) and nitrogen deposition (Ndep) in 1990 for urban greenspace sites. Ndep for Baltimore is given for 2000 as data were not available for 1990.

City	MAT (°C)	Nitrogen Deposition (g m^{-2} yr^{-1})	References
Baltimore	13.24	1.18*	Pouyat et al. (2015)
Brno	9.72	2.37	Pizl and Schlaghamersky (2007)
Budapest	11.67	2.02	Pouyat et al. (2015)
Chelyabinsk	3.45	1.16	Stoma et al. (2020)
Geneva	10.50	1.76	Tobias et al. (2023)
Helsinki	6.23	1.04	Pouyat et al. (2015)
Lahti	5.18	0.92	Pouyat et al. (2015)
Liverpool	10.41	1.93	Beesley (2012)
Santiago de Compostela	14.28	1.63	Gómez-Brandón et al. (2022)
Sochi	14.63	1.74	Stoma et al. (2020)
Warsaw	9.05	2.04	Oktaba et al. (2014)
Wroclaw	9.00	1.72	Bekier et al. (2023)

Where SOC stock values were reported at depths other than 15 cm, they were converted to a common 0–15 cm depth to allow direct comparability with the topsoil SOC fraction represented in the N14CP model. Depth conversions were calculated according to the following equations (Jobbágy & Jackson, 2000):

$$Y = 1 - \beta^{d} \tag{1}$$

where Y is the proportion of total SOC contained above a given depth, $d\ (cm)$, and β is a unitless parameter describing the rate of SOC decline with depth. Reported values for an original sampling depth, d_0, were converted to a standard 0–15 cm equivalent using

$$X_{15} = \frac{1 - \beta^{15}}{1 - \beta^{d_0}} \times X_{d_0} \tag{2}$$

Where $X_{d_0}\ (gm^{-2})$ is the SOC stock at depth $d_0\ (cm)$ and $X_{15}\ (gm^{-2})$ is the SOC stock at depth 15cm. The global average soil C depth distribution (β = 0.976) was adopted, consistent with previous urban greenspace research, and in line with its application in global and regional SOC syntheses as a framework for harmonising stocks derived from heterogeneous sampling protocols (Chien & Krumins, 2022; Guo et al., 2024a; Li et al., 2012).

Historical nitrogen deposition inputs for each site were derived from modelled datasets to provide continuous coverage across the historical simulation period. For each European site, annual total nitrogen deposition was estimated from the EMEP MSC-W model for the period 1990-2022 and for North American sites was estimated from NADP-NTN data for the period 2000-2022 (MET-Norway, 2024; NADP, 2023). A temporal anomaly based on Schöpp et al. (2003) was applied to provide continuous nitrogen deposition estimates, prior to modelled data, for all European sites from 1800 to 1989 and from 1800 to 1999 in North American sites, similarly to Davies et al. (2016).

Mean quarterly temperature and mean quarterly precipitation data for each site between 1901 and 2022 were derived from Berkeley Earth high-resolution city level data and CRU TS4.08 data respectively (Harris et al., 2020; Rohde & Hausfather, 2020). A temporal anomaly based on Davis et al. (2003) was applied to the long-term average (1901-1930) mean quarterly temperature to estimate mean quarterly temperatures prior to 1901. Mean quarterly precipitation prior to 1901 was fixed at the long-term average (1901-1930).

Forest-cover estimates on usable land were taken from Kaplan et al. (2009) at eight benchmark dates between 1000 BCE and 1850 CE. A fixed threshold of 75% forestation was used to mark substantial clearance: for regions initially above the threshold, the first year below it was identified by linear interpolation between the nearest bracketed dates; for regions already below the threshold at 1000 BCE, linear extrapolation to earlier centuries was applied. Regions that never dropped below the threshold by 1850 CE were noted as having no transition until the urban greenspace land use applied at the urban land-use transition date. Grassland land-use was applied post-deforestation for each site until the urban land-use transition.

Urban land-use transition years were determined from the Land-Use Harmonization 2 dataset, which provides annual gridded land-use fractions from 850 CE at 0.25° resolution (Hurtt et al., 2020). For each site, the grid cell which contains the site coordinates was extracted, and the urban land-use fraction was used as the indicator of urban expansion. The transition year was defined as the first year in which either (i) the urban fraction reached at least 10% of the grid cell area or (ii) the urban fraction reached at least 25 % of its 2015 value. This dual-threshold method preserved comparability across sites while accounting for variation in local urbanisation trajectories.

Model calibration

The N14CP model is designed to be non-site-specific, employing a generalisable parameter set and running with readily available input data. However, previous applications have demonstrated that model outputs are particularly sensitive to the size of the initial weatherable P pool (P_{weath0}), a site-specific parameter that remains poorly constrained by empirical measurements (Davies et al., 2016). Consistent with earlier site-scale studies (Janes-Bassett et al., 2020; Toth et al., 2025), P_{weath0} was calibrated on a site-by-site basis, permitting it to vary within the plausible range established by (Goll et al., 2012). Calibration was performed by comparing observed SOC stocks at each site with simulated values for the corresponding observation years. The P_{weath0} parameter was adjusted within the range 50–1000 g m^{-2} until the simulated SOC was within 1% of the observed value. Where observed SOC fell outside the achievable range, P_{weath0} was fixed at the respective upper or lower bound.

Model-observation agreement was quantified using the coefficient of determination (R^2) and the root mean squared error (RMSE). RMSE was calculated following:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_{mod,i} - X_{obs,i}\right)^2} \tag{3}$$

where n is the number of sites, $X_{\mathrm{mod},i}$ is the modelled SOC stock for site i, and $X_{\mathrm{obs},i}$ is the corresponding observed SOC stock. RMSE is expressed in the same units as SOC stock (g C m^{-2}).

Temperature scenarios

Future temperature projections were incorporated to represent a range of plausible climate warming conditions for the study sites. These were obtained from the UKESM1-0-LL global climate model, part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Sellar et al., 2019). Four Shared Socioeconomic Pathways (SSPs) were selected to span low to high radiative forcing and emissions emission trajectories. SSP1-2.6, a low-end radiative forcing scenario representing significant emissions reduction, SSP2-4.5, a medium radiative forcing scenario representing a middle of the road scenario, SSP3-7.0, a medium-high radiative forcing scenario with little mitigation and SSP5-8.5, a high-end radiative forcing scenario representing unmitigated emissions (O'Neill et al., 2016). Only the first ensemble member was used for each scenario. Bias correction was performed using the delta change method, with the reference period defined as 1990–2022 to align with the Berkely Earth historical temperature data used in the historical simulations (Hay et al., 2000).

For temperature, an additive correction was applied:

$$T_{corrected} = T_{sim} + (\overline{T_{obs}} - \overline{T_{sim}}) \tag{4}$$

where $T_{corrected}$ is the bias-adjusted temperature, T_{sim} is the scenario temperature, and $\overline{T_{obs}}$ and $\overline{T_{sim}}$ are the mean observed and simulated temperatures over the reference period, respectively. The calculated correction factors were applied to all mean quarterly temperature values from 2023–2100, producing bias-adjusted climate inputs for each SSP scenario.

Mean quarterly precipitation for 2023–2100 was fixed at the 1990–2022 average for each site. This approach was adopted to isolate the effects of temperature and nitrogen deposition, which exhibit more directionally consistent trajectories, from the effects of projected precipitation changes, which show high inter-model spread, lack a monotonic relationship with emissions scenarios, and often display disagreement even in the direction of change at regional and local scales (Holtanová et al., 2022; Palmer et al., 2021; Ritzhaupt & Maraun, 2023; Szabó & Szépszó, 2016; Zhang & Chen, 2021).

Projected temperature change under SSP scenarios

Average warming across the 12 sites (2091–2100 relative to the 2023–2032 baseline) reached 1.6 °C under SSP1-2.6, 3.8 °C under SSP2-4.5, 5.5 °C under SSP3-7.0, and 7.3 °C under SSP5-8.5. Warming for all sites under the SSP2-4.5, the most plausible, middle of the road scenario, is shown in Figure 2. Variation among sites was substantial, with end-century warming ranging from 0.7–2.4 °C in SSP1-2.6 up to 5.1–9.0 °C in SSP5-8.5. A clear latitudinal-temperature gradient was evident ($R^2 = 0.40$, $p = 0.027$). Higher-latitude cities such as Helsinki, Lahti, and Chelyabinsk experienced the strongest warming, while lower-latitude locations including Santiago de Compostela, Geneva, and Sochi exhibited comparatively smaller temperature increases under the same SSPs.

Figure 2. End-century temperature change (2091–2100 relative to 2023–2032) across 12 sites under SSP2-4.5.

Nitrogen deposition scenarios

Future nitrogen deposition scenarios were developed to represent a plausible range of trajectories consistent with varying levels of emission mitigation and were generated using the 2022 site-specific annual total nitrogen deposition value as the baseline. Three scenarios were defined for 2023–2100:

1. High deposition – constant at the 2022 baseline value.
2. Medium deposition – linear decline to 50% of the 2022 value by 2100.
3. Low deposition – linear decline to 20% of the 2022 value by 2100.

Annual values for each scenario were calculated by linear interpolation between the 2022 baseline and the 2100 target, preserving site-specific differences in absolute deposition while imposing uniform relative changes across sites.

Urban heat island index levels

The potential influence of the urban hear island (UHI) effect on future soil carbon dynamics was incorporated by applying constant temperature offsets to the future temperature scenarios from 2023 to 2100. Two increments were used (+1 °C and +2.5 °C) to bracket a plausible range of long-term mean UHI intensities across all sites. Multi-city European analyses based on high-resolution modelling report mean UHI intensities of around 1.5 °C, with summer means spanning 0.5–3.0 °C (Iungman et al., 2023; Lauwaet et al., 2024). These values place the selected increments within empirically observed bounds. City-specific observations for Helsinki indicate average UHI intensities around 1.2 °C, supporting the lower offset, while larger and denser cities often exhibit higher mean or nocturnal intensities consistent with the upper offset (Lauwaet et al., 2024; Taylor et al., 2025; Zhou et al., 2017). The offsets were applied uniformly across locations to explore a realistic UHI envelope while avoiding site-specific assumptions about future urban form or adaptation. Each of the four SSP temperature scenarios were run without UHI offsets, and again with each of the two increments, producing outputs for all combinations of temperature scenario, nitrogen deposition pathway, and UHI intensity.

In total, the simulations comprised 36 unique scenario combinations for each site, representing the factorial combination of four climate trajectories (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5), three nitrogen deposition pathways (high, medium, low), and three UHI conditions (no offset, +1 °C, +2.5 °C).

Sensitivity analysis

To quantify the sensitivity of SOC stocks to temperature and nitrogen deposition, site-level regressions across all 12 scenario combinations were performed (4 temperature × 3 Ndep). For each site, the relative change in SOC stocks between 2023 and 2100 was regressed against the corresponding changes in mean annual temperature (2091–2100 relative to the 2023–2032 baseline) (ΔTemp) and nitrogen deposition (ΔNdep):

$$\Delta SOC\% = \beta_T \cdot \Delta Temp + \beta_N \cdot \Delta Ndep + \epsilon \tag{5}$$

where $\Delta SOC\%$is the percentage change in SOC stocks relative to 2023, and β_T and β_N represent sensitivities to temperature change (% per °C) and nitrogen deposition change (% per g N m^{-2} yr^{-1}), respectively. Regressions were performed separately for each site using ordinary least squares (OLS). The resulting coefficients provide direct estimates of SOC sensitivity to each driver, independent of scenario.

Results

Model performance

Model performance was evaluated by comparing observed and modelled soil organic carbon (SOC) stocks across the 12 study sites (Figure 3). The calibrated model reproduced the general magnitude of observed SOC stocks, with a mean observed value of 5841 gC m^{-2} compared to a mean modelled value of 5210 gC m^{-2}, indicating a small (~11%) underestimation. The agreement between observed and modelled values was modest (R^2 = 0.37). Despite variation from observed values among sites, the 1:1 comparison demonstrates that the model captures site-level variation sufficiently to provide a reasonable basis for scenario projections. SOC stocks in Sochi were significantly underestimated at only 42.4% of the observed value.

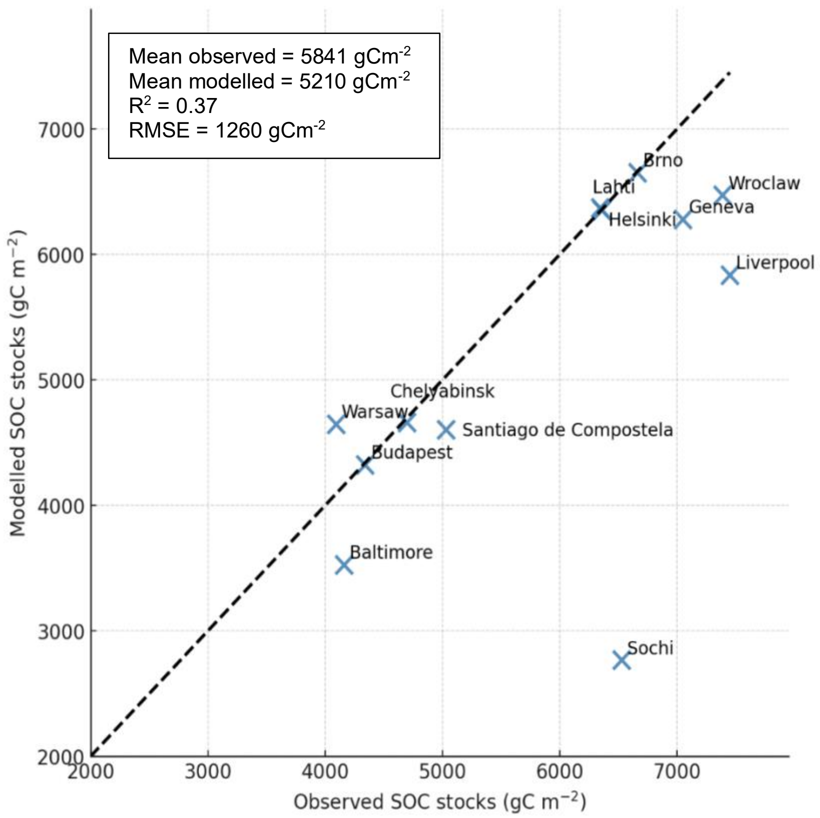

Figure 3. Model performance for simulated versus observed SOC stocks across the 12 study sites. Statistics are presented including the mean observed and modelled SOC stocks for each site, R^2, RMSE, and the 1:1 line.

Soil organic carbon stock trends

Across all 12 study sites, simulated SOC stock change to 2100 depended strongly on the combination of temperature and nitrogen deposition scenarios. All sites showed SOC decline across all nitrogen deposition scenarios under SSP3-7.0 and SSP5-8.5 and SOC stock gains were observed only in Budapest, Chelyabinsk, Lahti, and Sochi under SSP1-2.6 and SSP2-4.5 (Figure 4). Higher warming consistently led to more negative SOC stock change, with the largest declines occurring under SSP5-8.5. In contrast, greater nitrogen deposition reduced SOC stock losses in all cases, with higher nitrogen deposition scenarios producing less negative, or more positive, SOC stock change.

Under the reference scenario (SSP2-4.5, medium Ndep), SOC stocks declined by an average of 6.5% across the 12 sites between 2023 and 2100. Most sites showed moderate reductions of 7–10%, including Brno (−10.5%), Budapest (−9.4%), Warsaw (−9.0%), and Wroclaw (−9.3%). Smaller losses were projected in Lahti (−3.7%) and Sochi (−2.6%), while Chelyabinsk diverged from the overall pattern with a net increase of 3.5%. For comparison, under the best-case scenario (SSP1-2.6, high Ndep), SOC stocks were essentially stable overall (site-averaged mean of 0.0%), with several cities showing modest gains, most notably Chelyabinsk (+10.2%) and Sochi (+7.6%). In contrast, the worst-case scenario (SSP5-8.5, low Ndep) resulted in an average decline of 14.4%, with severe losses in Baltimore (−20.5%), Budapest (−19.0%), and Warsaw (−18.0%).

Figure 4. Projected change in soil organic carbon (SOC) stock (%) from 2023 to 2100 across 12 urban greenspace sites, under four SSP-based temperature scenarios and three nitrogen deposition (Ndep) scenarios. Bars represent the percent change in SOC stock relative to 2023 values (positive values indicate SOC stock gain, negative values indicate SOC stock loss). Each subplot corresponds to one city. Climate scenarios are shown on the x-axis (SSP1-2.6 to SSP5-8.5), and bars are coloured according to Ndep scenario (Low, Medium, High).

The spatial distribution of SOC change revealed clear regional contrasts (Figure 5). Central European cities (Brno, Budapest, Warsaw, Wroclaw) displayed the largest proportional losses, whereas northern cities such as Helsinki and Lahti experienced more moderate declines. Western sites including Liverpool and Geneva also exhibited relatively high losses, while southern locations such as Sochi and Santiago de Compostela showed smaller reductions. Chelyabinsk diverged from the broader European pattern, with SOC stock gains under SSP2-4.5, medium Ndep. Across all sites, the magnitude of SOC stock loss showed a significant relationship with nitrogen deposition, with higher-deposition cities exhibiting greater declines ($R^2 = 0.38$, $p = 0.03$), while no consistent trends were observed with MAT or latitude.

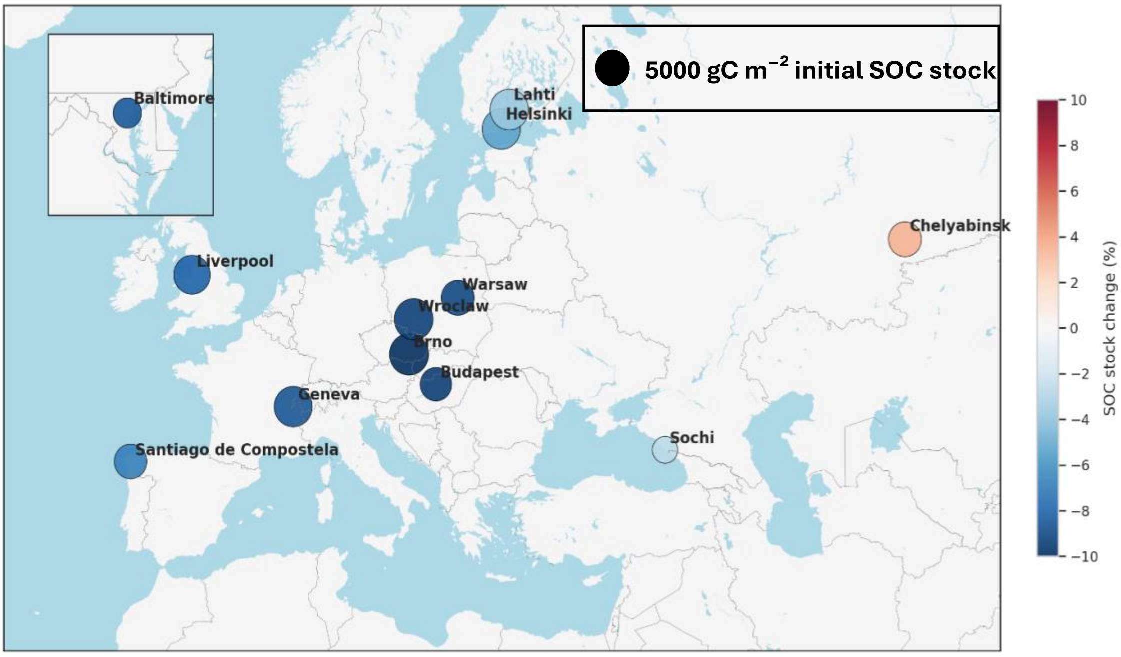

Figure 5. Spatial variation in simulated soil organic carbon (SOC) stock change (2023–2100) across the 12 study cities under the reference scenario (SSP2-4.5, medium nitrogen deposition). Marker size indicates initial SOC stock in 2023, while colour denotes the percentage change by 2100. Blue shading indicates SOC stock decline whereas red shading indicates SOC stock gain.

The time series reveal contrasting site-level trajectories under different scenario combinations (Figure 6). In Liverpool, SOC stocks declined steadily throughout the century across all SSPs, with the steepest declines under SSP5-8.5 and the most gradual under SSP1-2.6. Higher nitrogen deposition consistently reduced the rate of decline but did not prevent long-term losses. In Chelyabinsk, by contrast, SOC stocks increased under lower warming pathways, with gains most pronounced under SSP1-2.6 and high nitrogen deposition. Stocks remained stable or slightly positive under SSP2-4.5, but declined under stronger warming with decline beginning around 2070 under SSP3-7.0 and around 2050 under SSP5-8.5.

Across sites showing general decline across scenarios, the relationship between SSP temperature scenario and SOC stock trajectory was remarkably consistent. Under SSP1-2.6, the fastest SOC stock change generally occurred before 2050 and stabilised by 2100, under SSP 2-4.5, SOC stock changed at a fairly consistent rate throughout the entire simulation period and under SSPs 3-7.0 and 5-8.5 SOC stock change tended to accelerate towards the end of the century. These patterns illustrate how scenario combinations drive persistent declines at some sites while enabling long-term increases at others.

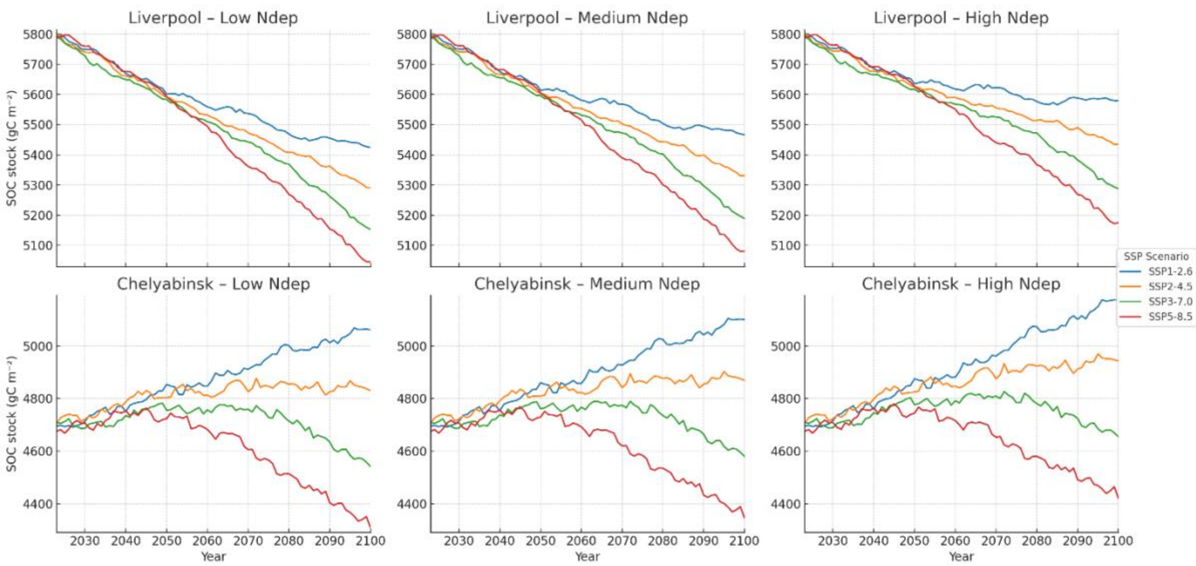

Figure 6. Time series of soil organic carbon (SOC) stock from 2023 to 2100 for Liverpool and Chelyabinsk under four temperature scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) and three nitrogen deposition (Ndep) scenarios (Low, Medium, High). Each subplot corresponds to a single Ndep scenario, with lines representing the SOC stock trajectory under each climate scenario.

Sensitivity of soil organic carbon stocks to temperature and nitrogen deposition

SOC stock responses were consistently negative in relation to warming but positive in relation to atmospheric nitrogen deposition change (Figure 7). Across all 12 sites, regression analyses showed SOC stock sensitivity to temperature change ranging from −2.5% to −1.4% per °C of warming by 2100, with a mean of −1.8% per °C across all sites. The strongest temperature senstivity occurred in Baltimore, followed by Sochi and Budapest, while Liverpool exhibited the weakest sensitivity. This indicates that although warming uniformly drives SOC losses, the magnitude of the relationship between warming and SOC stock loss is strongly site-dependent.

By contrast, nitrogen deposition acted as a mitigating influence on SOC stock decline. Across all 12 sites, regression analyses indicated positive SOC stock sensitivities to nitrogen deposition change by 2100, ranging from +2.0% to +6.7% per g N m^{-2} yr^{-1} with a mean of +3.9% per g N m^{-2} yr^{-1}. In practice, because all scenarios involved steady or declining nitrogen deposition, greater declines resulted in greater SOC stock losses, equivalent, on average, to a 3.9% SOC stock loss per g m^{-2} yr^{-1} of nitrogen deposition decline from 2023-2100. The strongest nitrogen deposition sensitivities were found in Sochi, while the weakest were in Helsinki. Model fits were uniformly strong (R^2 > 0.90 for all cities), indicating that variations in SOC stock change across scenario combinations within the same site were well explained by the combined influence of temperature and nitrogen deposition change.

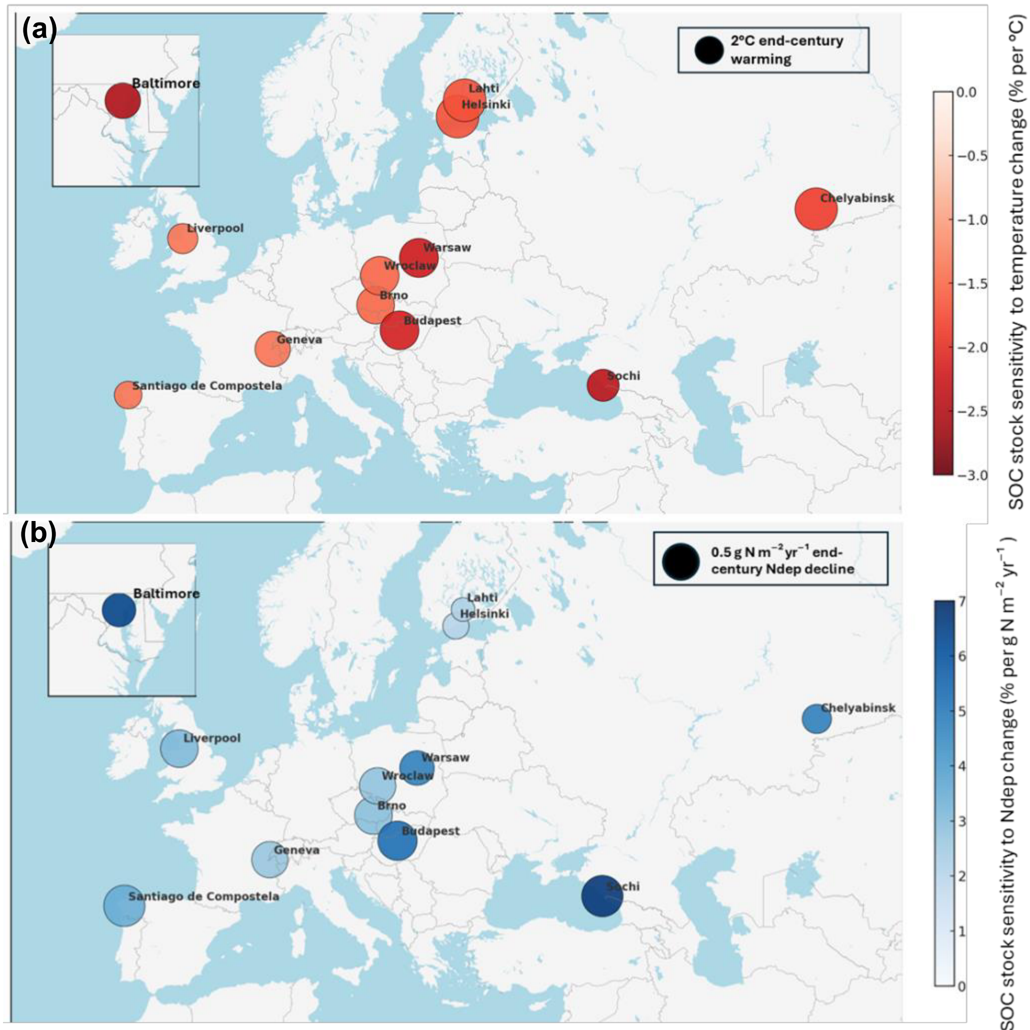

Figure 7. Spatial distribution of soil organic carbon (SOC) stock sensitivity to environmental drivers across 12 urban study sites.

(a) Sensitivity to temperature change, expressed as the relative change in SOC stocks per °C warming by 2100 (2091–2100 relative to the 2023–2032 baseline) (% per °C).

(b) Sensitivity to nitrogen deposition (Ndep) change, expressed as the relative change in SOC stocks per unit deposition change by 2100 (% per g N m^{-2} yr^{-1}).

Marker size for the temperature sensitivity map represents the end century temperature gain under SSP2-4.5 for each site and marker size for the Ndep sensitivity map represents the end century Ndep decline under the medium Ndep scenario for each site. Marker colour for both represents the strength of the sensitivity of SOC stocks to each factor.

Urban heat island effects on soil organic carbon stocks

Under SSP-2.45 with medium nitrogen deposition, UHI warming led to mean additional SOC stock change by 2100 of −2.5% at +1 °C and −6.2% at +2.5 °C, relative to the no-UHI baseline. Across cities, the incremental effect ranged from −2.1% to −3.4% at +1 °C and −5.1% to −8.1% at +2.5 °C (Figure 8). The largest additional declines occurred in Sochi, Warsaw, and Budapest, while the smallest were observed in Geneva, Liverpool, and Wroclaw.

Under SSP-1.26 with high nitrogen deposition, Budapest and Lahti shifted from positive or stable SOC trajectories at UHI 0°C to net declines under +1°C, while Sochi shifted to a net decline under +2.5 °C. Under SSP2-4.5, Chelyabinsk shifted to net SOC losses at +2.5 °C across all nitrogen deposition levels. Across all sites, climate and nitrogen deposition pathways, the per-degree effect of UHI warming was highly consistent, with sensitivities in all sites but Sochi constrained between 2% and 3% SOC stock loss by 2100 per °C, demonstrating that the incremental response was robust across scenarios and sites.

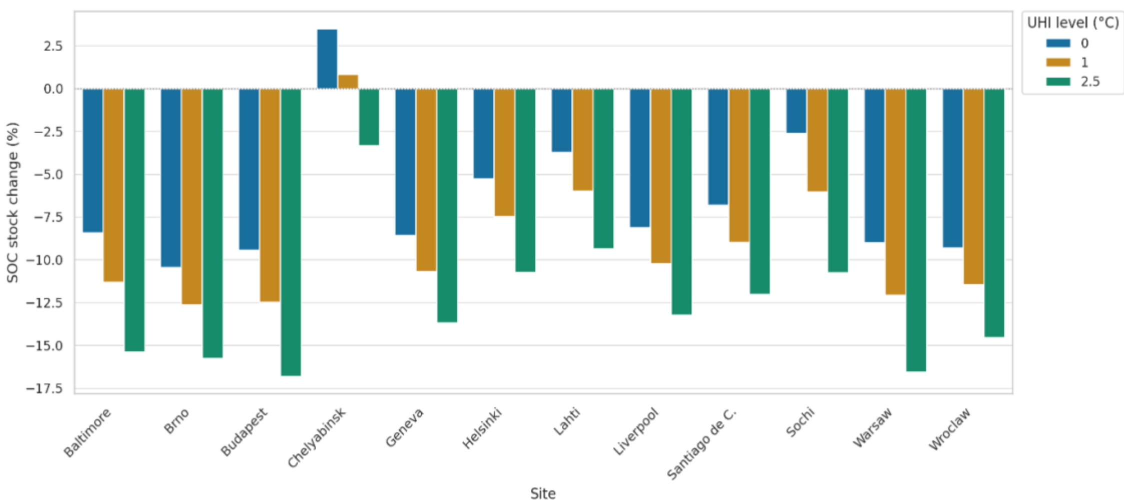

Figure 8. Percentage change in soil organic carbon (SOC) stocks from 2023 to 2100 under three urban heat island (UHI) levels for each study city, shown for SSP-2.45 with medium nitrogen deposition. Results are presented for no UHI (0 °C), +1 °C UHI, and +2.5 °C UHI increments.

Discussion

Model performance

The underestimation of soil organic carbon (SOC) stocks in six of the 12 sites is likely attributable to the absence of site-specific information on land-use history and management practices, which could not be incorporated into the model simulations. Several urban-specific processes are known to influence soil carbon accumulation but cannot be represented here because their presence and magnitude are unknown at individual sites. These include historical black carbon deposition (Burke et al., 2024), the development of nutrient-rich cultural layers derived from anthropogenic materials associated with past agriculture or urban construction (Alexandrovskaya & Alexandrovskiy, 2000; Bae & Ryu, 2020; Mazurek et al., 2016), fertiliser inputs linked to historical land use or contemporary greenspace management, and altered hydrological regimes arising from increased surface runoff in urban landscapes (Kaye et al., 2006; Lorenz & Lal, 2009).

SOC stocks in Sochi were the least accurately reproduced by the model at 42.4% of the observed value. This discrepancy likely reflects the combination of high mean annual temperature (14.6 °C) and recent forest clearance, conditions that lie outside the calibration ranges of the model (Davies et al., 2016; Janes-Bassett et al., 2020). Similar limitations may also apply to Santiago de Compostela and Baltimore, where mean annual temperatures likewise exceed the ranges represented in previous calibration studies.

These findings highlight both the strengths and limitations of the N14CP framework when applied to urban greenspaces. On one hand, the model was able to reproduce relative variation in SOC across sites, supporting its use for comparative scenario analysis. On the other, reliance on calibration of a poorly constrained parameter (P_{weath0}) and the paucity of urban greenspace data introduce uncertainties that propagate into long-term projections. Expanding empirical datasets on urban soil C stocks and nutrient cycling processes will therefore be critical for refining model applications in this context.

Overall stock change findings

The results strongly suggest that climate change-induced warming may result in significant SOC stock declines across grassland urban greenspaces in temperate and boreal cities. Across the 12 study sites, mean SOC stocks declined by 6.5% under SSP2-4.5 with medium Ndep, relative to 2023 baselines. Although this decline may appear modest, this represents a rapid shift relative to equilibrium SOC dynamics, in which soil carbon turnover times, particularly in the more stable fractions, are generally characterised in centuries to millennia (Luo et al., 2019b; Shi et al., 2020; Tan et al., 2024). Losses on the order of 0.1% yr^{-1} observed in urban greenspace sites therefore represent a pace of change that is unusually fast compared with baseline dynamics and imply a significant disequilibrium between carbon inputs and decomposition under warming that is unsustainable on a centuries-long timescale. This decline, integrated with the country-level estimations of urban greenspace topsoil SOC stocks per Guo et al. (2024), produces estimated urban greenspace SOC stock losses of 21.5TgC in Europe and 27.2TgC in North America by 2100. Together, these losses represent approximately 40% of the UK's terrestrial carbon sequestration potential up to 2100, even under the most optimistic climate and land-use scenarios (Yumashev et al., 2022).

When considered in the context of other projections of SOC stock change, the mean change simulated is broadly comparable. Multi-decadal modelling on local, regional, and national scales generally projects end-century soil carbon stock reductions of 5–20% under moderate climate change scenarios across both grassland, cropland, and natural ecosystems with changes dependant on land-use, management, nutrient inputs, and precipitation patterns (Gonçalves et al., 2021; Grace et al., 2006; Meersmans et al., 2016; Mondini et al., 2012; Wiesmeier et al., 2016; Zhong & Xu, 2014). The stability of SOC stocks under low emission, SSP1-2.6 scenarios projected in this study show similar patterns of limited SOC stock change to national scale analysis in Australia, China, and the United States (Gonçalves et al., 2021; Grace et al., 2006; Zhang et al., 2023). On the other hand, the losses produced by high emission, SSP5-8.5 scenarios, reaching as high as 20.5%, reflect extreme SOC stock loss that approach and, in some cases, surpass, those observed as a result of grassland to cropland land-use conversions (Cai et al., 2025; Liang et al., 2023; Yellajosula et al., 2020).

In most sites displaying SOC stock decline, such as Liverpool (Figure. 6), SOC stock trajectories only approached a new equilibrium by the end of the 21st century under SSP1-2.6, with most change occurring before 2050 and relative stability thereafter. In all other scenarios, particularly SSP3-7.0 and SSP5-8.5, no such stabilisation was evident, with losses continuing or even accelerating towards 2100. This suggests that under stronger warming pathways, SOC stock decline in urban greenspaces is unlikely to plateau within the 21st century and instead is likely to intensify beyond it. Under SSP2-4.5, medium Ndep, end-century stable SOC stocks are only projected in Chelyabinsk, with all other sites projected to continue declines beyond 2100.

Spatial patterns

A strong divergence in SOC stock change was evident between sites (Figure. 5), spanning from +3.5% to −10.5% under SSP2-4.5 with medium Ndep. In particular, central and western European sites and Baltimore tended to show the largest proportional SOC stock losses, northern and southern European sites showed intermediate losses while Chelyabinsk showed slight gains. These regional outcomes can be understood as the product of interactions between climate change, site histories, and the biogeochemical balance of inputs and losses in urban greenspaces. In N14CP, temperature effects are represented both through temperature controls on potential net primary productivity (NPP), increasing maximum NPP where temperature was the limiting factor, and, more critically, through Q10-type responses of soil organic matter turnover. While increased rates of soil organic matter turnover increase the size of the available N pool and therefore have the potential to increase NPP and associated litter inputs, these gains are typically outweighed by the faster cycling of organic matter itself, so the net effect of rising temperature without additional deposition is a tendency for SOC to decline. The strong losses observed in central and western European sites are consistent with this mechanism. Their urban greenspaces are long-established, meaning they are unlikely to still be accruing the SOC typically associated with newly established turfgrasses. This legacy places them on a downward trajectory: NPP is no longer strongly enhanced due to historical nitrogen deposition that peaked around 1990 and is unlikely to be temperature limited and therefore respond strongly to climate change-driven temperature increases, instead facing compounding losses as warming accelerates decomposition. Together, these conditions explain why central and western European sites emerged as the most vulnerable to proportional SOC declines under future warming. Sites displaying intermediate losses: Helsinki, Lahti, Santiago, and Sochi, despite varying climatic conditions, showed smaller declines. These sites consistently underwent more recent deforestation than central European sites and remained on an upward adjustment toward a higher grassland SOC equilibria, typically produced in European sites simulated by N14CP (Davies et al., 2016; Tipping et al., 2017), which likely offset part of the warming-driven losses.

By contrast, Chelyabinsk diverged most strongly from this pattern of SOC stock decline, showing net SOC gains under moderate warming and medium nitrogen deposition. This outcome reflects its relatively low initial SOC stocks in the process of accumulation, consistent with young urban greenspaces, as suggested by previous observations that SOC in urban greenspaces accumulates over decades to centuries following establishment (Cambou et al., 2021; Lindén et al., 2020; Phillips et al., 2023; Qian & Follett, 2002). Chelyabinsk has historically received comparatively low levels of nitrogen deposition and therefore is not likely to have already experienced strong SOC stock declines associated with declines in nitrogen deposition since 1990 and exogenous nutrient inputs are proportionally more influential than in Central European sites. Together, these conditions position Chelyabinsk at an earlier point in the SOC accumulation trajectory, allowing SOC stock gains resulting from historical land-use transitions to counteract the negative effects of warming on SOC stocks.

Sensitivity to nitrogen deposition and temperature

Across all sites, both changes in temperature and nitrogen deposition displayed consistent directional effects on SOC stock. Higher levels of warming consistently resulted in more negative SOC stock change, on average across sites, each 1 °C of warming by 2100 was associated with an additional 1.8% SOC stock loss. This implies that across all sites, additional warming-driven acceleration of decomposition and SOM turnover outweighs the effects of increased litter inputs due to enhanced NPP and fertilisation effects of greater N availability. The negative response of SOC stocks in temperate grasslands to warming is confirmed by both experimental warming and modelling studies (Garcia-Franco et al., 2024; Phillips et al., 2016; Wang et al., 2022b). Even sites that simulated net SOC stock gains, such as Chelyabinsk, exhibited sensitivities to temperature change that were comparable to or exceeded those of declining sites. The divergent SOC stock trajectories observed between cities therefore do not reflect intrinsic resilience to warming in some locations, but predominantly differences in their historical trajectories in response to historical climate and nitrogen deposition change and varying land-use histories. For example, Chelyabinsk remains on a strong accumulation trajectory due to its relatively young greenspaces and low initial SOC stocks, which enables continued net gains under moderate warming, yet the rate of accumulation is nevertheless reduced as temperatures rise, at a similar rate to sites already displaying decline. The broader implication is that no sites demonstrate genuine resilience to warming, across all urban greenspace sites, higher temperature scenarios consistently amplify SOC losses regardless of site-specific differences, and the continuation of warming beyond 2100 would be expected to drive further negative SOC stock changes irrespective of present trajectories.

On average across sites, each 1 g N m^{-2} yr^{-1} decline in deposition was associated with an additional 3.8% SOC stock loss by 2100, indicating that higher nitrogen inputs consistently mitigated warming-driven SOC losses. Higher nitrogen deposition pathways reliably reduced the magnitude of decline and, under low levels of warming, occasionally stabilised SOC trajectories. This conforms with observational evidence that low levels of nitrogen additions increase grassland SOC stocks as well as modelled responses of SOC stocks to both historic and future nitrogen deposition (Fang et al., 2014; Liu et al., 2023; Tipping et al., 2017; Yumashev et al., 2022). This effect arises as with greater levels of nitrogen deposition, there is a greater quantity of N available to plants, alleviating a key growth constraint. This stimulation of plant productivity raises litter inputs, which in turn expand the flux of organic carbon entering the soil. As these inputs accumulate, topsoil SOC pools are enlarged, producing the simulated net gains in SOC under higher deposition scenarios. Although the modelled sensitivity to changes in nitrogen deposition is large, the absolute magnitude of this effect was modest compared to the influence of temperature. This asymmetry likely reflects the historical trajectory of deposition: atmospheric nitrogen inputs have already fallen substantially from their late twentieth-century peak, with an average decline of 43% across the sites between 1990 (1.63 g N m^{-2} yr^{-1}) and 2022 (0.93 g N m^{-2} yr^{-1}), limiting the magnitude of SOC declines associated with further reductions in nitrogen deposition.

Urban heat island effect

The simulations of the UHI effect across the sites indicate that UHI warming exerts a strong additional pressure on urban SOC stocks, with mean incremental losses of −2.5% at +1 °C and −6.2% at +2.5 °C under SSP2-4.5 with medium nitrogen deposition. Across all sites in this reference scenario, the lower-bound UHI increment (+1 °C) produced additional SOC losses greater than those associated with a shift to the low nitrogen deposition pathway under the same SSP. The upper-bound increment (+2.5 °C) exceeded the effect of moving from SSP2-4.5 to SSP3-7.0 under the same nitrogen deposition scenario. This highlights that localised urban warming can rival and even outweigh the influence of global climate trajectories. UHI sensitivity was relatively consistent across sites with all sites but Sochi displaying between 2% and 3% additional SOC loss for each 1 °C of UHI increment. This per-degree response is also consistently larger than the sensitivity of SOC stocks to SSP warming scenarios across sites, reflecting the fact that UHI increments are imposed as fixed, stepwise offsets sustained throughout the century rather than as gradual trajectories. Even modest deviations in long-term UHI intensity therefore have the potential to produce substantial additional soil carbon losses.

Mitigation of UHI warming through urban design interventions has been shown to deliver measurable reductions in local temperatures. Large-scale deployment of cool roofs in London reduced near-surface air temperatures by 1.2 °C in mesoscale simulations (Brousse et al., 2024), while modelling of UK heatwaves indicates average reductions of 0.5 °C and maxima approaching 3 °C (Macintyre & Heaviside, 2019). Urban tree planting provides additional potential, with meta-analyses reporting mean cooling of around 0.8 °C beneath tree canopies and more than 1 °C in urban forests along with strong evidence that increasing urban vegetation cover in general reduces the UHI effect (Aminipouri & Knudby, 2014; Bowler et al., 2010; Knight et al., 2021). Although effect sizes vary across cities and climate, these studies demonstrate that relatively modest reductions in UHI magnitude are achievable and that urban greenspaces themselves may play a key role in mitigating the UHI effect and therefore protecting their SOC stocks from even steeper declines under global warming. In the context of the simulations carried out in this study, reducing long-term UHI intensity by even 1°C would be expected to avoid ~2.5% SOC stock loss by 2100, highlighting the potential of UHI mitigation to moderate soil carbon decline in urban greenspaces.

Limitations and further work

This study is subject to several limitations that should be considered when interpreting the results. Firstly, while the N14CP model was extended to represent urban greenspaces, it remains a generalised biogeochemical framework with simplified assumptions. Vegetation management was represented as a fixed above-ground biomass threshold with quarterly cuts, according to the time resolution of the model, and assumed constant additional nutrient inputs. In reality, urban greenspaces are subject to a wide range of management practices, including variable mowing frequencies, fertilisation, irrigation, and organic amendments, which have strong impacts on soil carbon cycling and storage and can often increase rates of SOC sequestration (Gu et al., 2015; Thompson & Kao-Kniffin, 2019; Zirkle et al., 2011). Although sites with clear evidence of fertilisation, chemical amendments, or irrigation were excluded, unreported usage is likely. Such practices would introduce mismatches between the simplified nutrient cycling represented in the model and the actual processes operating at individual sites, which is consistent with the fact that more than half of the sites fell outside the calibration range. This underscores the need for more systematic and standardised data collection on urban greenspace soils, including detailed records of management regimes and site histories. Expanding such datasets would provide a stronger empirical foundation for calibrating and testing models, enabling more representative and robust projections of SOC dynamics in urban greenspaces. Larger and more comprehensive datasets spanning diverse management practices, land-use histories, and climatic contexts would also enable more powerful analyses of patterns and trends, helping to identify the key drivers of urban greenspace resilience or vulnerability to climate change.

SOC stocks used in the calibration of site-specific weatherable P pool values mean that the model-observation comparison reflects in-sample calibration performance rather than an independent validation. As all available observations contributed to the calibration process, the statistics primarily quantify the model's ability to reproduce measured SOC under calibrated parameter conditions rather than its predictive skill against a separate validation dataset.

The climate scenarios were represented only according to temperature increases from a single ensemble member of a single model. This inevitably limits confidence in the absolute magnitude of the projections, since inter-model spread can be substantial, particularly for regional climate responses (Palmer et al., 2023; Zhang & Chen, 2021). However, the approach was sufficient to capture the direction and strength of a range of climate change induced temperature effects on SOC stocks, and to resolve consistent differences between SSP scenarios, which was the primary focus of the scenario analysis. Future studies should build on this by employing multi-model SSP scenarios to quantify uncertainty ranges and evaluate the robustness of site-level SOC projections.

Additionally, UHI scenarios were implemented as simple uniform offsets across all sites, which was sufficient to bracket lower and upper bounds of potential effects. However, this approach does not capture inter-city differences in UHI intensity, seasonal and diurnal variability, interactions with broader climate warming, or the influence of mitigation by urban greenspaces, all of which can alter UHI magnitude depending on climate and city-specific factors (Demchenko & Ginzburg, 2018; Zhou et al., 2017). Future studies that use city-specific UHI estimates from urban climate models such as UrbClim, incorporating morphology and land cover, would be able to capture seasonal and diurnal variability, interactions with extreme events, and differences in UHI intensity among cities more accurately (De Ridder et al., 2015; Lauwaet et al., 2024). Coupling such models with observational data would allow more realistic quantification of UHI impacts on SOC stocks and enable scenario analysis of how urban planning and cooling strategies might mitigate future SOC losses under climate change.

Precipitation was held constant at historical means for all scenarios, excluding possible interactions between rainfall variability, soil moisture, and SOC dynamics. Because precipitation was held constant in the scenarios, the model omits potentially important effects of rainfall variability on SOC dynamics. Although model spread is high - drier summers, increased rainfall variability, more extreme rainfall events, and more frequent, longer droughts, are projected across most of Europe, including under CMIP6 projections (Coppola et al., 2021; Grillakis, 2019; Palmer et al., 2021). Increased rainfall variability has been shown to reduce soil CO_2 flux and NPP even where annual totals remain unchanged, weakening carbon cycling and storage (Forouzangohar et al., 2016; Knapp et al., 2002; Wang et al., 2023). Experimental droughts in temperate grasslands likewise reduce SOC inputs from litter decomposition, while long-term studies highlight that precipitation shifts interact with land-use and vegetation to alter SOC pools in complex ways (Joos et al., 2010; Rocci et al., 2023; Seeber et al., 2022). There is evidence from meta-analysis of temperate field experiments that, particularly in grasslands, the effects of altered precipitations regimes on SOC can even dominate the effects of temperature (Wei et al., 2023), stressing the importance of integration of precipitation changes into future modelling of urban greenspace soils.

A limitation of the N14CP simulations is that they did not include the effects of rising atmospheric CO_2. Evidence from grassland studies in Europe indicates that while warming alone generally drives SOC losses, elevated CO_2 can partly offset these declines by increasing NPP and soil carbon inputs (Chang et al., 2016). This fertilisation effect, however, weakens under stronger warming and may even disappear under conditions of nutrient limitation to NPP, which likely applies to low-input urban greenspaces (Chang et al., 2017; Köchy et al., 2015a; Puche et al., 2023). Although the effects of CO_2 fertilisation on SOC stocks are still highly uncertain, particularly in urban greenspaces, excluding CO_2 fertilisation may bias projections toward greater SOC loss than might occur under future conditions.

Nitrogen deposition scenarios in this study were linear pathways based on regional modelled data, which lack the spatial resolution to capture city-specific deposition patterns. This is a critical limitation, as multiple studies have shown that urban areas are consistently exposed to higher nitrogen inputs than surrounding rural environments, primarily due to traffic and fossil fuel combustion (Bettez & Groffman, 2013; Decina et al., 2020; Joyce et al., 2020). This likely resulted in underestimation of nitrogen deposition during historical urban periods, as well as an underestimation of the magnitude of present and future nitrogen deposition declines. Future work should aim to resolve deposition at urban scales, either through expanded monitoring networks or by extending urban downscaling approaches, such as urban EMEP (uEMEP) (Denby et al., 2020), beyond primary pollutant concentrations to include deposition, thereby providing a more accurate representation of nutrient inputs to urban greenspaces.

Conclusions

This study suggests that temperate and boreal urban greenspaces may respond to climate change in much the same way as other land-use types, with warming driving soil organic carbon (SOC) stock losses and nitrogen deposition exerting a countervailing effect. What sets them apart is the degree to which recent land-use histories and urbanisation trajectories shape their outcomes. Divergent pasts have placed urban greenspace soils on very different SOC stock trajectories, with some sites still accumulating carbon following recent conversion, while others are trending downwards with previously stable SOC pools already beginning to decline as a result of historically warming temperatures and falling nitrogen deposition. These contrasting legacies interact with future changes in temperature and nitrogen deposition, producing outcomes that may either buffer against, or amplify, climate-driven losses.

Urban greenspaces constitute a highly heterogeneous land-use category that cannot be characterised by a single directional response. Their SOC stock trajectories are predictably forced by global drivers, principally warming and atmospheric nitrogen deposition, yet are unevenly modulated by local legacies of land use, management, and urban heat island effects. As such, they should be analysed and reported with explicit attention to site history, current and historical management regimes, and city-specific local thermal regimes. Under moderate warming, most sites are likely to experience significant SOC stock declines over the 21st century and beyond, with stability or modest gains emerging chiefly under low-warming pathways in sites that are already experiencing rapid enough SOC accumulation to offset the increased decomposition rates associated with warming.

A notable finding is that the additional impact of the urban heat island effect, particularly in larger cities with more intense local warming, may outsize global warming effects under moderate climate scenarios. This effect was large enough to exceed the impacts between climate scenarios, underscoring that, for urban greenspace soils, local management and urban cooling measures may prove the most effective and feasible in the protection of SOC stocks.

Progress in urban greenspace soils research will depend on more systematic and standardised data collection for urban greenspace soils and their environments, including detailed management records, historical land-use information, and city-scale estimates of nitrogen deposition and urban heat island intensity. Methodologically, future modelling studies may then integrate these improved datasets with multi-model climate scenarios, dynamic precipitation, and CO_2 fertilisation effects to generate more robust predictions of urban greenspace SOC stock change.

In summary, urban greenspaces represent both a fragile and complex component of the terrestrial carbon cycle, with their capacity to act as either a carbon source or sink hinging on the interaction between inherited legacies, ongoing management, and the scale of future environmental change.

Appendices

Appendix A -Full site soil organic carbon stock trajectories

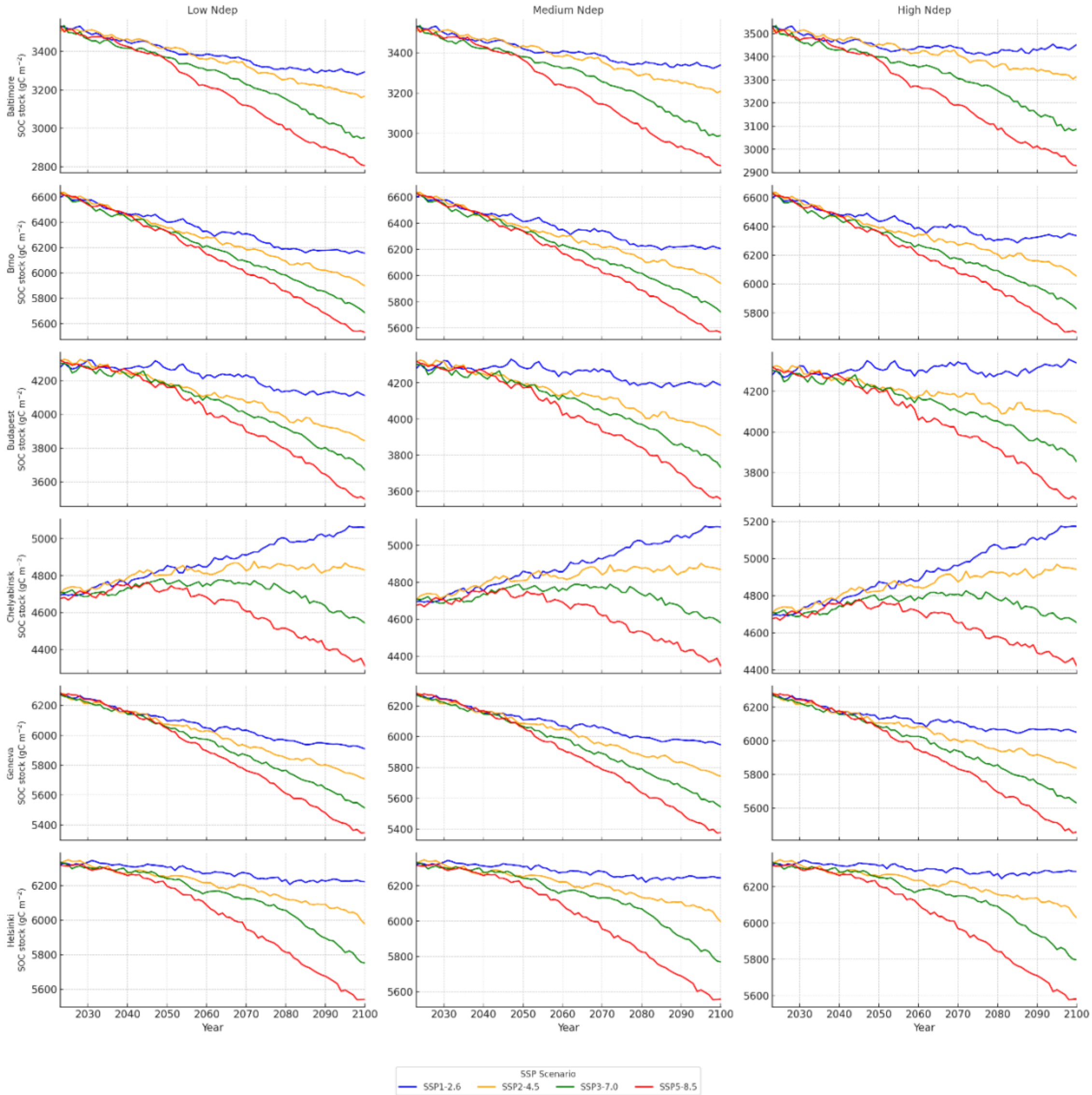

Figure A1. Time series of soil organic carbon (SOC) stock from 2023 to 2100 for sites Baltimore to Helsinki under four climate scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) and three nitrogen deposition (Ndep) scenarios (Low, Medium, High). Each subplot corresponds to a single Ndep scenario, with lines representing the SOC stock trajectory under each climate scenario.

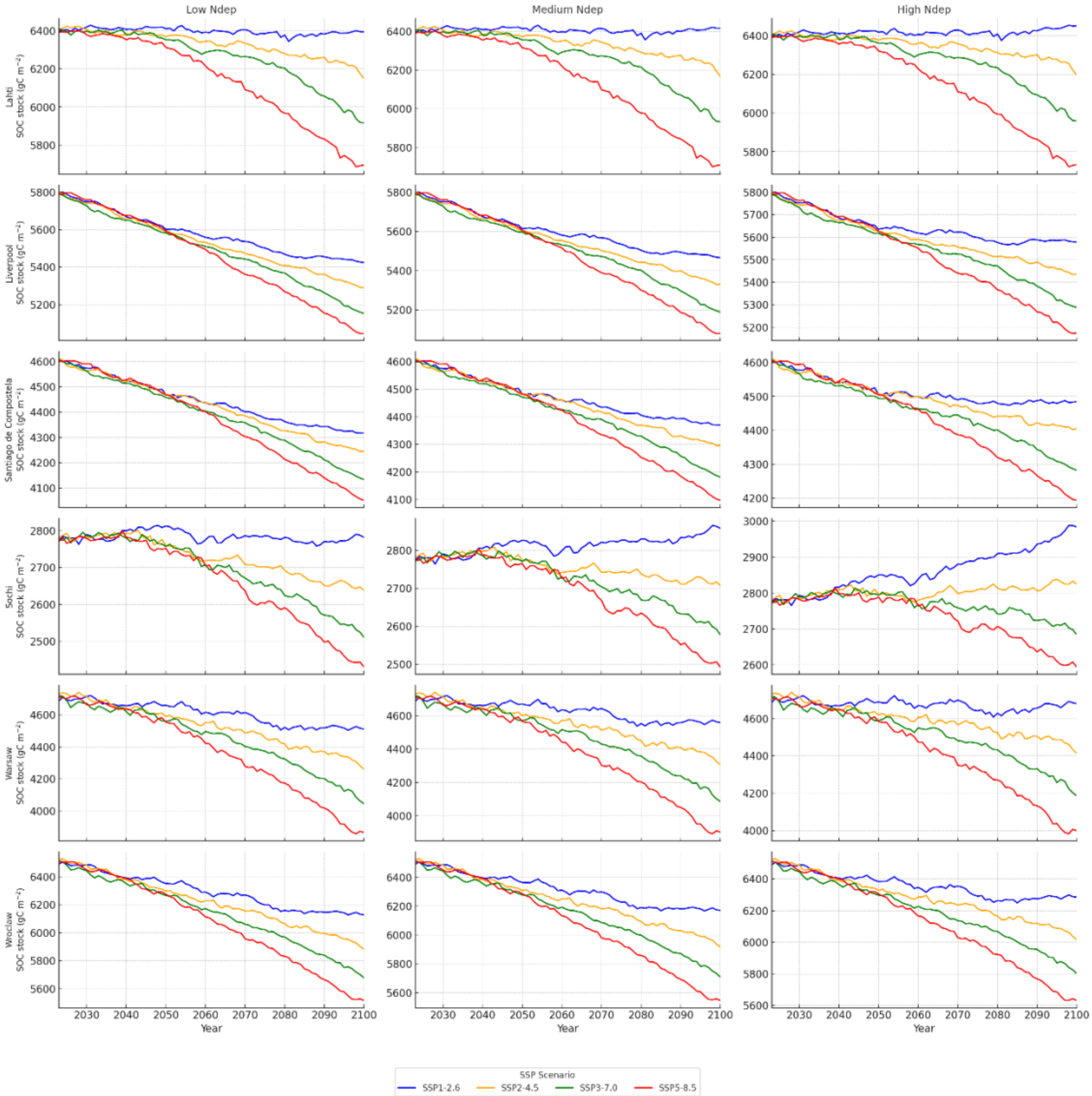

Figure A2. Time series of soil organic carbon (SOC) stock from 2023 to 2100 for sites Lahti to Wroclaw under four climate scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) and three nitrogen deposition (Ndep) scenarios (Low, Medium, High). Each subplot corresponds to a single Ndep scenario, with lines representing the SOC stock trajectory under each climate scenario.

Abbreviations

- C – Carbon
- IPCC – Intergovernmental Panel on Climate Change
- MAT – Mean annual temperature
- N – Nitrogen
- Ndep – Nitrogen deposition
- NPP – Net primary productivity
- P – Phosphorus
- SOC – Soil organic carbon
- SSP - Shared socioeconomic pathway
- UHI – Urban heat island
- UKGGI – United Kingdom greenhouse gas inventory

Reference list

Alexandrovskaya, E. I., & Alexandrovskiy, A. L. (2000). History of the cultural layer in Moscow and accumulation of anthropogenic substances in it. *Catena*, *41*(1-3), 249-259.

Amelung, W., Bossio, D., de Vries, W., Kogel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nature Communications*, *11*(1).

Aminipouri, M., & Knudby, A. (2014). Spatio-Temporal Analysis of Surface Urban Heat Island (Suhi) Using Modis Land Surface Temperature (Lst) for Summer 2003-2012, a Case Study of the Netherlands. *2014 Ieee International Geoscience and Remote Sensing Symposium (Igarss)*.

Andrade, C., Fonseca, A., & Santos, J. A. (2023). Climate Change Trends for the Urban Heat Island Intensities in Two Major Portuguese Cities. *Sustainability*, *15*(5), 3970.

Bae, J., & Ryu, Y. (2015). Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park. *Landscape and Urban Planning*, *136*, 57-67.

Bae, J., & Ryu, Y. (2020). High soil organic carbon stocks under impervious surfaces contributed by urban deep cultural layers. *Landscape and Urban Planning*, *204*.

Bai, S. H., Xu, Z. H., Blumfield, T. J., & Reverchon, F. (2015). Human footprints in urban forests: implication of nitrogen deposition for nitrogen and carbon storage. *Journal of Soils and Sediments*, *15*(9), 1927-1936.

Beesley, L. (2012). Carbon storage and fluxes in existing and newly created urban soils. *Journal of Environmental Management*, *104*, 158-165.

Beillouin, D., Corbeels, M., Demenois, J., Berre, D., Boyer, A., Fallot, A., Feder, F., & Cardinael, R. (2023). A global meta-analysis of soil organic carbon in the Anthropocene. *Nature Communications*, *14*(1).

Beillouin, D., Demenois, J., Cardinael, R., Berre, D., Corbeels, M., Fallot, A., Boyer, A., & Feder, F. (2022). A global database of land management, land-use change and climate change effects on soil organic carbon. *Scientific Data*, *9*(1).

Bekier, J., Jamroz, E., Walenczak-Bekier, K., & Uscila, M. (2023). Soil Organic Matter Composition in Urban Soils: A Study of Wroclaw Agglomeration, SW Poland. *Sustainability*, *15*(3).

Bettez, N. D., & Groffman, P. M. (2013). Nitrogen Deposition in and near an Urban Ecosystem. *Environmental Science & Technology*, *47*(11), 6047-6051.

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, *97*(3), 147-155.

Bradford, M. A., Wieder, W. R., Bonan, G. B., Fierer, N., Raymond, P. A., & Crowther, T. W. (2016). Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change*, *6*(8), 751-758.

Bradley, R. I., Milne, R., Bell, J., Lilly, A., Jordan, C., & Higgins, A. (2005). A soil carbon and land use database for the United Kingdom. *Soil Use and Management*, *21*(4), 363-369.

Brousse, O., Simpson, C., Zonato, A., Martilli, A., Taylor, J., Davies, M., & Heaviside, C. (2024). Cool Roofs Could Be Most Effective at Reducing Outdoor Urban Temperatures in London (United Kingdom) Compared With Other Roof Top and Vegetation Interventions: A Mesoscale Urban Climate Modeling Study. *Geophysical Research Letters*, *51*(13).

Brown, P., Cardenas, L., Del Vento, S., Karagianni, E., MacCarthy, J., Mullen, P., Passant, N., Richmond, B., Thistlethwaite, G., & Thomson, A. (2023). *UK Greenhouse Gas Inventory 1990 to 2021: annual report for submission under the Framework Convention on Climate Change*.

Burke, M., Marín-Spiotta, E., & Ponette-González, A. G. (2024). Black carbon in urban soils: land use and climate drive variation at the surface. *Carbon Balance and Management*, *19*(1).

Cai, Y., Yang, Y., Jiang, J., Long, T., Gu, X., Guo, Y., Li, M., & Xie, Y. (2025). Response of soil organic carbon stocks and soil microbial biomass carbon to natural grassland conversion: A global meta-analysis. *Science of the Total Environment*, *965*, 178481.

Cambou, A., Saby, N. P. A., Hunault, G., Nold, F., Cannavo, P., Schwartz, C., & Vidal-Beaudet, L. (2021). Impact of city historical management on soil organic carbon stocks in Paris (France). *Journal of Soils and Sediments*, *21*(2), 1038-1052.

Canedoli, C., Ferrè, C., Abu El Khair, D., Padoa-Schioppa, E., & Comolli, R. (2020). Soil organic carbon stock in different urban land uses: high stock evidence in urban parks. *Urban Ecosystems*, *23*(1), 159-171.

Chang, J., Ciais, P., Viovy, N., Soussana, J.-F., Klumpp, K., & Sultan, B. (2017). Future productivity and phenology changes in European grasslands for different warming levels: implications for grassland management and carbon balance. *Carbon Balance and Management*, *12*(1).

Chang, J., Ciais, P., Viovy, N., Vuichard, N., Herrero, M., Havlík, P., Wang, X., Sultan, B., & Soussana, J. F. (2016). Effect of climate change, CO2 trends, nitrogen addition, and land-cover and management intensity changes on the carbon balance of European grasslands. *Global Change Biology*, *22*(1), 338-350.

Chen, Z. H., Wei, X. Y., Ni, X. Y., Wu, F. Z., & Liao, S. (2023). Changing precipitation effect on forest soil carbon dynamics is driven by different attributes between dry and wet areas. *Geoderma*, *429*.

Chien, S. C., & Krumins, J. A. (2022). Natural versus urban global soil organic carbon stocks: A meta-analysis. *Science of the Total Environment*, *807*.

Conrad-Rooney, E., Gewirtzman, J., Pappas, Y., Pasquarella, V. J., Hutyra, L. R., & Templer, P. H. (2023). Atmospheric wet deposition in urban and suburban sites across the United States. *Atmospheric Environment*, *305*.

Coppola, E., Nogherotto, R., Ciarlo', J. M., Giorgi, F., Van Meijgaard, E., Kadygrov, N., Iles, C., Corre, L., Sandstad, M., Somot, S., Nabat, P., Vautard, R., Levavasseur, G., Schwingshackl, C., Sillmann, J., Kjellström, E., Nikulin, G., Aalbers, E., Lenderink, G., . . . Wulfmeyer, V. (2021). Assessment of the European Climate Projections as Simulated by the Large EURO-CORDEX Regional and Global Climate Model Ensemble. *Journal of Geophysical Research: Atmospheres*, *126*(4).

Davies, J. A. C., Tipping, E., Rowe, E. C., Boyle, J. F., Pannatier, E. G., & Martinsen, V. (2016). Long-term P weathering and recent N deposition control contemporary plant-soil C, N, and P. *Global Biogeochemical Cycles*, *30*(2), 231-249.

Davis, B. A. S., Brewer, S., Stevenson, A. C., Guiot, J., & Contributors, D. (2003). The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews*, *22*(15-17), 1701-1716.

De Frenne, P., Cougnon, M., Janssens, G. P. J., & Vangansbeke, P. (2022). Nutrient fertilization by dogs in peri-urban ecosystems. *Ecological Solutions and Evidence*, *3*(1).

De Pauw, K., Depauw, L., Cousins, S. A. O., De Lombaerde, E., Diekmann, M., Frey, D., Kwietniowska, K., Lenoir, J., Meeussen, C., Orczewska, A., Plue, J., Spicher, F., Vanneste, T., Zellweger, F., Verheyen, K., Vangansbeke, P., & De Frenne, P. (2024). The urban heat island accelerates litter decomposition through microclimatic warming in temperate urban forests. *Urban Ecosystems*, *27*(3), 909-926.

De Ridder, K., Lauwaet, D., & Maiheu, B. (2015). - A fast urban boundary layer climate model. *Urban Climate*, *12*, 21-48.

Decina, S. M., Hutyra, L. R., & Templer, P. H. (2020). Hotspots of nitrogen deposition in the world's urban areas: a global data synthesis. *Frontiers in Ecology and the Environment*, *18*(2), 92-100.

Delbecque, N., Dondeyne, S., Gelaude, F., Mouazen, A. M., Vermeir, P., & Verdoodt, A. (2022). Urban soil properties distinguished by parent material, land use, time since urbanization, and pre-urban geomorphology. *Geoderma*, *413*.

Demchenko, P. F., & Ginzburg, A. S. (2018). Influence of Feedbacks in the Climate–Energetics System on the Intensity of an Urban Heat Island. *Izvestiya, Atmospheric and Oceanic Physics*, *54*(4), 313-321.

Denby, B. R., Gauss, M., Wind, P., Mu, Q., Grøtting Wærsted, E., Fagerli, H., Valdebenito, A., & Klein, H. (2020). Description of the uEMEP_v5 downscaling approach for the EMEP MSC-W chemistry transport model. *Geoscientific Model Development*, *13*(12), 6303-6323.

Edmondson, J. L., Davies, Z. G., Gaston, K. J., & Leake, J. R. (2014a). Urban cultivation in allotments maintains soil qualities adversely affected by conventional agriculture. *Journal of Applied Ecology*, *51*(4), 880-889.

Edmondson, J. L., Davies, Z. G., McHugh, N., Gaston, K. J., & Leake, J. R. (2012). Organic carbon hidden in urban ecosystems. *Scientific Reports*, *2*.

Edmondson, J. L., O'Sullivan, O. S., Inger, R., Potter, J., Mchugh, N., Gaston, K. J., & Leake, J. R. (2014b). Urban Tree Effects on Soil Organic Carbon. *Plos One*, *9*(7), e101872.

Edmondson, J. L., Stott, I., Potter, J., Lopez-Capel, E., Manning, D. A. C., Gaston, K. J., & Leake, J. R. (2015). Black Carbon Contribution to Organic Carbon Stocks in Urban Soil. *Environmental Science & Technology*, *49*(14), 8339-8346.

Fang, H. J., Cheng, S. L., Yu, G. R., Yang, X. M., Xu, M. J., Wang, Y. S., Li, L. S., Dang, X. S., Wang, L., & Li, Y. N. (2014). Nitrogen deposition impacts on the amount and stability of soil organic matter in an alpine meadow ecosystem depend on the form and rate of applied nitrogen. *European Journal of Soil Science*, *65*(4), 510-519.

Forouzangohar, M., Setia, R., Wallace, D. D., Nitschke, C. R., & Bennett, L. T. (2016). Predicted consequences of increased rainfall variability on soil carbon stocks in a semiarid environment. *Climate Research*, *67*(1), 61-69.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., . . . Zheng, B. (2022). Global Carbon Budget 2022. *Earth System Science Data*, *14*(11), 4811-4900.

Gao, J., & O'Neill, B. C. (2020). Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways. *Nature Communications*, *11*(1).

Garcia-Franco, N., Wiesmeier, M., Buness, V., Berauer, B. J., Schuchardt, M. A., Jentsch, A., Schlingmann, M., Andrade-Linares, D., Wolf, B., Kiese, R., Dannenmann, M., & Kögel-Knabner, I. (2024). Rapid loss of organic carbon and soil structure in mountainous grassland topsoils induced by simulated climate change. *Geoderma*, *442*.

Georgiou, K., Jackson, R. B., Vindusková, O., Abramoff, R. Z., Ahlström, A., Feng, W. T., Harden, J. W., Pellegrini, A. F. A., Polley, H. W., Soong, J. L., Riley, W. J., & Torn, M. S. (2022). Global stocks and capacity of mineral-associated soil organic carbon. *Nature Communications*, *13*(1).

Goll, D. S., Brovkin, V., Parida, B. R., Reick, C. H., Kattge, J., Reich, P. B., van Bodegom, P. M., & Niinemets, Ü. (2012). Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling. *Biogeosciences*, *9*(9), 3547-3569.

Golubiewski, N. E. (2006). Urbanization increases grassland carbon pools: Effects of landscaping in Colorado's front range. *Ecological Applications*, *16*(2), 555-571.

Gómez-Brandón, M., Herbón, C., Probst, M., Fornasier, F., Barral, M. T., & Paradelo, R. (2022). Influence of land use on the microbiological properties of urban soils. *Applied Soil Ecology*, *175*.

Gonçalves, D. R. P., Mishra, U., Wills, S., & Gautam, S. (2021). Regional environmental controllers influence continental scale soil carbon stocks and future carbon dynamics. *Scientific Reports*, *11*(1).

Grace, P. R., Post, W. M., & Hennessy, K. (2006). The potential impact of climate change on Australia's soil organic carbon resources. *Carbon Balance and Management*, *1*(1).

Grillakis, M. G. (2019). Increase in severe and extreme soil moisture droughts for Europe under climate change. *Science of the Total Environment*, *660*, 1245-1255.

Grosse, G., Harden, J., Turetsky, M., Mcguire, A. D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K. P., French, N., Waldrop, M., Bourgeau-Chavez, L., & Striegl, R. G. (2011). Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research*, *116*.

Gu, C. H., Crane, J., Hornberger, G., & Carrico, A. (2015). The effects of household management practices on the global warming potential of urban lawns. *Journal of Environmental Management*, *151*, 233-242.

Guo, H. B., Du, E., Terrer, C., & Jackson, R. B. (2024a). Global distribution of surface soil organic carbon in urban greenspaces. *Nature Communications*, *15*(1).

Guo, Y., Han, J. T., Bao, H. J., Wu, Y. Z., Shen, L. Y., Xu, X. R., Chen, Z. W., Smith, P., & Abdalla, M. (2024b). A systematic analysis and review of soil organic carbon stocks in urban greenspaces. *Science of the Total Environment*, *948*.

Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, *7*(1).

Hay, L. E., Wilby, R. L., & Leavesley, G. H. (2000). A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States 1. *JAWRA Journal of the American Water Resources Association*, *36*(2), 387-397.

Holtanová, E., Belda, M., & Halenka, T. (2022). Projected changes in mean annual cycle of temperature and precipitation over the Czech Republic: Comparison of CMIP5 and CMIP6. *Frontiers in Earth Science*, *10*.

Howard, J. L., & Olszewska, D. (2011). Pedogenesis, geochemical forms of heavy metals, and artifact weathering in an urban soil chronosequence, Detroit, Michigan. *Environmental Pollution*, *159*(3), 754-761.

Hu, Y., Deng, Q., Kätterer, T., Olesen, J. E., Ying, S. C., Ochoa-Hueso, R., Mueller, C. W., Weintraub, M. N., & Chen, J. (2024). Depth-dependent responses of soil organic carbon under nitrogen deposition. *Global Change Biology*, *30*(3).

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Goldewijk, K. K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T., Lawrence, D., . . . Zhang, X. (2020). Harmonization of global land use change and management for the period 850-2100 (LUH2) for CMIP6. *Geoscientific Model Development*, *13*(11), 5425-5464.

IPCC. (2006). IPCC Guidelines for National Greenhouse Gas Inventories. In. Japan: IGES.

Iungman, T., Cirach, M., Marando, F., Barboza, E. P., Khomenko, S., Masselot, P., Quijal-Zamorano, M., Mueller, N., Gasparrini, A., Urquiza, J., Heris, M., Thondoo, M., & Nieuwenhuijsen, M. (2023). Cooling cities through urban green infrastructure: a health impact assessment of European cities. *Lancet*, *401*(10376), 577-589.

Janes-Bassett, V., Bassett, R., Rowe, E. C., Tipping, E., Yumashev, D., & Davies, J. (2021a). Changes in carbon storage since the pre-industrial era: A national scale analysis. *Anthropocene*, *34*.

Janes-Bassett, V., Bassett, R., Yumashev, D., Blair, G., & Davies, J. (2021b). Mapping regional impacts of agricultural expansion on terrestrial carbon storage. *Regional Studies Regional Science*, *8*(1), 336-340.

Janes-Bassett, V., Davies, J., Rowe, E. C., & Tipping, E. (2020). Simulating long-term carbon nitrogen and phosphorus biogeochemical cycling in agricultural environments. *Science of the Total Environment*, *714*.

Jo, H. K., & Mcpherson, E. G. (1995). Carbon Storage and Flux in Urban Residential Greenspace. *Journal of Environmental Management*, *45*(2), 109-133.

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(2), 423436.

Joos, O., Hagedorn, F., Heim, A., Gilgen, A. K., Schmidt, M. W. I., Siegwolf, R. T. W., & Buchmann, N. (2010). Summer drought reduces total and litter-derived soil CO2 effluxes in temperate grassland – clues from a 13C litter addition experiment. *Biogeosciences*, *7*(3), 1031-1041.

Joyce, E. E., Walters, W. W., Le Roy, E., Clark, S. C., Schiebel, H., & Hastings, M. G. (2020). Highly concentrated atmospheric inorganic nitrogen deposition in an urban, coastal region in the US. *Environmental Research Communications*, *2*(8).

Kaplan, J. O., Krumhardt, K. M., & Zimmermann, N. (2009). The prehistoric and preindustrial deforestation of Europe. *Quaternary Science Reviews*, *28*(27-28), 3016-3034.

Kaye, J. P., Groffman, P. M., Grimm, N. B., Baker, L. A., & Pouyat, R. V. (2006). A distinct urban biogeochemistry? *Trends in Ecology & Evolution*, *21*(4), 192-199.

Knapp, A. K., Fay, P. A., Blair, J. M., Collins, S. L., Smith, M. D., Carlisle, J. D., Harper, C. W., Danner, B. T., Lett, M. S., & McCarron, J. K. (2002). Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. *Science*, *298*(5601), 2202-2205.

Knight, T., Price, S., Bowler, D., Hookway, A., King, S., Konno, K., & Richter, R. L. (2021). How effective is ‘greening’ of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure and the ‘urban heat island effect’? An updated systematic review. *Environmental Evidence*, *10*(1).

Köchy, M., Don, A., van der Molen, M. K., & Freibauer, A. (2015a). Global distribution of soil organic carbon - Part 2: Certainty of changes related to land use and climate. *Soil*, *1*(1), 367-380.

Köchy, M., Hiederer, R., & Freibauer, A. (2015b). Global distribution of soil organic carbon - Part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. *Soil*, *1*(1), 351-365.

Kortleve, A. J., Mogollón, J. M., Heimovaara, T. J., & Gebert, J. (2023). Topsoil Carbon Stocks in Urban Greenspaces of The Hague, the Netherlands. *Urban Ecosystems*, *26*(3), 725-742.

Lauwaet, D., Berckmans, J., Hooyberghs, H., Wouters, H., Driesen, G., Lefebre, F., & De Ridder, K. (2024). High resolution modelling of the urban heat island of 100 European cities. *Urban Climate*, *54*.

Li, D. J., Niu, S. L., & Luo, Y. Q. (2012). Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta-analysis. *New Phytologist*, *195*(1), 172-181.

Liang, C., VandenBygaart, A. J., MacDonald, D., Liu, K., & Cerkowniak, D. (2023). Change in soil organic carbon storage as influenced by forestland and grassland conversion to cropland in Canada. *Geoderma Regional*, *33*.

Liang, Y., Hu, H., Crowther, T. W., Jörgensen, R. G., Liang, C., Chen, J., Sun, Y., Liu, C., Ding, J., Huang, A., Zhou, J., & Zhang, J. (2024). Global decline in microbial-derived carbon stocks with climate warming and its future projections. *National Science Review*, *11*(11).

Lin, H., & Li, X. (2025). The Role of Urban Green Spaces in Mitigating the Urban Heat Island Effect: A Systematic Review from the Perspective of Types and Mechanisms. *Sustainability*, *17*(13), 6132.

Lindén, L., Riikonen, A., Setälä, H., & Yli-Pelkonen, V. (2020). Quantifying carbon stocks in urban parks under cold climate conditions. *Urban Forestry & Urban Greening*, *49*.

Liu, H. Y., Huang, N., Zhao, C. M., & Li, J. H. (2023). Responses of carbon cycling and soil organic carbon content to nitrogen addition in grasslands globally. *Soil Biology & Biochemistry*, *186*.

Livesley, S. J., Ossola, A., Threlfall, C. G., Hahs, A. K., & Williams, N. S. G. (2016). Soil Carbon and Carbon/Nitrogen Ratio Change under Tree Canopy, Tall Grass, and Turf Grass Areas of Urban Green Space. *Journal of Environmental Quality*, *45*(1), 215-223.

Lorenz, K., & Lal, R. (2009). Biogeochemical C and N cycles in urban soils. *Environment International*, *35*(1), 1-8.

Lu, X. K., Vitousek, P. M., Mao, Q. G., Gilliam, F. S., Luo, Y. Q., Turner, B. L., Zhou, G. Y., & Mo, J. M. (2021). Nitrogen deposition accelerates soil carbon sequestration in tropical forests. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(16).

Luo, R. Y., Fan, J. L., Wang, W. J., Luo, J. F., Kuzyakov, Y., He, J. S., Chu, H. Y., & Ding, W. X. (2019a). Nitrogen and phosphorus enrichment accelerates soil organic carbon loss in alpine grassland on the Qinghai-Tibetan Plateau. *Science of the Total Environment*, *650*, 303-312.

Luo, S. H., Mao, Q. Z., & Ma, K. M. (2014). Comparison on soil carbon stocks between urban and suburban topsoil in Beijing, China. *Chinese Geographical Science*, *24*(5), 551-561.

Luo, Z., Wang, G., & Wang, E. (2019b). Global subsoil organic carbon turnover times dominantly controlled by soil properties rather than climate. *Nature Communications*, *10*(1).

Macdonald, E., Otero, N., & Butler, T. (2021). A comparison of long-term trends in observations and emission inventories of NOx. *Atmospheric Chemistry and Physics*, *21*(5), 4007-4023.

Macintyre, H. L., & Heaviside, C. (2019). Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city. *Environment International*, *127*, 430-441.

Mazurek, R., Kowalska, J., Gasiorek, M., & Setlak, M. (2016). Micromorphological and physico-chemical analyses of cultural layers in the urban soil of a medieval city - A case study from Krakow, Poland. *Catena*, *141*, 73-84.

Mccarthy, M. P., Best, M. J., & Betts, R. A. (2010). Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, *37*(9), n/an/a.

Meersmans, J., Arrouays, D., Van Rompaey, A. J. J., Pagé, C., De Baets, S., & Quine, T. A. (2016). Future C loss in mid-latitude mineral soils: climate change exceeds land use mitigation potential in France. *Scientific Reports*, *6*(1), 35798.

MET-Norway. (2024). Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components, EMEP Status Report 1/2024, ISSN 1504-6109 (print), ISSN 1504-6192 (online).

Milne, R., & Brown, T. A. (1997). Carbon in the vegetation and soils of Great Britain. *Journal of Environmental Management*, *49*(4), 413-433.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z. S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., . . . Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59-86.

Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, *197*, 522-538.

Mondini, C., Coleman, K., & Whitmore, A. P. (2012). Spatially explicit modelling of changes in soil organic C in agricultural soils in Italy, 2001-2100: Potential for compost amendment. *Agriculture Ecosystems & Environment*, *153*, 24-32.

Mori, K., Ise, T., Kondo, M., Kim, Y., & Enomoto, H. (2012). The effect of the feedback cycle between the soil organic carbon and the soil hydrologic and thermal dynamics. *Open Journal of Ecology*, *02*(02), 90-95.

NADP. (2023). Total Deposition Maps, version 2023.01.

https://nadp.slh.wisc.edu/committees/tdep/ . [27/01/25].

Ng, B. J. L., Hutyra, L. R., Nguyen, H., Cobb, A. R., Kai, F. M., Harvey, C., & Gandois, L. (2015). Carbon fluxes from an urban tropical grassland. *Environmental Pollution*, *203*, 227-234.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461-3482.

O'Rourke, S. M., Angers, D. A., Holden, N. M., & Mcbratney, A. B. (2015). Soil organic carbon across scales. *Global Change Biology*, *21*(10), 3561-3574.

Oktaba, L., Paziewski, K., Kwasowski, W., & Kondras, M. (2014). The effect of urbanization on soil properties and soil organic carbon accumulation in topsoil of Pruszkow - a medium-sized city in the Warsaw Metropolitan Area, Poland. *Soil Science Annual*, *65*(1), 10-17.

Palmer, T. E., Booth, B. B. B., & Mcsweeney, C. F. (2021). How does the CMIP6 ensemble change the picture for European climate projections? *Environmental Research Letters*, *16*(9), 094042.

Palmer, T. E., Mcsweeney, C. F., Booth, B. B. B., Priestley, M. D. K., Davini, P., Brunner, L., Borchert, L., & Menary, M. B. (2023). Performance-based subselection of CMIP6 models for impact assessments in Europe. *Earth System Dynamics*, *14*(2), 457-483.

Phillips, C. L., Murphey, V., Lajtha, K., & Gregg, J. W. (2016). Asymmetric and symmetric warming increases turnover of litter and unprotected soil C in grassland mesocosms. *Biogeochemistry*, *128*(1-2), 217-231.

Phillips, C. L., Wang, R. Y., Mattox, C., Trammell, T. L. E., Young, J., & Kowalewski, A. (2023). High soil carbon sequestration rates persist several decades in turfgrass systems: A meta-analysis. *Science of the Total Environment*, *858*.

Pizl, V., & Schlaghamersky, J. (2007). The impact of pedestrian activity on soil annelids in urban greens. *European Journal of Soil Biology*, *43*, S68-S71.

Poeplau, C., & Dechow, R. (2023). The legacy of one hundred years of climate change for organic carbon stocks in global agricultural topsoils. *Scientific Reports*, *13*(1).

Pouyat, R. V., Yesilonis, I. D., Dombos, M., Szlavecz, K., Setälä, H., Cilliers, S., Hornung, E., Kotze, D. J., & Yarwood, S. (2015). A Global Comparison of Surface Soil Characteristics Across Five Cities: A Test of the Urban Ecosystem Convergence Hypothesis. *Soil Science*, *180*(4-5), 136-145.

Pouyat, R. V., Yesilonis, I. D., & Nowak, D. J. (2006). Carbon storage by urban soils in the United States. *Journal of Environmental Quality*, *35*(4), 1566-1575.

Puche, N. J. B., Kirschbaum, M. U. F., Viovy, N., & Chabbi, A. (2023). Potential impacts of climate change on the productivity and soil carbon stocks of managed grasslands. *Plos One*, *18*(4).

Qian, Y., & Follett, R. F. (2002). Assessing Soil Carbon Sequestration in Turfgrass Systems Using Long-Term Soil Testing Data. *Agronomy Journal*, *94*(4), 930935.

Qian, Y., Zhou, W., Yu, W., & Pickett, S. T. A. (2015). Quantifying spatiotemporal pattern of urban greenspace: new insights from high resolution data. *Landscape Ecology*, *30*(7), 1165-1173.

Raciti, S. M., Groffman, P. M., & Fahey, T. J. (2008). Nitrogen retention in urban lawns and forests. *Ecological Applications*, *18*(7), 1615-1626.

Raciti, S. M., Groffman, P. M., Jenkins, J. C., Pouyat, R. V., Fahey, T. J., Pickett, S. T. A., & Cadenasso, M. L. (2011). Accumulation of Carbon and Nitrogen in Residential Soils with Different Land-Use Histories. *Ecosystems*, *14*(2), 287297.

Raciti, S. M., Hutyra, L. R., Rao, P., & Finzi, A. C. (2012). Inconsistent definitions of "urban" result in different conclusions about the size of urban carbon and nitrogen stocks. *Ecological Applications*, *22*(3), 1015-1035.

Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Rao, C. S., Sandeep, S., Rinklebe, J., Ok, Y. S., Choudhury, B. U., Wang, H. L., Tang, C. X., Wang, X. J., Song, Z. L., & Freeman, O. (2019). Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Advances in Agronomy, Vol 156*, *156*, 1-107.

Ritzhaupt, N., & Maraun, D. (2023). Consistency of Seasonal Mean and Extreme Precipitation Projections Over Europe Across a Range of Climate Model Ensembles. *Journal of Geophysical Research-Atmospheres*, *128*(1).

Rizwan, A. M., Dennis, Y. C. L., & Liu, C. H. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences*, *20*(1), 120-128.

Rocci, K. S., Bird, M., Blair, J. M., Knapp, A. K., Liang, C., & Cotrufo, M. F. (2023). Thirty years of increased precipitation modifies soil organic matter fractions but not bulk soil carbon and nitrogen in a mesic grassland. *Soil Biology & Biochemistry*, *185*.

Rocci, K. S., Lavallee, J. M., Stewart, C. E., & Cotrufo, M. F. (2021). Soil organic carbon response to global environmental change depends on its distribution between mineral-associated and particulate organic matter: A meta-analysis. *Science of the Total Environment*, *793*.

Rohde, R. A., & Hausfather, Z. (2020). The Berkeley Earth Land/Ocean Temperature Record. *Earth System Science Data*, *12*(4), 3469-3479.

Rojas, L. A. R., Adhikari, K., & Ventura, S. J. (2018). Projecting Soil Organic Carbon Distribution in Central Chile under Future Climate Scenarios. *Journal of Environmental Quality*, *47*(4), 735-745.

Rumpel, C., Amiraslani, F., Chenu, C., Cardenas, M. G., Kaonga, M., Koutika, L. S., Ladha, J., Madari, B., Shirato, Y., Smith, P., Soudi, B., Soussana, J. F., Whitehead, D., & Wollenberg, E. (2020). The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio*, *49*(1), 350-360.

Rumpel, C., Amiraslani, F., Koutika, L.-S., Smith, P., Whitehead, D., & Wollenberg, E. (2018). Put more carbon in soils to meet Paris climate pledges. *Nature*, *564*(7734), 32-34.

Schöpp, W., Posch, M., Mylona, S., & Johansson, M. (2003). Long-term development of acid deposition (1880-2030) in sensitive freshwater regions in Europe. *Hydrology and Earth System Sciences*, *7*(4), 436-446.

Seeber, J., Tasser, E., Rubatscher, D., Loacker, I., Lavorel, S., Robson, T. M., Balzarolo, M., Altimir, N., Drösler, M., Vescovo, L., Gamper, S., Barancok, P., Staszewski, T., Wohlfahrt, G., Cernusca, A., Sebastia, M. T., Tappeiner, U., & Bahn, M. (2022). Effects of land use and climate on carbon and nitrogen pool partitioning in European mountain grasslands. *Science of the Total Environment*, *822*.

Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., O'connor, F. M., Stringer, M., Hill, R., & Palmieri, J. (2019). UKESM1: Description and evaluation of the UK Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513-4558.

Setälä, H. M., Francini, G., Allen, J. A., Hui, N., Jumpponen, A., & Kotze, D. J. (2016). Vegetation Type and Age Drive Changes in Soil Properties, Nitrogen, and Carbon Sequestration in Urban Parks under Cold Climate. *Frontiers in Ecology and Evolution*, *4*.

Shi, B., Tang, C.-S., Gao, L., Liu, C., & Wang, B.-J. (2012). Observation and analysis of the urban heat island effect on soil in Nanjing, China. *Environmental Earth Sciences*, *67*(1), 215-229.

Shi, Z., Allison, S. D., He, Y., Levine, P. A., Hoyt, A. M., Beem-Miller, J., Zhu, Q., Wieder, W. R., Trumbore, S., & Randerson, J. T. (2020). The age distribution of global soil carbon inferred from radiocarbon measurements. *Nature Geoscience*, *13*(8), 555-559.

Smith, P., Fang, C. M., Dawson, J. J. C., & Moncrieff, J. B. (2008). Impact of global warming on soil organic carbon. *Advances in Agronomy, Vol 97*, *97*, 1-43.

Stoma, G. V., Manucharova, N. A., & Belokopytova, N. A. (2020). Biological Activity of Microbial Communities in Soils of Some Russian Cities. *Eurasian Soil Science*, *53*(6), 760-771.

Strohbach, M. W., Arnold, E., & Haase, D. (2012). The carbon footprint of urban green space-A life cycle approach (vol 104, pg 220, 2012). *Landscape and Urban Planning*, *105*(4), 445-445.

Suratt, A., Behl, K., Hong, W. L., Yoon, Y. E., & Allison, S. D. (2024). Characterizing suburban soil and microbial properties along a soil age chronosequence. *Ecosphere*, *15*(12).

Szabó, P., & Szépszó, G. (2016). Quantifying Sources of Uncertainty in Temperature and Precipitation Projections over Different Parts of Europe. *Mathematical Problems in Meteorological Modelling*, *24*, 239-261.

Tan, W. B., Yu, H. X., Xiao, H. Y., Wang, T., Hossain, M. A., Wu, Y. S., & Yadav, N. (2024). Radiocarbon evidence of organic carbon turnover response to grassland grazing: A soil aggregate fraction perspective. *Sustainable Horizons*, *12*.

Taylor, J., Simpson, C. H., Vanhtalo, J., Sohail, H., Brousse, O., & Heaviside, C. (2025). Analysing cold-climate urban heat islands using personal weather station data. *Buildings & Cities*, *6*(1), 182-200.

Thomas, R. Q., Canham, C. D., Weathers, K. C., & Goodale, C. L. (2010). Increased tree carbon storage in response to nitrogen deposition in the US. *Nature Geoscience*, *3*(1), 13-17.

Thompson, G. L., & Kao-Kniffin, J. (2019). Urban Grassland Management Implications for Soil C and N Dynamics: A Microbial Perspective. *Frontiers in Ecology and Evolution*, *7*.

Tian, H. Q., Lu, C. Q., Yang, J., Banger, K., Huntzinger, D. N., Schwalm, C. R., Michalak, A. M., Cook, R., Ciais, P., Hayes, D., Huang, M. Y., Ito, A., Jain, A. K., Lei, H. M., Mao, J. F., Pan, S. F., Post, W. M., Peng, S. S., Poulter, B., . . . Zeng, N. (2015). Global patterns and controls of soil organic carbon dynamics as simulated by multiple terrestrial biosphere models: Current status and future directions. *Global Biogeochemical Cycles*, *29*(6), 775-792.

Tipping, E., Davies, J. A. C., Henrys, P. A., Kirk, G. J. D., Lilly, A., Dragosits, U., Carnell, E. J., Dore, A. J., Sutton, M. A., & Tomlinson, S. J. (2017). Long-term increases in soil carbon due to ecosystem fertilization by atmospheric nitrogen deposition demonstrated by regional-scale modelling and observations. *Scientific Reports*, *7*.

Tobias, S., Davies, M., Imhof, C. S., Psomas, A., & Boivin, P. (2023). Greening and browning of urban lawns in Geneva (Switzerland) as influenced by soil properties. *Geoderma Regional*, *34*.

Toth, M., Davies, J., Quinton, J., Davies, J., Stumpp, C., Klik, A., Mehdi-Schulz, B., Strauss, P., Liebhard, G., Bartmann, J., & Strohmeier, S. (2025). Long-term effects of tillage practices and future climate scenarios on topsoil organic carbon stocks in Lower Austria - A modelling and long-term experiment study. *International Soil and Water Conservation Research*, *13*(2), 486-499.

Townsend-Small, A., & Czimczik, C. I. (2010). Carbon sequestration and greenhouse gas emissions in urban turf (vol 37, L06707, 2010). *Geophysical Research Letters*, *37*.

Trammell, T. L. E., Pataki, D. E., Pouyat, R., Groffman, P. M., Rosier, C., Bettez, N., Cavender-Bares, J., Grove, M. J., Hall, S. J., Heffernan, J., Hobbie, S. E., Morse, J. L., Neill, C., & Steele, M. (2020). Urban soil carbon and nitrogen converge at a continental scale. *Ecological Monographs*, *90*(2).

Tresch, S., Moretti, M., Le Bayon, R. C., Mäder, P., Zanetta, A., Frey, D., Stehle, B., Kuhn, A., Munyangabe, A., & Fliessbach, A. (2018). Urban Soil Quality Assessment-A Comprehensive Case Study Dataset of Urban Garden Soils. *Frontiers in Environmental Science*, *6*.

UN. (2019). *World Urbanization Prospects: The 2018 Revision*. ((ST/ESA/SER.A/420)). New York: United Nations

Varney, R. M., Chadburn, S. E., Friedlingstein, P., Burke, E. J., Koven, C. D., Hugelius, G., & Cox, P. M. (2020). A spatial emergent constraint on the sensitivity of soil carbon turnover to global warming. *Nature Communications*, *11*(1).

Vasenev, V., & Kuzyakov, Y. (2018). Urban soils as hot spots of anthropogenic carbon accumulation: Review of stocks, mechanisms and driving factors. *Land Degradation & Development*, *29*(6), 1607-1622.

Vasenev, V., Varentsov, M., Konstantinov, P., Romzaykina, O., Kanareykina, I., Dvornikov, Y., & Manukyan, V. (2021). Projecting urban heat island effect on the spatial-temporal variation of microbial respiration in urban soils of Moscow megalopolis. *Science of the Total Environment*, *786*.

Wang, B., Chen, Y. L., Li, Y., Zhang, H., Yue, K., Wang, X. C., Ma, Y. D., Chen, J., Sun, M., Chen, Z., & Wu, Q. Q. (2021). Differential effects of altered precipitation regimes on soil carbon cycles in arid versus humid terrestrial ecosystems. *Global Change Biology*, *27*(24), 6348-6362.

Wang, B., Gray, J. M., Waters, C. M., Anwar, M. R., Orgill, S. E., Cowie, A. L., Feng, P. Y., & Liu, D. L. (2022a). Modelling and mapping soil organic carbon stocks under future climate change in south-eastern Australia. *Geoderma*, *405*.

Wang, D., Xu, P.-Y., An, B.-W., & Guo, Q.-P. (2024). Urban green infrastructure: bridging biodiversity conservation and sustainable urban development through adaptive management approach. *Frontiers in Ecology and Evolution*, *12*.

Wang, H. Y., Wu, J. Q., Li, G., Yan, L. J., & Liu, S. A. (2023). Effects of extreme rainfall frequency on soil organic carbon fractions and carbon pool in a wet meadow on the Qinghai-Tibet Plateau. *Ecological Indicators*, *146*.

Wang, M., Guo, X., Zhang, S., Xiao, L., Mishra, U., Yang, Y., Zhu, B., Wang, G., Mao, X., Qian, T., Jiang, T., Shi, Z., & Luo, Z. (2022b). Global soil profiles indicate depth-dependent soil carbon losses under a warmer climate. *Nature Communications*, *13*(1).

Wang, Q., & Lan, Z. L. (2019). Park green green spaces, public health and social inequalities: Understanding the interrelationships for policy implications. *Land Use Policy*, *83*, 66-74.

Wei, X., Meerbeek, V., Koenraad, Yue, K., Ni, X., Desie, E., Heděnec, P., Yang, J., & Wu, F. (2023). Responses of soil C pools to combined warming and altered precipitation regimes: A meta-analysis. *Global Ecology and Biogeography*, *32*(9), 1660-1675.

Weissert, L. F., Salmond, J. A., & Schwendenmann, L. (2016). Variability of soil organic carbon stocks and soil CO2 efflux across urban land use and soil cover types. *Geoderma*, *271*, 80-90.

Wiesmeier, M., Poeplau, C., Sierra, C. A., Maier, H., Frühauf, C., Hübner, R., Kühnel, A., Spörlein, P., Geuß, U., Hangen, E., Schilling, B., Von Lützow, M., & KögelKnabner, I. (2016). Projected loss of soil organic carbon in temperate agricultural soils in the 21st century: effects of climate change and carbon input trends. *Scientific Reports*, *6*(1), 32525.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Liess, M., Garcia-Franco, N., Wollschläger, U., Vogel, H. J., & Kögel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma*, *333*, 149-162.

Wu, S. B., Chen, B., Webster, C., Xu, B., & Gong, P. (2023). Improved human greenspace exposure equality during 21st century urbanization. *Nature Communications*, *14*(1).

Yang, X., Ma, S., Huang, E., Zhang, D., Chen, G., Zhu, J., Ji, C., Zhu, B., Liu, L., & Fang, J. (2025). Nitrogen addition promotes soil carbon accumulation globally. *Science China Life Sciences*, *68*(1), 284-293.

Yellajosula, G., Cihacek, L., Faller, T., & Schauer, C. (2020). Soil Carbon Change Due to Land Conversion to Grassland in a Semi-Arid Environment. *Soil Systems*, *4*(3).

Yigini, Y., & Panagos, P. (2016). Assessment of soil organic carbon stocks under future climate and land cover changes in Europe. *The science of the total environment.*, *557-558*, 838-850.

Yumashev, D., Janes-Bassett, V., Redhead, J. W., Rowe, E. C., & Davies, J. (2022). Terrestrial carbon sequestration under future climate, nutrient and land use change and management scenarios: a national-scale UK case study. *Environmental Research Letters*, *17*(11), 114054.

Zhang, S. B., & Chen, J. (2021). Uncertainty in Projection of Climate Extremes - A Comparison of CMIP5 and CMIP6. *Journal of Meteorological Research*, *35*(4), 646-662.

Zhang, Z. P., Ding, J. L., Zhu, C. M., Wang, J. J., Ge, X. Y., Li, X., Han, L. J., Chen, X. Y., & Wang, J. Z. (2023). Historical and future variation of soil organic carbon in China. *Geoderma*, *436*.

Zhong, B., & Xu, Y. J. (2014). Predicting climate change effects on surface soil organic carbon of Louisiana, USA. *Environmental Monitoring and Assessment*, *186*(10), 6169-6192.

Zhou, B., Rybski, D., & Kropp, J. P. (2017). The role of city size and urban form in the surface urban heat island. *Scientific Reports*, *7*.

Zirkle, G., Lal, R., & Augustin, B. (2011). Modeling Carbon Sequestration in Home Lawns. *Hortscience*, *46*(5), 808-814.