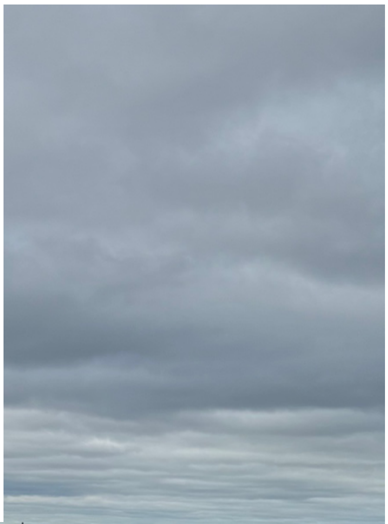
CARBON ON YOUR STREET: ORGANIC CARBON STORAGE IN NOTTINGHAM



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Contents

1. Executive Summary

To quantify Nottingham's organic carbon storage and it potential contribution to the Carbon Neutral Nottingham (CN28 target), this study assessed topsoil (< 30 cm depth) and tree organic carbon. Soil organic matter was determined through analysis of topsoil samples collected from 10 green spaces with replicate samples (n=65). Loss on ignition (LOI) was used to estimate organic matter content, and soil depth used to calculate volume at an assumed bulk density of 1.0 g cm^{-3}, used to estimate organic matter mass per hectare. After calculating an overall average, this was applied to all NCC managed green spaces giving city-wide topsoil organic matter mass, which was converted to organic carbon using a 0.58 conversion rate. Tree carbon was estimated using data from the National Tree Map (NTM) 2019, which provides tree location, height, and canopy size. To estimate tree biomass and subsequently carbon content, allometric equations were applied relating tree dimensions to total biomass. A generalised allometric model was used to calculate biomass based on tree canopy radius and height. A conversion factor of 50% was applied to estimate carbon content from total biomass. To ensure data accuracy, ground truthing was conducted by measuring tree height and diameter at breast height (DBH) for a sample of trees, comparing these measurements to NTM data.

LOI of soil samples an average topsoil organic matter content of 226.85 tonnes per hectare, equating to 485,959.37 tonnes of organic matter across all the cities green space topsoil, approximately 281,856 tonnes of organic carbon. Council-managed trees store approximately 141,165 tonnes of carbon, while non-council managed trees store 523,740 tonnes. Carbon distribution is uneven across the city. Wards with large green spaces like Wollaton West and Dales have high soil carbon, while Wards such as the Castle and Berridge have considerably less. NCC managed Woodlands in green spaces, such as parks and nature reserves, are some of the most significant carbon sinks in the city and affect the carbon density between wards. Street trees planted along roadsides and those in private gardens contribute to carbon storage in more urbanised areas. The distribution of trees in urbanised areas often reflects historical planning decisions, with more affluent neighbourhoods, such as those in the Mapperley ward, typically having higher densities of trees, both in street trees and those in private garden. Typically, less affluent areas, where resources for urban greening may be more limited, tend to have fewer trees.

Protecting existing carbon stores, enhancing soil carbon sequestration through soil amendments, and expanding tree cover are crucial for Nottingham's carbon reduction goals. Prioritising actions such as targeted tree planting, protecting woodlands, and integrating carbon considerations into urban planning can help Nottingham achieve its carbon neutrality ambitions. Ongoing monitoring of carbon stocks is essential for evaluating the effectiveness of carbon reduction strategies.

To deepen understanding, future research should:

- Analyse the entire soil profile for organic and inorganic carbon
- Investigate the relationship between land use and soil carbon storage
- Test different soil amendments to enhance carbon sequestration
- Monitor tree carbon over time to assess growth and carbon storage
- Expand to other Midland's cities for a regional carbon inventory and strategy

2. Background and Context

2.1. Introduction

Although reliance on fossil fuels is decreasing in the UK from increased production of renewable energy, a significant amount of industrial and domestic energy still comes from combustion of fossil fuels, releasing greenhouse gasses into the atmosphere. In particular, reducing emissions from the heating of homes via combustion of natural gas, and the use of petroleum and diesel fuelled cars is particularly difficult, owing to the cost per household in doing so. In the transition to carbon neutrality, maintaining and enhancing carbon sequestration in natural stores will be vital in offsetting the emissions from continued fossil fuel use, until alternatives are adopted at scale. Following carbon neutrality, nature-based solutions will be equally vital in sequestering excess atmospheric carbon and mitigating anthropogenic climate change.

Trees are well discussed and implemented as a carbon offsetting strategy, absorbing atmospheric carbon through photosynthesis and storing it in their tissues. By weight, most tree species are around 50% carbon once at maturity and sequester carbon across their lifetimes, providing they are growing more tissue than they are losing (Baccini et al. 2012). Globally, by planting an extra 0.9 billion hectares of tree canopy cover in areas that would naturally support woodlands and forests, an extra 205 gigatonnes of carbon could be sequestered, equivalent to around 25% of the atmospheric carbon pool (Bastin et al. 2019). In urban areas, total tree carbon storage in the USA is estimated to be 643 million tonnes, with 18.9 million tonnes sequestered annually (Nowak et al. 2013). Trees also have many other benefits of particular importance in urban areas, including biodiversity provision, improved air quality and a reduction of the urban heat island effect (Pataki et al. 2021). Therefore, efforts to increase tree carbon storage in urban areas to offset emissions can have a number of secondary benefits.

Less discussed outside of farming and conservation circles is the contribution of soils to carbon sequestration. In urban greenspaces, the total global organic carbon storage is estimated to be 1.4 Pg (1.4 g $\times 10^{15}$) of carbon in the top 20 cm, 2.7% of the global terrestrial stocks (543 Pg) at the same soil depth (Guo et al. 2024). During growth, plants produce roots, which transports carbon captured during photosynthesis below ground during growth. Following death, soil microbial and invertebrate communities consume this carbon as a food source, re-emitting some of this carbon back to the atmospheric pool but transitioning much into various stable and unstable fractions (e.g. mineralised, microbial biomass) (Cambou et al. 2023). Surface deposition of above ground growth, such as leaves, are also gradually incorporated into soil. This live and decaying organic carbon input supports a whole food web of microbes, invertebrates and vertebrate, that all contribute to the organic pool of soil carbon. Inorganic carbon comes from the weathering of parent material (which forms the mineral component of soil) or reaction of soil minerals with atmospheric CO_2. Soil carbon is greatly influenced by management practices, with practices that disturb soil structure and expose stored carbon to the surface, such as tillage or clearance for construction, greatly reducing carbon stocks (Majidzadeh et al. 2017, Wang et al. 2019). Managing organic inputs, through vegetation species and through amendments can also increase or reduce overall carbon stored. In offsetting emissions and mitigating climate change, good management of our soil carbon pool will be vital.

2.2. Nottingham and CN28

Nottingham's aim to become the UK's first carbon-neutral city by 2028 through its Carbon Neutral Nottingham 2028 (CN28) initiative, launched in 2019 following the City Council's declaration of a climate and ecological emergency. This ambitious goal is supported by the Carbon Neutral Charter and a detailed Carbon Neutral Action Plan, which outlines strategic actions in carbon reduction, carbon removal, resilience and adaptation, and ecology and biodiversity. The city's approach includes transitioning the council's fleet to Ultra Low Emission Vehicles (ULEVs) or electric vehicles, installing solar panels on council properties, enhancing energy efficiency of social housing, and promoting sustainable travel through e-bikes, improved cycling and walking infrastructure, and better public transport. Significant progress has already been made, with a 44.7% reduction in citywide CO_2 emissions between 2005 and 2021(Carbon Neutral Policy Team NCC 2023).

Although gains in terms of emissions reduction have already been obtained, in order to meet the 2028 target, significant amounts of carbon sequestration in natural stores will be required to offset the substantial emissions still produced on the city (still 1.125 million tonnes in 2021) (IBID). Strategies to increase sequestration are already underway, with 37,000 trees planted since 2019, with some consideration in the 2022-2023 annual review for improving soil management practices and incorporating biochar to increase soil carbon sequestration (IBID). To monitor sequestration efforts, first a comprehensive assessment of carbon stored in the city is required, to act as a base line by which subsequent assessments are compared. As well as this, by mapping its distribution, areas of high carbon density requiring protection and areas of low carbon density suitable for targeted improvement can ensure good distribution of carbon stores along with the other benefits they provide.

2.3. Aims and objectives

This project, funded by City as Lab (University of Nottingham) through Higher Education Innovation Funding (HEIF) and in collaboration with the Greenspace and Natural Environment team and GIS team at Nottingham City Council (NCC), and Bluesky International, aimed to: quantify and map organic carbon stored in the trees and council managed greenspace topsoil within the NCC administrative boundary to act as a baseline for subsequent sequestration efforts. Our objectives to achieve this were:

- Using Bluesky's National Tree Map (NTM) data (2019), perform allometric modelling of tree carbon for every tree within that data set that falls within the NCC administrative boundary
- Compare and merge the NTM and NCC's own tree management data set to allow distinction between council managed and non-council managed trees
- Ground truth tree location and size measurements to ensure reliability of remotely sensed data sets and modelling via physical measurements of tree location, height and diameter at breast height

- Collect replicate topsoil cores from numerous NCC managed green spaces to estimate average soil organic matter per unit area in green spaces across the city
- Scale up the average soil organic matter content per unit area across the city and produce city wide soil organic matter and soil organic carbon estimate.

In this report we also aim to provide recommendations on implementation of the project results into CN28 strategy, including areas suitable for targeted efforts, provide insight into strategies on preserving and increasing soil carbon, identify caveats to increasing carbon storage and identify future avenues of related research.

3. Methodology

3.1. Estimating topsoil carbon

Replicate topsoil cores were collected from 10 green spaces managed by NCC (Arboretum, Broxtowe Country Park, Colwick Country Park, Corporation oaks, Forrest Recreation ground, Meadows Recreation Ground, Nottingham Castle, Victoria Park, Wollaton Hall, Woodthorpe Grange Park) up to a depth of 30 cm using a 15 cm length hand corer, requiring the collection of 2 separate core sections, 0-15 cm and 15-30 cm. Soil depth up to 30 cm was measured at each sample site using a soil pin, for use in calculating soil volume and subsequent organic carbon per unit area estimates. Sampling locations within each green space were selected via walking in multiple zig-zag patterns across through the green space, attempting uniform distribution of sampling within each green space but avoid sampling bias. The number of replicates collected from each green space depended on total area, with larger green spaces requiring more replicates, with a minimum of 3 replicates for each green space. A total of 65 soil cores were collected from across the 10 sampling sites.

The 2 sections of soil core were stored in the same sample bag and refrigerated at 5°C. Soil organic matter content was estimated using loss on ignition (LOI) methods, that estimate organic matter from mass loss through burning. Before initial weighing, each sample was homogenised to ensure uniformity throughout, so each sample was representative of the full 30 cm sampling depth. Approximately 5 g of each homogenized sample were placed in pre-weighed crucibles. The samples were first dried at 105°C for 24 hours to remove any moisture content, and following cooling in a desiccator were weighed again to calculate moisture content. Following this, the crucibles were transferred to a muffle furnace and heated to 550°C for 5 hours to ensure the complete combustion of organic matter. After cooling to room temperature in a desiccator, the crucibles were once weighed again. The weight loss due to ignition was calculated as the difference between the initial and final weights. This loss was estimated to represent the organic matter content of the sample as % of total weight. Using an assumed bulk density of 1.0 g cm^{-3} informed from previous work on Nottingham soils (Henrys et al. 2012), and volume calculated from soil depth, average mass of organic matter in t ha^{-1} for each green space was calculated from this, and an overall average also produced. The organic carbon content was calculated by applying a conversion factor to this overall average, assuming that organic matter generally if not always contains 58% carbon (Pribyl 2010).

3.2. Data sets

For estimating tree carbon storage across Nottingham in council managed and non-council managed trees, 2 different data sets were used. The primary data for this was the National Tree Map (NTM) 2019 from Bluesky International. Bluesky's National Tree Map™ (NTM™) is the most detailed dataset of its kind ever produced. With coverage across the whole of England, Wales, Scotland and the Republic of Ireland. NTM™ provides a unique, comprehensive database of location, height and canopy/crown extents for every single tree 3m and above in height. The NTM is Created from Bluesky's high resolution national aerial photography, accurate terrain and surface data, and colour infrared imagery. The NTM product consists of a tree canopies, geo-location and tree height. Further geospatial data was provided by NCC via its publicly available tree management data set, containing data of the location, species, age, and size of trees under active management by NCC, which was used to identify NCC managed trees within the NTM data set via 8m buffers created around the central points of each tree in ARCPro. This allowed trees to be partitioned into council managed trees and non-council managed trees. Nottingham Green Spaces data set, also publicly available via NCC, provided area data of green spaces, e.g parks within the NCC boundary, to which the average soil organic carbon mass per hectare was applied. Some spaces within the data set were filtered if deemed unsuitable for inclusion e.g BMX parks.

3.3. Modelling tree carbon

Following partitioning of trees into council managed trees and non-council managed trees, tree canopy radius and height was extracted for each individual tree point and used to calculate the generalised allometric model. This model estimates tree biomass based on the size metrics derived from the canopy and height data, following the method of Jucker et al. (2016). Trees below 3 m in height and over 40 m in height were excluded from the data set, owing to the inaccuracy of the model at estimating biomass at these sizes and to avoid over estimation. Organic carbon mass of each tree is assumed to be on average 50% of total biomass, so this conversion was used to estimate organic carbon mass of each tree in the data set.

3.4. Ground truthing of data for allometric modelling

To ensure the general accuracy of the remotely sensed NTM dataset, ground truthing was conducted on a sample of trees within the study area (n=38). This process involved directly measuring the location, height, and diameter at breast height (DBH) of selected trees using field instruments. Tree locations were recorded using GPS coordinates, while tree heights were measured using a laser range finder. The laser range finder provided precise measurements by calculating the distance from the observer to the top of the tree, taking into account the angle of inclination. DBH was measured using a diameter tape at 1.3 metres above ground level. The ground-measured data were compared against the corresponding attributes derived from the NTM dataset, to determine if data produced remotely was realistically applicable to the study. As the NTM data was from 2019, and the ground truthing conducted in 2024, some variation in height and DBH were to be expected, and so statistical tests were not conducted, and accuracy was determined based on qualitative similarity of data. The accuracy of the NTM data was determined to be satisfactory for the purposes of this study,

3.5. Analysis and mapping

To assess for significant differences in soil organic matter content and soil organic mass per unit area between different green spaces, ANOVA analysis was conducted in R-studio, tested to a significance of 0.05. The overall average organic matter mass in t ha^{-1} from sampled sites was applied to the green space areas in the Nottingham green space data set, with estimated mass of organic matter attributed to each green space polygon in ARCPro. Organic matter mass for each greenspace was also exported as a CSV file and totalled, and the 0.58 organic matter-organic carbon conversion applied to produce total greenspace topsoil organic carbon estimate. Tree carbon density was modelled using kernel-based density analysis of the individual tree carbon mass data in ARCPro, with resulting components rendered at 3x3m to generate tree carbon density per hectare. All maps were produced in ARCpro.

4. Results

4.1. Topsoil organic matter

Although there was a range of soil organic matter between samples (Figure 1a), % of topsoil organic matter did not significantly differ between Nottingham green spaces ($F_{(9,55)}$ = 0.784, p= 0.632). When considered as mass of topsoil organic matter per unit area (Figure 1b), there is also no significant difference between Nottingham green spaces ($F_{(9,55)}$ = 0.892, p= 0.539). Averaging across the sampled green spaces, the topsoil mass of organic matter in topsoil was 226.85 tha^{-1} (Figure 1c). Following application to the filtered list of council managed green spaces, totalling 2142.2 ha area, this equates to 485,959.37 t of organic matter stored within Nottingham's green space topsoil. In terms of just stored carbon, this is equal to 281,856.435 t of organic carbon (following 0.58 conversion factor of organic matter to organic carbon). Considering distribution of topsoil organic matter across Nottingham's green spaces (Figure 2), wards with large open green spaces (e.g. Dales, Wollaton West) naturally store more organic matter, and therefore carbon, than others. What is particularly noticeable is the low density of topsoil organic matter in highly urbanised wards in the city centre, specifically in the Castle, Radford and Berridge wards.

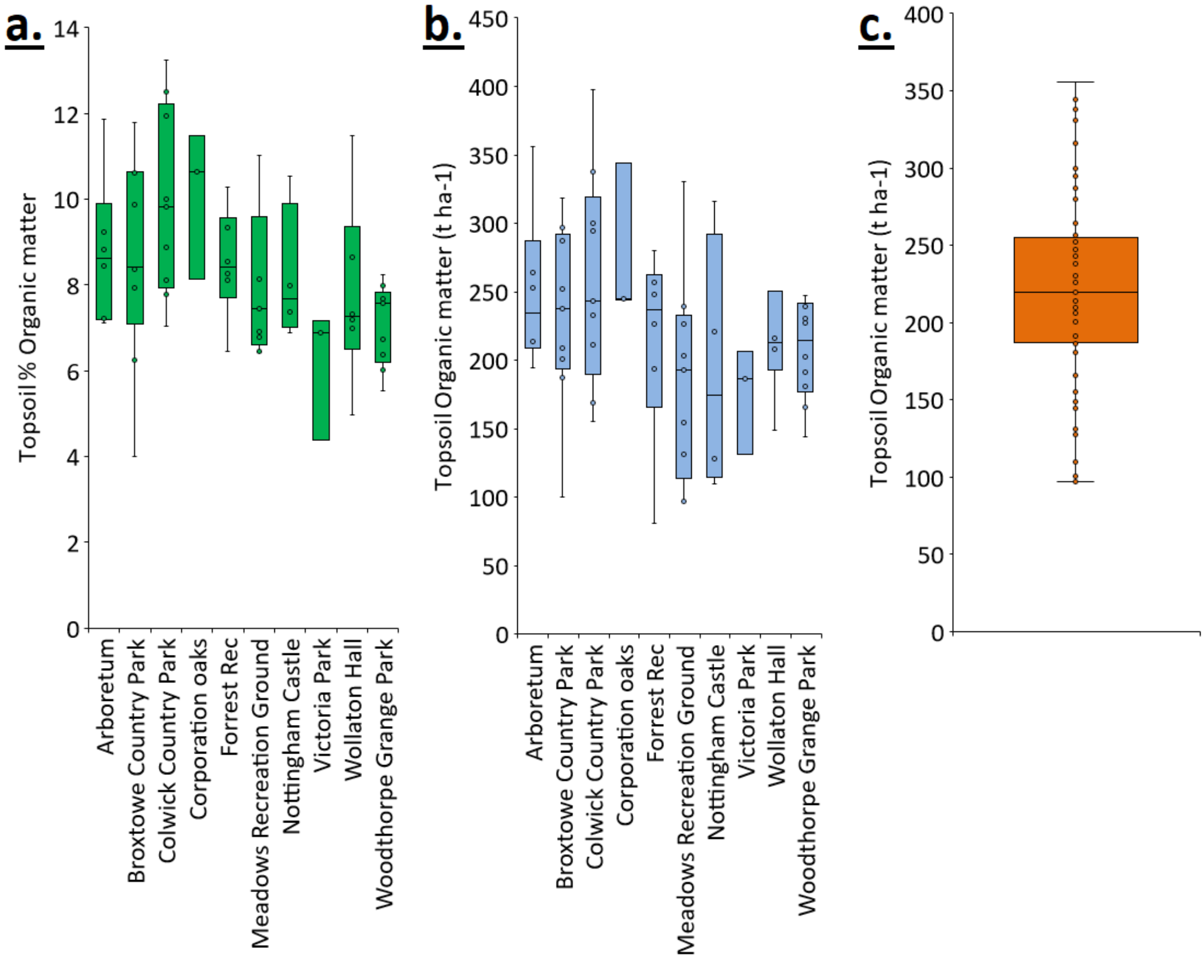

Figure 1a) Organic matter as % of total mass of topsoil (up to 30 cm depth) in Nottingham City Council Managed green spaces (outliers removed). b) Organic matter in tonnes per hectare in topsoil (up to 30 cm depth) in Nottingham City Council Managed green spaces. c) Average organic matter in tonnes per hectare in topsoil (up to 30 cm depth) in Nottingham City Council Managed green spaces

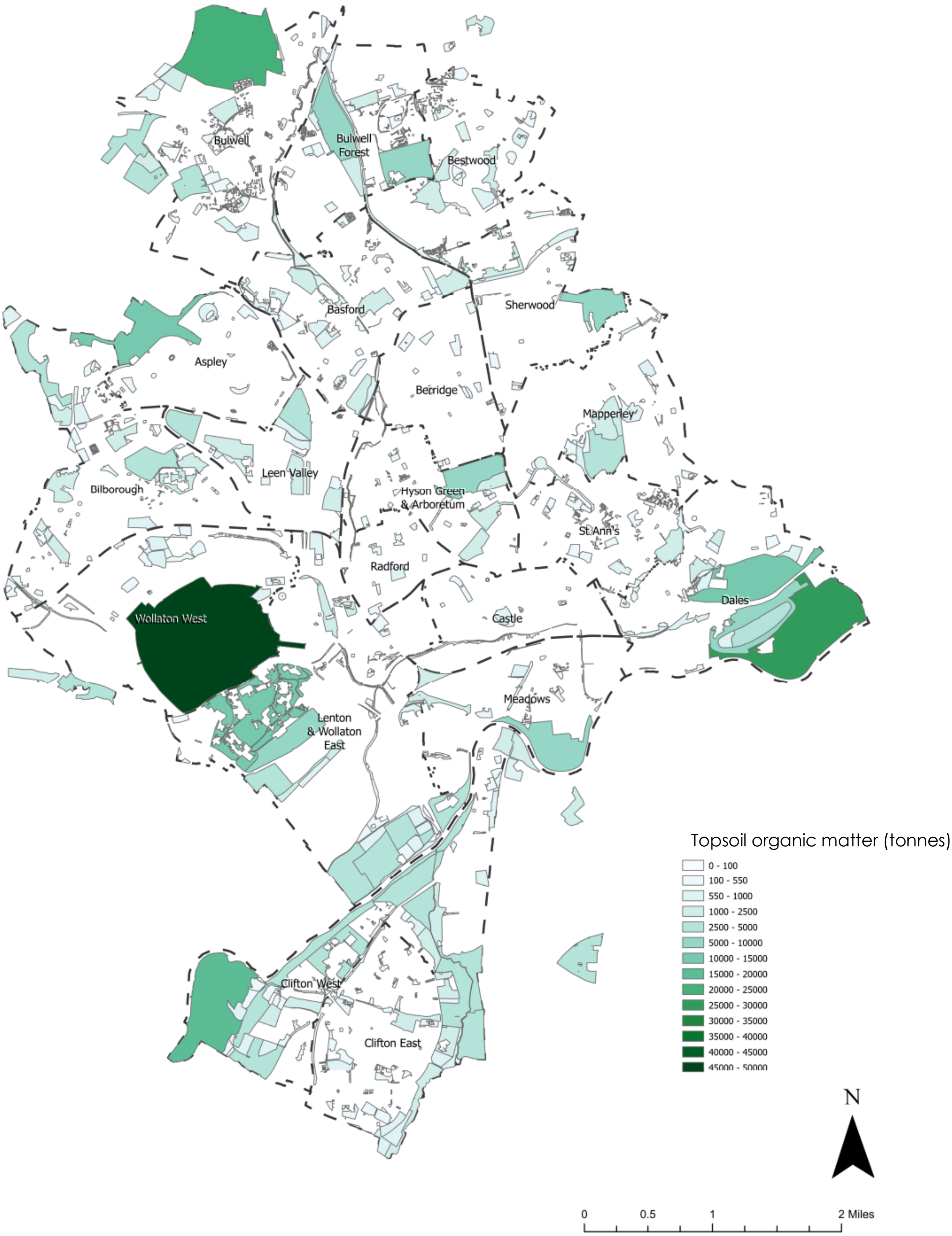

Figure 2: Distribution of topsoil (up to 30 cm depth) organic matter in metric tonnes across NCC managed green spaces within the NCC administrative boundary.

4.2. Tree distribution and carbon

The distribution of council and non-managed council trees (Figure 3) varies in location and density. Council managed trees are found across the scale of densities, from isolated street trees to high density urban woodland patches within council managed green spaces. High density council managed woodland includes those in Wollaton Hall grounds, Colwick Country Park and Phoenix. Outside of a few high-density patches, non-council managed trees are predominantly found as lone or a small number of trees within the gardens of private residence. Exceptions with a high density of non-council managed trees include the Park Estate, University Park campus, and the non-council managed Aspley Allotment site. When council managed and non-council managed tress are considered together, there is still uneven distribution of trees between wards. Castle and surrounding wards in the urban centre of the city have lowest densities, with densities generally increasing in wards more towards suburban areas.

Considering carbon density at the ward scale, the discrepancy between wards is more apparent. For council managed trees (Figure 4) tree carbon density is highest in the Wollaton West, Dales and Bulwell wards, with considerably lower density in the Castle, Berridge, Bestwood and Meadows wards. For non-council managed trees (Figure 5), tree carbon density is highest in the Lenton & Wollaton East and Mapperley wards, with considerably lower density in the Meadows, Radford, St Ann's and Bestwood wards. Combining the tree carbon density of council managed and non-council managed trees (Figure 6) shows a more ubiquitous density, but there are still wards with greater density than others. Wollaton West, Lenton & Wollaton East, Dales and Mapperley wards are of particular high density, with Berridge and Bestwood wards being noticeably low in overall tree carbon density. In terms of tonnage, across the entirety of Nottingham (Figure 7) 141165.01 tonnes of carbon is estimated to be stored in council managed trees, with 523740.60 tonnes of carbon estimated to be stored in non-council managed trees, totalling 664905.61 tonnes of carbon stored in trees in Nottingham.

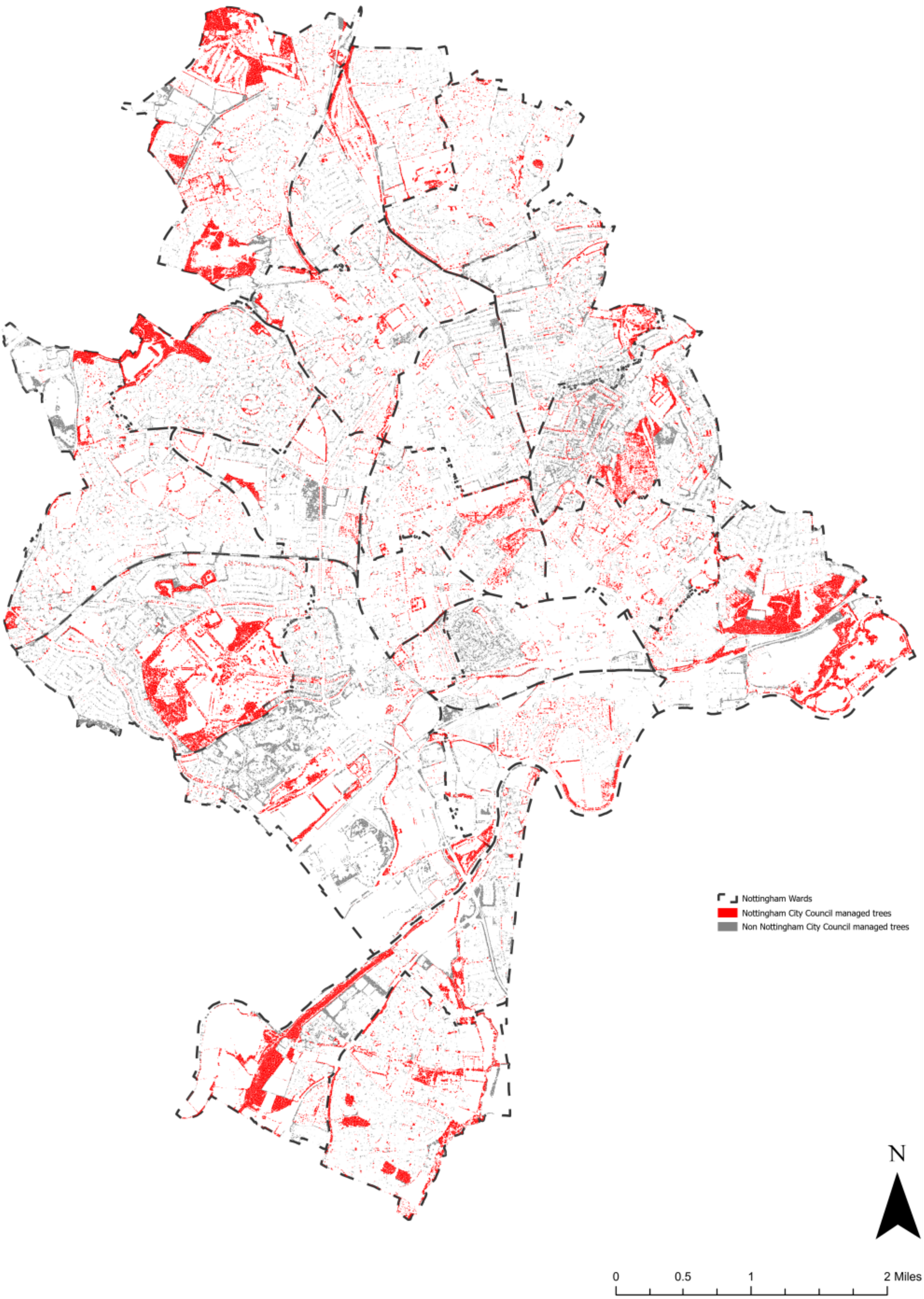

Figure 3: Distribution of NCC managed trees (red) and non NCC managed trees (grey) within the NCC administrative boundary.

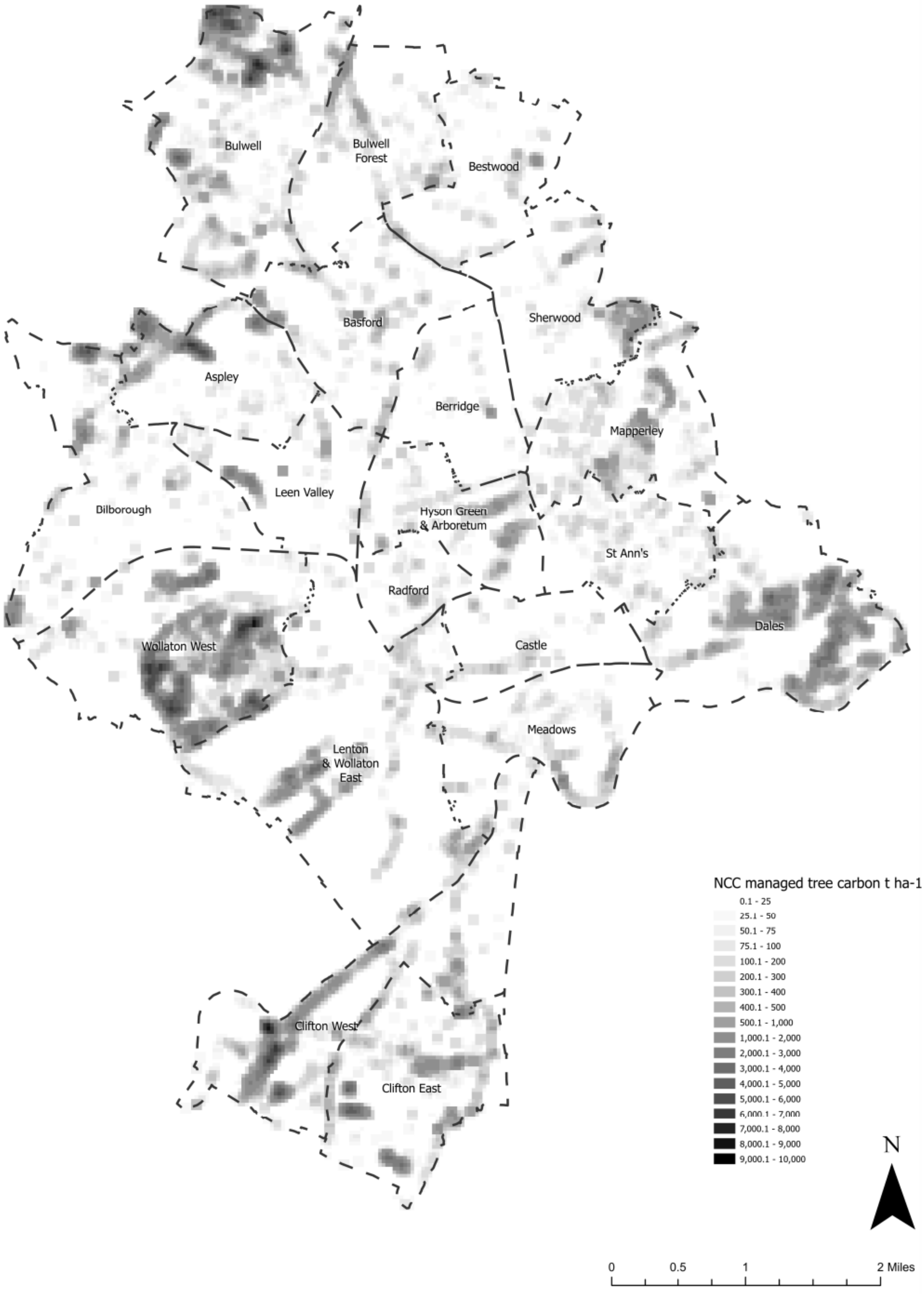

Figure 4: Distribution of carbon stored in NCC managed trees in tonnes per hectare (tha^{-1}), with darker colouration indicating greater carbon density, within the NCC administrative boundary.

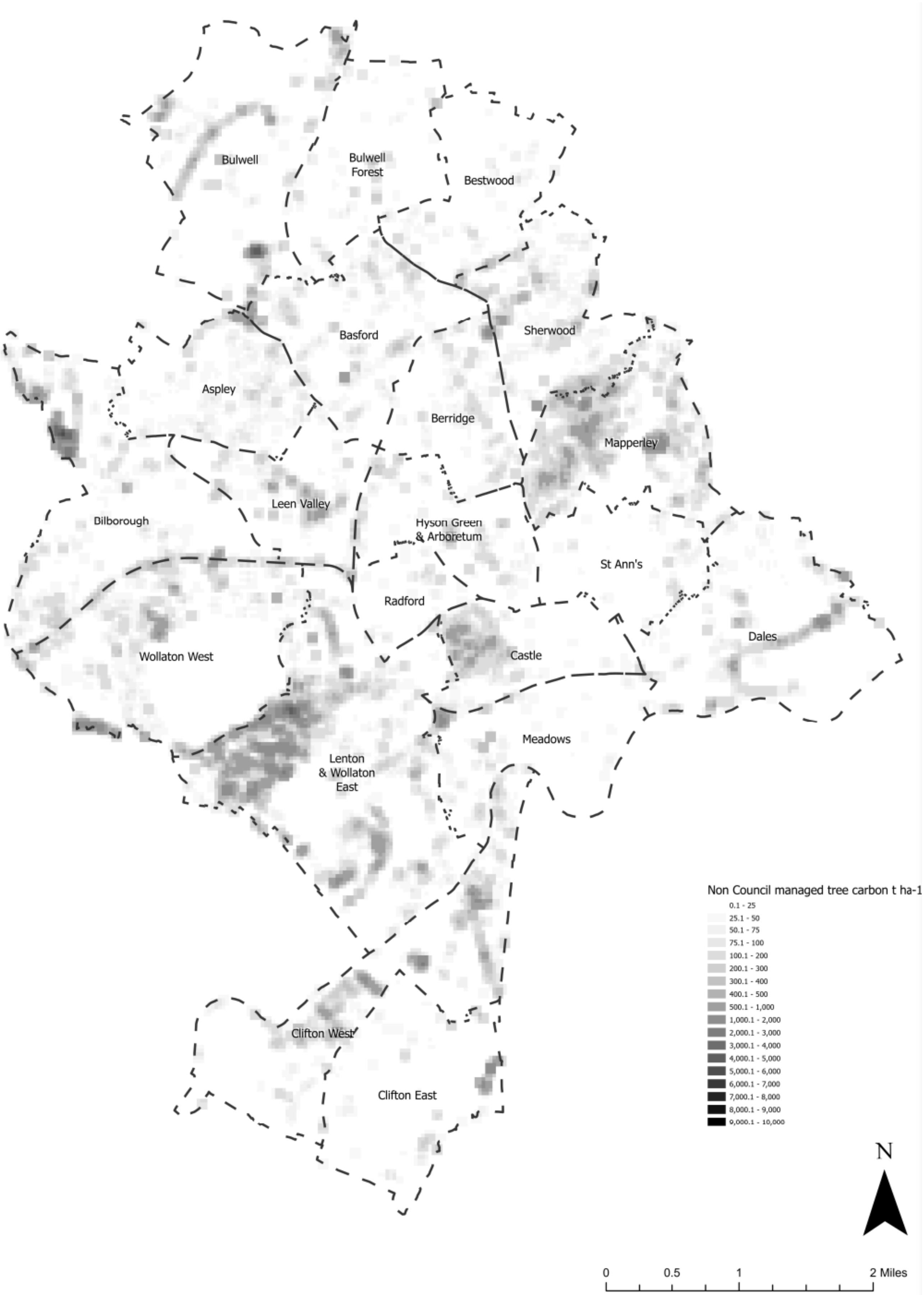

Figure 5: Distribution of carbon stored in non NCC managed trees in tonnes per hectare (tha^{-1}), with darker colouration indicating greater carbon density, within the NCC administrative boundary.

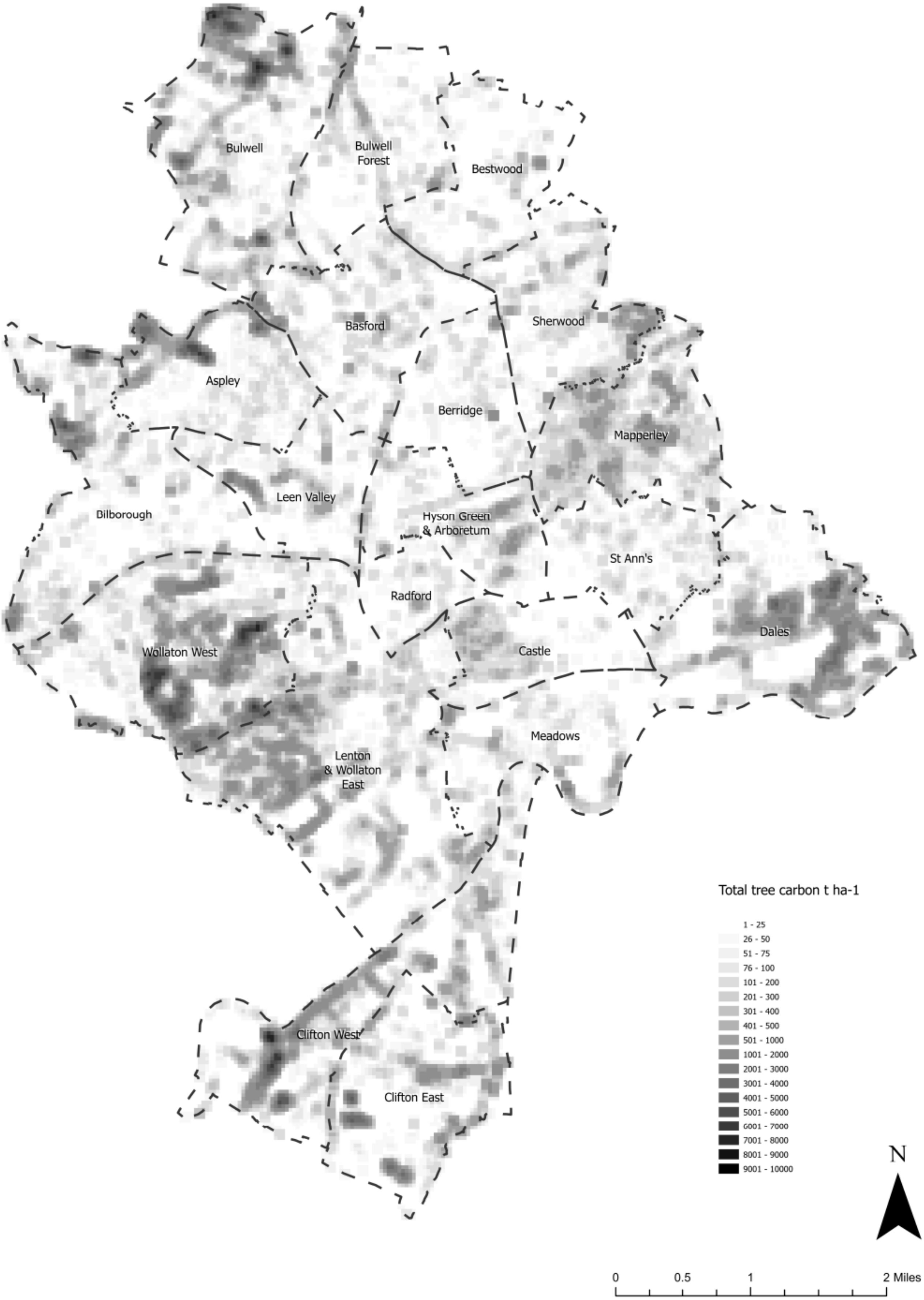

Figure 6: Distribution of carbon stored in NCC managed and non NCC managed trees combined in tonnes per hectare (tha^{-1}), with darker colouration indicating greater carbon density, within the NCC administrative boundary.

4.3. Total organic carbon in Nottingham

When holistically viewing organic carbon storage in Nottingham (Figure 7), topsoil organic carbon and the cities council managed, and non-council managed trees equate to a significant mass of carbon stored within NCC's administrative boundary. Topsoil organic carbon storage down to 30 cm depth is estimated to be 131165.01 tonnes across the council managed and affiliated green spaces across the city. 141165.01 tonnes of carbon is estimated to be stored in council managed trees, with 523740.60 tonnes of carbon estimated to be stored in non-council managed trees. Combined, this totals an estimated 935762.05 tonnes of organic carbon stored across the city, or 935.8 kt.

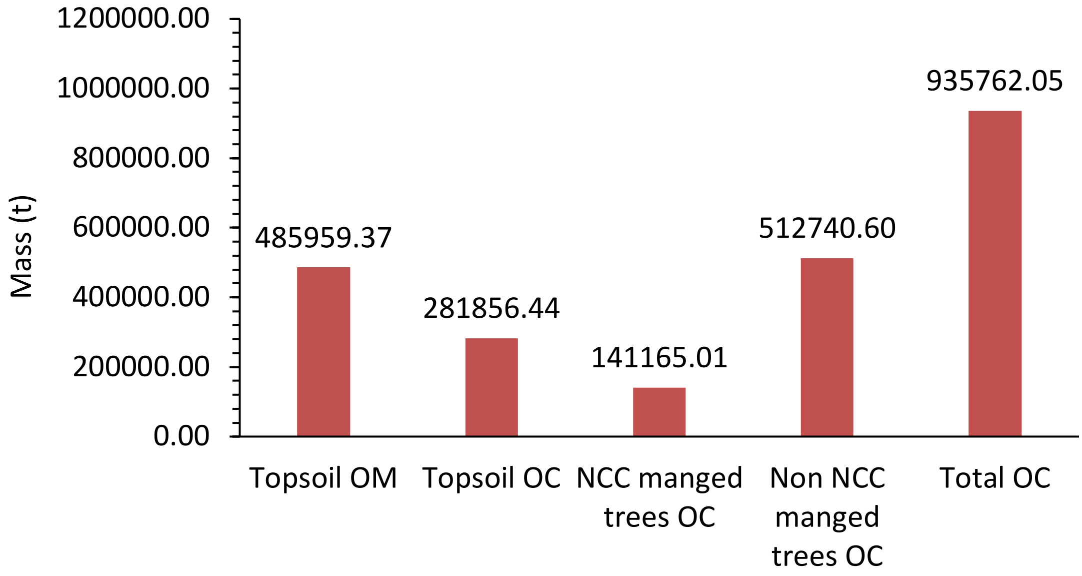

Figure 7: Mass of topsoil organic matter to 30 cm depth, topsoil organic carbon to 30 cm depth, council managed tree organic carbon, non-council managed trees and total overall organic carbon stored in Nottingham within NCC's administrative boundary.

5. Application and strategies for improvement

5.1. Distribution of carbon and caveats

The spatial distribution of soil and tree carbon density across Nottingham shows significant variation, reflecting differences in distribution of green spaces, dense woodland and street trees between the wards of Nottingham. Wollaton West, Lenton & Wollaton East and the Dales wards exhibit higherdensity of carbon storage. These areas benefit from large areas of longstanding vegetation, tree coverage and undisturbed soils, which contribute to substantial organic carbon accumulation above and below ground.

Although we observed no significant difference in organic matter content per unit area of topsoil between sampled green space site, soil carbon generally varies with land use and management history (Beillouin et al. 2022). In this study we only sampled topsoil from parkland, including open grassland and woodland patches, but did not sample from a variety of other possible types of urban green space e.g. reclaimed industrial, allotments, and so cannot account for possible variation in this type of land use or variation in management practice. Topsoil organic carbon accumulates due to decomposition of plant material, living roots, and microorganisms in the top layer of soil. Management practices that disturb these components can lower carbon content. The removal of surface vegetation through mowing and collection, soil compaction from heavy machinery use, and exposure of subsoil during construction can lead to significant losses in soil organic carbon through reduced input and emission of stored carbon to the atmosphere (IBID).

When interpreting topsoil organic carbon storage on Nottingham, several caveats must be considered. Soil carbon content can vary seasonally, influenced by factors such as temperature, moisture, and organic matter input (Wuest 2014). In this study we only sampled during a single season, where more accurate estimates could be produced from sampling throughout the year. Additionally, the depth of soil sampling can significantly affect carbon estimates, with deeper layers potentially holding more carbon, and here we only sampled the topsoil to a depth of 30 cm, not considering deeper horizons. The soil profile can be multiple metres in depth, and so more accurate and holistic estimates would consider organic carbon stored throughout the entire soil profile in all horizons. Truly accurate estimates of soil carbon storage would include inorganic carbon, which is derived from the weathering of bedrock material that forms the mineral component of soil.

Woodlands in green spaces, such as parks and nature reserves, are some of the most significant carbon sinks in the city and affect the carbon density between wards. The dense tree cover in these green spaces contributes to substantial organic carbon accumulation both above ground and potentially below it. Soil enriched by carbon from substantial leaf litter and root systems, which although not accounted for in this study, would likely be demonstrated in a more holistic study. Street trees planted along roadsides contribute to carbon storage in more urbanised areas. Although individual street trees store less carbon than those in large woodlands, collectively they play a vital role in enhancing the urban environment, providing shade, reducing the urban heat island effect, and improving air quality (Pataki et al. 2021). However, the carbon storage capacity of street trees can be limited by factors such as available root space, pollution, greater management action (Jim 2019, Czaja et al. 2020). The distribution of street trees also often reflects historical planning decisions, with more affluent neighbourhoods, such as those in the Mapperley ward, typically having higher densities of street trees as well as those in private gardens, leading to higher levels of carbon sequestration (Lin et al. 2021). In contrast, less affluent areas, where resources for urban greening may be more limited, tend to have fewer trees, resulting in lower carbon storage. For instance, wards such as St Ann' may display disparities in tree cover and carbon storage due to varying levels of investment in green infrastructure and maintenance.

5.2. Managing and preserving existing soil carbon

Preserving existing soil carbon is essential for maintaining Nottingham's carbon balance and contributing to climate mitigation efforts. The preservation of soil organic carbon is particularly important in areas with high organic matter content and previous minimal disturbance, such as mature woodlands and long-established green spaces such as those in the Wollaton West, Dales and Bulwell wards. These areas serve as significant carbon sinks and their protection should be a priority. To preserve soil carbon, it is crucial to minimise soil disturbance. This can be achieved through practices such as reduced tillage of plant beds, maintaining permanent vegetation cover, and reducing activities that lead to soil compaction that will later require remediation such as heavy machinery use (Beillouin et al. 2022). Avoiding soil sealing, covering the soil with impermeable materials like concrete or asphalt, is also vital, as it can lead to the loss of soil carbon storage capacity (Tóth et al. 2022). Soil storage and reuse should be integrated into urban development and landscaping projects. For instance, topsoil removed during construction should be stored and later reused in landscaping or tree planting projects, minimising carbon loss of soil that is typically set to landfill (Hale et al. 2021). Proper management of this stored soil, including measures to prevent erosion and carbon loss (e.g covering) and remediation of contaminated soils, can improve safety and help maintain its carbon content until it is reused. Storage and reuse is optional in England and Wales, but may countries in the EU and beyond have successful and compulsory programs (IBID). In addition to directly protecting soils, it is essential to safeguard existing trees, particularly in areas with high tree density, such as Wollaton hall. Trees in these areas not only contribute to carbon sequestration but also play a role in maintaining soil structure and preventing erosion, further aiding in carbon retention.

5.3. Increasing soil carbon sequestration

Enhancing soil carbon sequestration is a difficult possible strategy for increasing Nottingham's overall carbon storage. One effective method is the use of soil amendments, materials added to soil to alter its properties, produced from organic waste to sequester excess carbon on the soil. This could be in the form of mulch derived from biodigested residential garden waste, collected during domestic bin collection. Biodigestion is the breakdown of organic material by microorganisms in an oxygen-free environment, which primary purpose is to produce energy but as a byproduct produces a nutrient-rich residue ideal for soil enhancement (Lee et al. 2020). This approach not only recycles organic materials but also adds valuable carbon and nutrients to the soil, improving its fertility, structure and suitability for further plant growth (IBID). Applying these soil amendments can be particularly beneficial in areas with degraded soils or low organic matter content. The use of biodigested mulch helps to increase microbial activity in the soil, which is crucial for the stabilisation of organic carbon, lowering soil emissions and leading to higher, longer-term sequestration of carbon (Duddigan et al. 2022).

Incorporation of biochar, a form of charcoal produced by heating organic material in the absence of oxygen, also offers significant potential for increasing soil carbon sequestration. Biochar is highly stable, effectively locking away carbon that would otherwise return to the atmosphere for long periods of time. When added to soil, biochar not only enhances carbon storage but also improves soil structure, water retention, and nutrient availability (Cen et al. 2021). Applying biochar can be particularly beneficial in areas with degraded soils or low organic matter content. It can also complement other soil amendments, such as compost or biodigested mulch, by further enhancing soil fertility and microbial activity. This, in turn, supports healthier plant growth, contributing to additional carbon sequestration through increased biomass. To maximise the benefits of biochar, it is important to carefully consider its source and the conditions under which it is produced, as these factors influence its properties and effectiveness as a soil amendment. By integrating biochar into soil management practices, Nottingham can boost its soil carbon sequestration capacity while simultaneously improving soil health and resilience.

5.4. Areas and considerations for targeted tree planting

Targeted tree planting is an effective way to increase Nottingham's carbon storage. Identifying areas with low existing tree cover but high potential for tree growth is essential for optimising carbon sequestration. Suitable areas for targeted tree planting include the Castle, Berridge, St Ann's and Meadows wards, which currently have low tree density but present opportunities for planting of street trees and reforestation or afforestation of green spaces. In addition to increasing carbon storage, targeted tree planting in these areas can provide co-benefits such as reducing the urban heat island effect, where urban areas become significantly warmer than surrounding rural areas due to human activities and infrastructure. Planting trees can also improve air quality, enhance biodiversity, and support community well-being (Wolf et al. 2020, Pataki et al. 2021). The selection of appropriate tree species is crucial to ensure the long-term success of these planting initiatives. Native species are typically better adapted to local conditions, require less maintenance, and provide better support for local wildlife and ecosystems (Berthon et al. 2021). Moreover, prioritising areas that currently have low organic carbon content in the soil but are suitable for tree growth can create synergistic effects, where both soil and tree biomass carbon storage are enhanced.

When planning tree planting for carbon sequestration, several factors must be carefully considered to maximise the effectiveness of these efforts. Tree species selection is paramount. Fast-growing species, such as poplars or willows, can sequester carbon quickly, but they often have shorter lifespans and may require more maintenance (Black et al. 2008). In contrast, slow-growing, long-lived species like oaks or beeches can store carbon for extended periods, contributing to sustained carbon sequestration over centuries.

When importing non-domestically produced trees to plant, it's essential to consider CO_2 emissions associated with transporting the trees from their place of origin to the planting site. Trees imported from abroad can have a higher carbon footprint due to transportation, which may offset some of the carbon sequestration benefits they provide. To minimise carbon miles, it is preferable to source trees from local nurseries or nearby regions where possible. This not only reduces the environmental impact of transportation but also supports local economies.

The age and health of trees play a significant role in their carbon sequestration potential. Younger trees typically sequester carbon proportional to their size at a faster rate due to their rapid growth phase, while mature trees store large amounts of carbon in their biomass, but may have a lower rate of sequestration despite the total mass sequestered being greater (Boukili et al. 2017). A mixed approach, planting both young and mature trees, can ensure a continuous carbon uptake and storage over time. Location is another critical consideration. Trees planted in areas with suitable soil conditions, adequate water supply, and minimal competition from other vegetation are more likely to thrive and reach their full carbon sequestration potential. However, care must be taken to avoid planting trees too close to infrastructure, where they may pose risks or require removal in the future, leading to a loss of stored carbon (Widney et al. 2016). Finally, ongoing maintenance and monitoring are essential to ensure the success of tree planting initiatives. Regular care, including watering, mulching, and protection from pests and diseases, will help young trees establish and grow (Hofmann et al. 2016). In the long term, monitoring the health and growth of these trees will provide valuable data on their carbon sequestration performance, allowing for adjustments to management practices as needed. This is vital in preventing high die off rates of young trees planted as part of mass planting efforts designed to offset emissions.

6. Avenues of future work

6.1. Full soil profile, inorganic carbon and land use consideration in Nottingham

This study focused solely on topsoil organic carbon. However, deeper soil horizons which can extend to multiple metres in depth, can contain significant stores of organic and inorganic carbon. Future work should involve vertical soil sampling to assess organic and inorganic carbon storage throughout the full soil profile. This would provide a more accurate estimate of Nottingham's total soil carbon stocks and offer insights into the stability of this carbon over time. Understanding the distribution of carbon with depth will help in evaluating the soil's potential for additional carbon sequestration and identifying the best management practices to enhance this capacity.

Different urban land uses, such as residential, industrial, urban agricultural areas and parkland can significantly impact soil carbon storage. Urban development often leads to soil sealing, which reduces the soil's ability to sequester carbon. Conversely, green spaces like parks and community gardens can enhance soil carbon storage through plant growth and organic matter accumulation. Further research should explore deeper the spatial distribution of land uses across Nottingham and its impacts on both organic and inorganic soil carbon. This could involve detailed mapping of land use changes over time and correlating these changes with soil carbon data to understand the impact of urbanisation, green space management, and agricultural practices on carbon sequestration. Where possible, privately owned green space such as domestic gardens should also be incorporated into sampling. Identifying high-priority areas for carbon management, such as rapidly developing zones or areas with potential for green space creation, will enable targeted interventions to protect and enhance stored carbon.

Another important avenue for further research is conducting trials of soil amendments to assess their effectiveness in enhancing soil carbon sequestration in different land use contexts. For instance, biochar, compost, and biodigested mulch derived from organic waste could be trialled in various parts of Nottingham across land use types to determine their impact on soil carbon, soil health, and plant growth. These trials would involve applying different soil amendments to selected sites, monitoring changes in soil carbon content, soil structure, moisture retention, and nutrient availability over time. The results could provide valuable data on the most effective soil amendments for different soil types and land uses in Nottingham, guiding future efforts to enhance soil carbon sequestration across the city.

6.2. Time series of tree carbon in Nottingham

Understanding the temporal dynamics of tree carbon storage is crucial for predicting future trends and evaluating the success of carbon sequestration efforts. Here we have produced a baseline using remotely sensed data in the form of Blueskys NTM from 2019. A time series analysis using data from subsequent years of the NTM would allow for a detailed examination of how Nottingham's tree coverage and growth change over time. This analysis would involve comparisons of tree canopies between years, enabling the assessment of growth rates and subsequent carbon sequestration. By tracking these variables, it will be possible to trees where carbon sequestration is increasing, as well as trees that are being lost or reaching mature status and limited in their carbon sequestration capacity. This will ultimately inform management decisions and provide accurate estimates of annual carbon sequestration in the city's trees.

Nottingham's CN28 program, has already planted 37000 trees to offset emissions since the production of the 2019 NTM used in this study. Subsequent NTM years would include these trees, and so the monitoring of the contribution of these trees to carbon sequestration is already possible. This monitoring would demonstrate tree survival rates, growth patterns, and carbon sequestration effectiveness over time. By integrating the monitoring of CN28 program trees with the time series analysis, the city can evaluate the success of its tree planting initiatives and make necessary adjustments to planting practices, species selection, and maintenance regimes. This will help ensure that the trees planted contribute maximally to Nottingham's carbon sequestration goals and broader environmental objectives. The results of these analyses will be invaluable for urban planning and environmental policy-making in Nottingham. Understanding how tree carbon stocks evolve over time and how the CN28 program contributes to these changes will enable city planners to make informed decisions about where to focus future tree planting efforts, how to prioritise the maintenance of existing trees, and how to integrate carbon sequestration goals into broader urban development plans.

6.3. Expansion across the Midlands region

The methodologies developed in this report for assessing soil and tree carbon in Nottingham can be easily adapted and scaled up to encompass all cities in the Midlands region. This expansion would involve applying the same combination of remote sensing, field sampling, and geospatial analysis across different administrative boundaries, and could include the scale between urban, peri-urban, rural, and agricultural areas. By applying our methodologies across this broader region, we can develop a comprehensive carbon inventory for cities in the Midlands, identifying key areas for carbon sequestration and potential risks to existing carbon stocks.

Expanding the study to the Midlands would allow for comparative analysis between different local authorities and regions. This would help identify best practices in land management, tree planting, and soil conservation that could be shared and implemented across the region. For example, regions with successful urban forestry programs or soil management strategies could serve as models for others. The insights gained from a regional expansion could inform the development of regional carbon management strategies, aligned with broader climate goals. This could include coordinated tree planting campaigns, region-wide soil carbon enhancement programs, and the integration of carbon sequestration targets into regional planning frameworks. Expanding the study to the wider region would also open up opportunities for collaborative research with universities, local governments, and environmental organisations across the region. Such collaborations could bring additional expertise, resources, and funding to the project, enabling more comprehensive and impactful research.

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