The limited potential of urban greenspace for nature-based offsetting of institutional carbon emissions

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Abstract

Urban greenspace can potentially contribute to ambitious climate action plans declared by city institutions and councils. We measured soil carbon at 42 sampling locations across three land-covers and vegetation carbon of 490 trees (67 species) over the city campus of Newcastle University. Soil carbon varied with pH and land-cover classes (lawned with some free-standing trees, woodland park, sports fields), and tree cover significantly enhanced soil carbon storage. Soil carbon storage from 0–30 cm depth averaged 18.85 $kg \cdot m^{-2}$, more than double the tree carbon storage (average 7.66 $kg \cdot m^{-2}$) estimated using biomass empirical equations. The carbon stock from 95 Large-Leaved Lime (*Tilia platyphyllos*, 40,721 kg) and 54 Sycamore (*Acer pseudoplatanus*, 40,238 kg) was similar. These two species together accounted for the largest percentage of carbon stock from all trees on campus (18% each). According to our scenarios, if all currently available urban greenspace were converted to woodland this would offset only 1% of annual greenhouse gas emissions of Newcastle University or, if implemented more widely, of Newcastle city overall. While urban woodland brings benefits beyond carbon storage, the limit to what can be achieved with the available urban greenspace emphasises the need to first reduce city emissions substantially. In exchange for helping cities with carbon abatement, their surrounding rural regions could improve their infrastructural provisions with the carbon offsetting payments. Overall, a carbon-friendly land management strategy should be developed with full consideration of the collaboration between urban and surrounding rural areas, particularly placing a high value on soil and tree carbon.

1. Introduction

Urban ecosystems represent a significant terrestrial carbon pool (Pouyat et al., 2002). In the UK, urban areas extend to over 1.8×10^6 hectares and represent an estimated 8% of total land area (Office for National Statistics, 2019), which will increase further in the future due to urbanization. A total of 1.06×10^6 tonnes of carbon is reportedly stored in residential and non-residential land (0-100 cm depth soils with vegetation) in the city of Leicester in the UK (Edmondson et al., 2012). In the city of Bristol, UK, an estimated 9.8×10^4 tonnes of carbon is stored in 618,800 trees (i-Tree Bristol, 2019). Meanwhile, Wilkes et al. (2018) has emphasized that trees in inner west London can provide a similar aboveground biomass density as tropical forests. The amount of carbon removed by woodland in urban areas across the UK in 2017 was estimated to represent a value of £89 million (Office for National Statistics, 2019). Along with carbon storage and sequestration, important ecosystem services of urban greenspace include stormwater drainage, mitigating the urban heat island effect, environmental amelioration, air pollution reduction (Office for National Statistics, 2019, Edmondson et al., 2012, Hand et al., 2019), noise mitigation, improved citizen well-being and higher biodiversity (Edmondson et al., 2014). However, the increasing urban sprawl and transformation of landscapes may also impair rural ecosystem functions, and disturb the carbon cycle in natural soils (Richter et al., 2020).

The planting and management of urban greenspace will affect soil carbon concentrations (Lindén et al., 2020), and this provides a carbon sequestration opportunity. Climate, geological features, and the surrounding environments are significantly associated with urban forestry development (Hand et al., 2019, Heusinkvelt, 2016, Limoges et al., 2018, Viherä-Aarnio and Velling, 2017), and influence the ecosystem's capacity for carbon sequestration. Tree deaths resulting from planting inappropriate tree species may exceed the sum of other insect- and disease-related mortality (International Society of Arboriculture, 2020, Morani et al., 2011), which hampers efforts to store carbon into urban planted woodlands.

Many large organizations like universities have declared a climate emergency, and thus take their responsibility to mitigate climate change seriously. Such declarations by universities are important, because of the large amounts of energy consumption and waste production from academic and associated support activities (De Villiers et al., 2014). Since many universities are located within cities, purposeful management of their greenspace to maximize carbon storage can set an example for these cities and their urban ecosystems (Cox, 2012, De Villiers et al., 2014, Wasikowski, 2017). Many universities regularly report their institutional carbon emissions, and they may also survey and identify the species type and planting position of each tree in campus estates for tree management, but these data sets are rarely put into context to purposefully manage terrestrial carbon for emission offsetting (Wasikowski, 2017). By considering augmentation of the carbon storage of trees and soil in greenspace on their campuses, universities and similar organizations can strengthen their carbon management and emission mitigation plans (De Villiers et al., 2014).

Only a few studies have investigated the carbon stock of trees owned by universities and have calculated the related potential for offsetting university carbon emissions (Cox, 2012, De Villiers et al., 2014, Sharma et al., 2020). In the UK, only the University of Leeds has quantified that 540 tonnes of carbon are stored in 1,450 trees on its campus (Gugan et al., 2019). In New Zealand, De Villiers et al. (2014) have calculated that 4,139 campus trees on a university campus can store a total of 1,585 tonnes of carbon. Cox (2012) estimated that the total carbon of all trees on a California State University campus was 862 tonnes. Across 24 hectares of urban campus of Amity University in India, a total of 1,997 trees from 45 different tree species presented a C pool of 140 tonnes (Sharma et al., 2020). But these works examined tree carbon without consideration of the related soil carbon stocks.

Newcastle University declared a climate emergency in 2019 and aims to achieve net-zero carbon by 2030 (Newcastle University, 2021), as does Newcastle City Council (Newcastle City Council, 2020). The university currently does not know nor actively manage the carbon stored in the soils and trees of its urban campus as part of its carbon management plan. The main objectives of this study were therefore to i) quantify the soil and tree carbon across the greenspace of the urban Newcastle University campus to produce a terrestrial carbon stock baseline; ii) to review the species selection, planting patterns and growth status of trees currently on campus with a view of optimizing their carbon stock potential; iii) to obtain from interviews with university estates and sustainability managers an understanding of the challenges in implementing institutional plans to enhance the carbon stock of urban greenspace; iv) to consider how lessons learned for the university campus could be applied more widely by the local council for terrestrial carbon management and off-setting at the city-scale. This is the first study of its type that integrates soil and biomass carbon in urban greenspace with institutional net-zero carbon aims and presents an approach that can be adopted widely and internationally.

2. Materials And Methods

2.1 Study areas

The city of Newcastle upon Tyne is in north-eastern England (54.97° N, 1.62° W) with a population of around 320,000 (Population UK). The city experiences a temperate oceanic climate characterized by a slightly hotter and drier summer (average 13.1°C), compared to other northern UK cities, a cloudy and wet winter (average 5.6°C), and about 718 mm rainfall each year (Climate-Data). Where natural soils are present, soil texture within the region is dominated by loamy and clayey soil (http://www.landis.org.uk/soilscapes/), although much of the city centre is built on soils that have been disturbed by hundreds of years of construction and demolition. Newcastle University is a public research university with 3,500 staff and 28,000 students, and was responsible for 6,406 tonnes CO_2-equivalent C of greenhouse gas emissions in the academic year 2019/20 (Newcastle University, 2021). Newcastle University campus is 25 hectares, which accounts for 1.4% of the urban greenspace areas (**Table S1 in supplementary information**). Its Heaton Sports Ground has been used for sports since at least the 1890s (Digimap, 2020), the topsoil being managed using specialist sands to produce a turf playing surface suitable for cricket, rugby and football.

2.2 Soil survey

In September 2020, soil sampling was performed across the greenspace of the main university campus and a suburban university sports area in the city centre of Newcastle (see Fig. 1). The top 0–30 cm of the soil profile were sampled as most organic carbon accumulates in this interval of the soil profile (Wang et al., 2021) and services (pipes and cables) that could have been damaged by the deeper sampling. Previous research recommended that 30–50 soil sampling points should provide a reliable representation of soil carbon for different land covers (Edmondson et al., 2014). Therefore, 42 locations were randomly generated across three land-cover classes: 13 sampling points were within a small campus woodland/park (0.2 hectares), 12 sampling points were across lawned areas (0.3 hectares) with some free-standing trees of the central campus, and 17 sampling points were at the University's Heaton Sports Ground (2.7 hectares). The collection and carbon measurement methods and the related calculation of carbon per soil surface area of samples as well as the methodology of soil pH and X-ray diffraction analysis can be found in **supplementary information** (**SI**).

2.3 Tree carbon quantification

The tree database for the main campus of Newcastle University was obtained from the estate support management office in July 2019 and contained 490 trees, including 473 free-standing trees and 17 small groups of trees (i.e. dense areas where trees grow extremely close together). A related report, based on qualified tree assessment guidance (Bethge and Mattheck, 1993, Lonsdale, 1999, Matheny, 1994), presented the detailed condition of trees with management suggestions for the main campus of Newcastle University. For this report, tree species, risk levels and health conditions were visually assessed by arborist consultants; the diameter at breast height (DBH) was measured at 1.3 m above ground using a diameter tape; the height of trees was visually estimated by the arborists; the possible canopy was obtained using either a tape or measuring wheel and an estimation was given where the site access was restricted.

Two methods were used to estimate the carbon stored by the trees listed in the database: (1) i-Tree Eco and (2) allometric biomass equations. i-Tree Eco is one programme package in i-Tree tools (https://www.itreetools.org/), developed by the United States Department of Agriculture Forest Service, which can effectively assess the benefits of green space and quantify the structure of community trees and has been utilized in many countries. The related tree biomass equations for each species were found from the literature. When applying these two approaches, if no specific plant category could be matched for a tree species or no biomass formula was found for a particular species, the tree species would be assigned to one species group which came from the most closely related family. As for tree groups, due to the difficulty in estimating the specific physical parameters of each tree species, a general tree aboveground biomass equation from Jenkins et al. (2003) was substituted. The details of how to upload tree parameters to i-Tree Eco and the calculations regarding total tree carbon stock (kg), tree canopy cover (m^2) and tree carbon storage (kg·m^{-2}) are provided as **SI**. Results of allometric biomass equations were included in the paper, while the output of i-Tree Eco was added to the **SI**.

Considering that many tree species in the database contributed only a single tree on campus, tree characteristics of these plants were unlikely to be representative of general growth conditions for that tree species in urban areas in north-eastern England. Therefore, this study only considered the eight largest groups in terms of tree numbers to statistically analyse the variations of life stage, DBH, tree height, tree canopy cover and carbon storage between various tree groups and within a group of an individual tree species.

2.4 Questionnaire design for interviewing sustainability practitioners

We drew on three sources of information to understand the land management and how it may relate to the climate action plan of Newcastle University, based on interviews with the estate manager who designs the campus greenspace, and two team members who frame the carbon management plan. In addition, the outcome from another interview related to the management of carbon at the farms managed by Newcastle University (Wang et al., 2021) was included in the analysis. In the questionnaire, we presented data obtained from the university farms (Wang et al., 2021) which was based on the same aim to offset institutional carbon emissions, and proposed several possible options to improve terrestrial carbon sequestration in Newcastle University's urban campus, and then inquired about any concerns in terms of acceptability that the managers had for the approaches we mentioned. The questions for each interviewee are attached in **SI**.

2.5 Data analysis

ArcGIS (version 10.6.1) was used to produce the maps with labelled soil carbon storage values. The effects of various land-cover classes or sampling locations on soil carbon storage and soil pH were analysed using multivariate analysis. Pearson correlation was applied to assess the relationship between soil pH and soil carbon. The statistical relationship between tree carbon and tree age was determined by one-way ANOVA. Both were processed by SPSS (IBM SPSS Statistics 26, USA). Statistical significance is acknowledged as $p \leq 0.05$.

3. Results

3.1 Carbon storage and mineral compositions of urban topsoil in campus green space

The carbon per soil surface area (kg·m^{-2}) for the 42 urban campus soil samples at 0–30 cm depth is shown in Table 1. To visualise these results, **Fig. S1-3 in SI** show the distribution of soil collection points and the correspondingly specific soil carbon values. The bulk density in the study sites was 0.77 ± 0.1 g·cm^{-3} in Heaton Sports Ground, 0.87 ± 0.08 g·cm^{-3} in campus lawn, and 0.83 ± 0.08 g·cm^{-3} in campus woodland. These data were all similar to the soil density recorded in other green areas from the same region (UK Soil Observatory, 2021). The average 0–30 cm soil total carbon (STC), organic carbon (SOC) and inorganic carbon (SIC) values for the whole institutional greenspace are 18.85 ± 6.34 kg·m^{-2}, 13.52 ± 4.23 kg·m^{-2} and 5.33 ± 2.81 kg·m^{-2}, respectively. STC in the urban campus woodland park (23.05 ± 6.43 kg·m^{-2}) and lawned areas with free-standing trees (22.29 ± 4.57 kg·m^{-2}) presented a significantly larger carbon storage than the suburban sports field (13.25 ± 1.65 kg·m^{-2}) ($p < 0.001$, Table 1). In addition, for the proportion of SOC to STC, the data in Heaton Sports Ground (76%) was slightly higher than urban lawned and woodland parks (both are 70%). Additionally, compared to soil pH in Heaton Sports areas (6.48), the value obtained in the urban campus was higher (lawn: 7.32; park: 7.45; $p < 0.001$, Table 1). Both organic and inorganic soil carbon, and total carbon, significantly increased with increasing soil pH, although this relationship was less obvious in SOC ($p < 0.05$, **Table S4**).

Table 1

Bulk density ($g \cdot cm^{-3}$), carbon storage ($kg \cdot m^{-2}$) and pH of the 0–30 cm profile of urban greenspace soils with the statistical significance for soil carbon caused by three different land-cover classes. STC: soil total carbon; SOC: soil organic carbon; SIC: soil inorganic carbon. SD: Standard deviation. Significant ($p < 0.05$) findings have been recognized

	Number of soil samples	Soil bulk density ($g \cdot cm^{-3}$)		STC ($kg \cdot m^{-2}$)		SOC ($kg \cdot m^{-2}$)		SIC ($kg \cdot m^{-2}$)		SOC %	SIC %	Soil pH	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD			Mean	SD
Heaton Sports Ground	17	0.77	0.10	13.25	1.65	10.07	1.66	3.18	0.79	76%	24%	6.48	0.60
Urban lawn with some free-standing trees	12	0.87	0.08	22.29	4.57	15.59	4.18	6.7	3.41	70%	30%	7.32	0.77
Urban woodland park	13	0.83	0.08	23.05	6.43	16.13	3.58	6.92	1.89	70%	30%	7.45	0.38
Total	42			18.85	6.34	13.52	4.23	5.33	2.81	72%	28%	7.02	0.74
Significant difference between different land - cover classes				< 0.001		< 0.001		< 0.001				< 0.001	

Put Table 1 *here.*

X-ray diffraction patterns of soil samples are displayed in Fig. 2. XRD diffractograms of soil samples in this study all showed the major peaks of quartz at similar positions (2θ = 20.8° and 2θ = 26°). In all 10 selected samples calcite (the major mineral host for inorganic carbon) was only identified in two urban woodland soils (a, b, in Fig. 2). Kaolinite, a clay mineral, was mainly found in urban campus samples but not at Heaton Sports Ground. Additionally, orthoclase, a potassium feldspar, was present in small amounts in soils from both locations.

Put Fig. 2 *here.*

3.2 Carbon stock of all trees on the central campus

Altogether 473 individual trees and 17 tree groups on Newcastle University campus were analysed, covering 67 tree species, and their allometric aboveground biomass equations and the number of trees per species are included in **Table S2**, citing literature source for equation coefficients. Across the central campus, for 23 tree species only one tree was found in each species; in 38 tree species the number of trees ranged from 2–20 and the population of the remaining six tree species were all above 20. Over 20% of the total tree population was accounted for by Large-Leaved Lime (*Tilia platyphyllos*), making lime the prevalent campus tree in Newcastle (Richter et al., 2020).

DBH is the most common variable to calculate aboveground tree biomass using allometric models. Overall, estimates of the entire tree canopy cover in the central campus of Newcastle University was 2.92 ha, measured by allometric biomass equations, corresponding to the total carbon stock from all trees of 223.5 tonnes (Table 2). Meanwhile, the average tree carbon storage was 76.6 tonnes per hectare of canopy by applying empirical biomass formulas (Table 2).

Table 2

Overview of carbon storage (tonnes·ha^{-1}) from different components of campus greenspace and the total estimated carbon stock (tonnes) over the greenspace of Newcastle University

Item	Unit	Data
Soil carbon storage in four Sports Grounds	tonnes·ha^{-1}	132.50
Soil carbon storage in central campus	tonnes·ha^{-1}	226.60
Soil carbon storage of all university-owned land (sports areas& central campus land)	tonnes·ha^{-1}	188.50
Carbon storage of 490 trees calculated from biomass equations	tonnes per hectare canopy	76.6
Area of four Sports Grounds	hectares	16.00
Area of central campus	hectares	9.00
Area of all university-owned land (sports areas& central campus land)	hectares	25.00
Area of 490 trees canopy	hectares	2.92
Carbon stock in four Sports Grounds	tonnes	2120
Carbon stock in central campus	tonnes	2039
Carbon stock of all university-owned land (sports areas& central campus land)	tonnes	4159
Carbon stock of 490 trees calculated from biomass equations	tonnes	223
Total terrestrial carbon stock in the university (soils & trees)	**tonnes**	**4383**

Put Table 2 *here.*

The carbon stock of 67 tree species calculated using allometric biomass equations is summarised in Fig. 3. The carbon stock from Large-Leaved Lime (40,721 kg) and Sycamore (*Acer pseudoplatanus*) (40,238 kg) was similar, where both together accounted for the largest percentage of carbon stock from all trees on campus (36.2%), although the number of Large-Leaved Lime (95) was almost double the number of Sycamore (54) (Fig. 4a). Twenty-nine Ash (*Fraxinus excelsior*) and seventeen Swedish Whitebeam (*Sorbus intermedia*) were the third (27,713 kg) and fourth group (16,756 kg) in terms of the total carbon stock per tree species. The carbon stock per tree species varied widely, which became clear when comparing tree species with the same population. Although Beech (*Fagus sylvatica*), Common Oak (*Querous robur*), and Lawson Cypress (*Chamaecyparis lawsoniana*), each accounted for 0.8% of the total campus tree population, their carbon stock was 9,982 kg, 1,361 kg, and 854 kg, respectively (Fig. 3**).**

Put Fig. 3 *here.*

3.3 The variation of tree characteristics and carbon content from the eight largest groups in tree numbers

The eight largest tree groups in terms of population are Large-Leaved Lime (95, 20.1% of total), Sycamore (54, 11.4% of total), Rowan (*Sorbus aucuparia*) (34, 7.2% of total), Ash (29, 6.1% of total), Silver Birch (*Betula pendula*) (23, 4.9% of total), Norway Maple (20, 4.2% of total), Swedish Whitebeam (17, 3.6% of total), and Kanzan Cherry (15, 3.2% of total). The change of mean tree DBH, tree height and tree cover area with tree age can be found in **Table S3**, and the distribution of life stage per tree species is displayed in Fig. 4a. There was a difference regarding tree age composition between various tree species in the urban campus. An assured planting date would be a great help to assess tree age, while other parameters of tree growth performance can assist to estimate the stage phase of trees, such as circumference of trunk, growing site conditions, size of buds, trunk colour, crown transparency, and loss/death of biomass, etc (ICP Forests, 2016, Ostberg et al., 2021). The latter method is how the arborists classified the maturity of campus trees in this study. Almost all Sycamore (98%) were mature trees, whereas just 6% of Rowan and 9% of Silver Birch were close to their fully mature stage. Semi-mature trees can be only found in Rowan (41%) and Large-Leaved Lime (14%), with relatively few in Kanzan Cherry (7%) and Norway Maple (5%). The remaining trees among eight tree species groups can be classified as early maturity trees, apart from 9% of Rowan recently planted which were not fully established yet. Over the eight different tree species, DBH, tree height and tree canopy area all increased with the increasing maturity of tree life stage in general, although there was a lack of statistically significant difference among some tree species (**Table S3**). Only data from Ash and Silver Birch demonstrated that all three tree dimensions would be significantly affected by tree ages in this report, while one or two plant physical parameters of Large-leaved Lime, Rowan and Norway Maple could show an important relationship with the tree mature stages ($p \le 0.05$, **Table S3**).

The average carbon content per square metre of tree canopy cover from Ash, was the largest (14.67 kg·m^{-2}), followed by Swedish Whitebeam (13.57 kg·m^{-2}), Sycamore (8.36 kg·m^{-2}), and Large-Leaved Lime (7.21 kg·m^{-2}) (Fig. 4b**&** Table 3). In contrast, considering the total carbon stock (kg) of each single tree from the eight tree species, the value from Swedish Whitebeam was the highest averaging 986 kg, which was slightly larger than Ash (956 kg). Furthermore, as a whole tree body, the single tree having the lowest capacity for storing carbon was Rowan (88 kg) (Fig. 4c). In general, the accumulation of carbon per square metre of tree canopy cover and per individual tree from the plant species whose trees were mostly in the mature stage was higher than for younger trees. Trees from the same age group still showed a different carbon storage ability for different species. For instance, for those tree species with trees of semi-mature stage, Kanzan Cherry had the highest carbon storage per square metre of tree canopy cover (7.26 kg·m^{-2}) while Rowan's was the lowest (1.87 kg·m^{-2}); in the early mature stage, the carbon storage of Swedish Whitebeam was greatest (7.29 kg·m^{-2}), and Large-leaved Lime showed the lowest ability in carbon storage (2.5 kg·m^{-2}). Again, in the mature stage, the carbon storage (kg·m^{-2}) was the highest for Swedish Whitebeam (17.96 kg·m^{-2}), slightly higher than Ash (17.53 kg·m^{-2}) and Silver Birch (15.17 kg·m^{-2}), while mature Kanzan Cherry showed a much lower carbon storage ability (4.83 kg·m^{-2}) (Table 3). Not all tree species could show a significantly statistical relationship between the biomass carbon index and growth stage. For example, Large-Leaved Lime, Rowan, and Silver Birch, had significantly higher carbon storage (kg·m^{-2}), and mean carbon stock per individual tree (kg) with increasing tree age ($p \le 0.05$, Fig. 4b**&c**, Table 3). However, only one index from Ash, the mean carbon stock per individual tree (kg), significantly increased with the tree growth ($p \le 0.05$, Fig. 4c, Table 3).

Table 3

Summary of the eight most frequently occurring trees and their corresponding mean carbon storage per m^2 of tree cover ($kg \cdot m^{-2}$) and carbon stock of individual trees (kg) within the different age classifications and the statistical significance of the division by age groups. SD: Standard deviation. Significant findings have been highlighted ($p < 0.05$); n.a: no data for that group

	Carbon storage per m^2 of tree cover ($kg \cdot m^{-2}$)					**Carbon stock of individual tree (kg)**					**Statistical significance as the change of maturity (*p* value)**	
	Young	Semi Mature	Early Mature	Mature	Mean	Young	Semi Mature	Early Mature	Mature	Mean	Carbon storage per m^2 of tree cover ($kg \cdot m^{-2}$)	Carbon stock of individual tree (kg)
Large-leaved Lime	n.a.	2.44	2.5	8.73	7.21	n.a.	114.16	127.04	527.32	428.64	**0.001**	**< 0.001**
SD	n.a.	2.37	0.7	7.34	6.98	n.a.	125.16	88.3	398.94	392.13		
Sycamore	n.a.	n.a.	4.94	8.49	8.36	n.a.	n.a.	387.56	759.33	745.56	0.471	0.377
SD	n.a.	n.a.	0	6.86	6.76	n.a.	n.a.	0	584.51	577.74		
Rowan	2.4	1.87	2.86	11.88	2.94	29.54	41.89	78.03	571.64	87.91	**< 0.001**	**< 0.001**
SD	1.54	0.92	1.33	12.79	3.4	0	22.49	49.72	493.37	155.11		
Ash	n.a.	n.a.	5.68	17.53	14.67	n.a.	n.a.	163.08	1207.8	955.63	0.299	**0.019**
SD	n.a.	n.a.	2.89	29.2	25.84	n.a.	n.a.	56.44	1096.71	1053.44		
Silver Birch	n.a.	n.a.	3.76	15.17	4.75	n.a.	n.a.	89.86	865.47	157.31	**< 0.001**	**< 0.001**
SD	n.a.	n.a.	0.8	0.37	3.38	n.a.	n.a.	26.51	164.07	227.58		
Norway Maple	n.a.	6.8	3.35	6.19	5.08	n.a.	768.58	192.79	389.08	329.54	0.356	0.101
SD	n.a.	n.a.	2.72	5.1	4.31	n.a.	n.a.	208.04	304.79	291.39		
Swedish Whitebeam	n.a.	n.a.	7.29	17.96	13.57	n.a.	n.a.	558.73	1284.51	985.66	0.136	0.189
SD	n.a.	n.a.	2.19	17.64	14.36	n.a.	n.a.	435.28	1333.97	1098.89		
Kanzan Cherry	n.a.	7.26	3.45	4.83	4.07	n.a.	684.39	309.1	1373.95	618.08	0.199	0.324
SD	n.a.	n.a.	1.56	3.22	2.23	n.a.	n.a.	312.59	2223.44	1163.58		

3.4 The entire carbon stock potential of the urban ecosystem

The estimated carbon stock from 0–30 cm topsoil and all trees in the central campus of Newcastle University and Newcastle City is summarised in Tables 2 and 4, respectively, based on extrapolation of the campus data to the larger city greenspace areas. The four sports grounds and other green spaces forming the urban campus of Newcastle University store 4,159 tonnes of soil carbon; if including the 223 tonnes of tree carbon, both contribute to the total greenspace carbon stock of 4,383 tonnes (175 $tonnes \cdot ha^{-1}$). This number is equivalent to 68% of the carbon emitted in the university in the academic year of 2019/20 (6,406 tonnes) (Newcastle University, 2021).

Table 4
The estimated carbon storage (tonnes·ha^{-1}) and the estimated total carbon stock (tonnes) over the city of Newcastle upon Tyne

Item	Unit	Data
Soil carbon storage in sports grounds (referenced from the value obtained in Newcastle University)	tonnes·ha^{-1}	132.50
Soil carbon storage in other greenspace (referenced from the value obtained in Newcastle University)	tonnes·ha^{-1}	226.60
Urban trees carbon storage (referenced from the value obtained in Newcastle University)	tonnes per hectare canopy	76.6
Area of sport pitches managed by Newcastle Council [a]	hectares	46
Area of other greenspace managed by Newcastle Council [a]	hectares	1728
Area of urban trees [b]	hectares	321
Greenspace soil carbon stock	tonnes	397,648
Urban trees carbon stock	tonnes	24,593
Total terrestrial carbon stock from open green space (soils & trees)	**tonnes**	**422,241**
[a]: Date sources of open space areas from Newcastle City Council (2018) and the detailed value can be found in **Table S1** in **SI**.		
[b]: The current tree cover of Newcastle is estimated as 18.1% (Newcastle City Council, 2019).		

Put Table 4 *here.*

For each greenspace and land-cover class, the geology and history of land management, soil compaction, etc., will affect carbon storage, but an initial estimate can nonetheless be obtained by extrapolation of the Newcastle University city campus field data to the total urban greenspace of Newcastle City. Accordingly, a total of 397,648 tonnes soil carbon and 24,593 tonnes tree carbon are the estimated current carbon stock of Newcastle city greenspace (Table 4). As a conclusion, an estimated terrestrial carbon pool of 422,241 tonnes is claimed across the whole urban greenspace owned by Newcastle City Council, which is 26% greater than the total carbon emissions of Newcastle City in the calendar year 2019 (335,400 tonnes) (Table 4) (National Atmospheric Emissions Inventory, 2019).

We have introduced four scenarios (**Table S5-8 in SI**) regarding the carbon offsetting potential of future land cover class conversion, accounting for the time needed for trees to become mature. The performance of carbon storage of trees varies for the different growth stages (Liepiņš et al., 2016), and this variation would differ between tree species, but for facilitating the calculation, this study estimated the time for trees to become fully mature as 57 years by referencing the relationship between tree age and DBH (**Table S5-8 in SI**) (McPherson et al., 2016). Meanwhile, it was assumed that soil would also need 57 years to reach the present carbon equilibrium of each land cover class. Therefore, in the scenarios below, we divided the difference between the future and current carbon storage ability of each greenspace by 57 years to obtain the annual carbon capture and storage which can be achieved with the land use change (tonnes·ha^{-1}·year^{-1}) until the trees have grown to maturity. The first scenario targets the university campus and the other three are for Newcastle City. Firstly, by converting all available green areas on campus to woodland containing the top 4 tree species with the highest carbon storage ability (Ash, Swedish Whitebeam, Sycamore, and Large-Leaved Lime; Fig. 4**)**, the estimated annual increase in the carbon stock of university greenspace (tonnes·year^{-1}) would compensate for only 1.13% of carbon emissions of the university produced per year at the rate stated for 2019. In the same way, under scenario 2, if extending the woodland with these 4 tree species over the total urban greenspace, the additional carbon captured and stored annually would offset only 0.95% of the annual carbon emissions of Newcastle City at the rate stated for 2019/20. For comparison, Newcastle City Council (2019) has targeted to increase urban tree cover of its greenspace from the current 18.1–20% by 2050, and thereby an extra 33.7 ha lands can be afforested. Either introducing only 4 tree species (Ash, Swedish Whitebeam, Large-Leaved Lime, Sycamore) or mixed woodland, the annual carbon captured and stored by the 33.7 ha of new urban woodland amounts for only 0.020% and 0.014% respectively of the annual carbon emissions of Newcastle City at the rate stated for 2019 (Scenarios 3&4). From these scenarios, we understand the current woodland expansion project only contributes a very small amount towards city council carbon offsetting. For each land cover type, the soil carbon pool will reach a new equilibrium state between the accumulation of fresh carbon from decaying leaves/grass clippings, etc. and soil respiration of organic matter by bacteria, while new urban woodland would also enhance terrestrial carbon accumulation in the biomass of tree trunks and branches. In stark contrast to the findings of only limited carbon offsetting opportunities for the urban campus greenspace, we have previously reported that afforestation at two research farms managed by Newcastle University could capture and store up to 50% of the annual institutional carbon emissions at current rates over a period of 40 years (Wang et al., 2021).

3.5 Questionnaire feedback about developing a new woodland

From the interview with university managers, Table 5 summarised the factors driving tree species selection and planting in Newcastle University. The tree species selection is not currently based on augmenting terrestrial carbon, which is in line with the unpublished work surveying 37 UK city councils (20 in England, 3 in Scotland, 3 in North Ireland, 1 in Wales) (Ross, 2020) and other findings from previous studies (Heusinkvelt, 2016, Limoges et al., 2018, Morani et al., 2011, Sanders et al., 2013, Scholz et al., 2016). Both interviewees suggested a higher density of tree plantation is less achievable if the greenspace location is near a commercial centre with a built-up nature and complex belowground services. Particularly, the estate manager was concerned that the shape and canopy of fully grown trees might interfere with electricity wires or traffic (Spengler and Ellis, 2019). Also, the roots of mature trees could damage fundamental urban infrastructures such as water lines, or cause root heave (where trees' roots encroach the sidewalk or curbs to "escape" limited space or compacted soil conditions), leading a considerable repair cost (Randrup et al., 2001, Scholz et al., 2016). All these considerations are important issues to evaluate in urban tree planning (Sanders et al., 2013). More importantly, in urban settings, the availability of areas for tree planting is highly constrained (Ross, 2020). Indeed, the carbon storage capability of specific tree species is worth considering when designing a campus ecosystem, but balancing benefits from other research and business interests is inevitable (Table 5). This series of thinking has affirmed the predominant role of socioeconomic variables rather than biophysical variables in determining the carbon storage potential of urban greenspace on an institution-scale.

Table 5
Summarized feedback from managers of the university about their tree species selection and challenges for increasing tree numbers

1. Factors influencing tree species selection	**Ground manager:** **• Being street replacement or not** **• The distance of trees to buildings nearby** **• Health condition of previous trees** **• Being a memorial tree or not** **• Size of planted ground** **• Shape and crown of trees** **• Survivability of trees at in-situ climate** **• Trees possessing a longer growing seasons are preferred, i.e. cherry trees, fruit trees** **• Popular tree types for gardening globally**
2. Considerations when planting additional trees for carbon abatement by the institution	**Ground manager**: • Limited plantation space because the central campus is close to city commercial centre • Necessity to balance other performances the tree presents • Possible shape of trees in the future • Risk of disease spread among same tree species **Carbon& Energy managers**: • Performance of other functions from the trees at the same time, i.e. well-being benefits. • Spatial constraints due to the compact nature of most of the central campus • Whether being the best use of institutional resources • Acceptability from other stakeholders in the university

Put Table 5 *here*.

4 Discussion

Some higher education organisations have already paid attention to tree planting and maintenance on campus, and undertaken tree surveys to produce reports like "Enhancing the benefits of trees on Campus" from the University of Leeds (Gugan et al., 2019), "Tree Management Strategy" from the University of Sheffield (Winnert and Henderson, 2020), “Tree Trail” of the University of Manchester (2021), “Tree Campus USA” (2008), “Tree Protection Standards” of the University of Kentucky (2017) and “Tree Preservation” of the University of North Texas (2009). But no previous project has wholistically assessed the terrestrial carbon stock of both trees and soils, in the greenspace of a university campus as a function of land cover to assess strategies for institutional carbon off-setting. Referencing our survey, on the campus of Newcastle University, the 0–30 cm topsoil presents a carbon storage per surface area on average 2.5 times higher than tree biomass. In terms of terrestrial carbon augmentation, introducing more trees presents the biggest opportunity as it not only adds the additional biomass carbon of trees, but also augments soil carbon according to our survey results (Table 1).

4.1 Topsoil carbon content and mineral compositions

Across the central campus of Newcastle University, as we expected, topsoil carbon storage is statistically greater in urban woodland than lawned parkland and the suburban sports area. This is a likely consequence of extra organic matter inputs that includes leaves and mulches, and the contribution of shrubs that tend to improve soil carbon content as reported previously (Edmondson et al., 2014). STC values in this study are generally higher than other reports conducted over 0–30 cm turf grass soils with tree cover in urban Melbourne (Livesley et al., 2016), urban green areas in Berlin (Richter et al., 2020), and Helsinki urban parks (Lindén et al., 2020). The soil carbon of lawn with some free-standing trees in the urban campus exceeds the values for sports ground. This could be because most sampling points in urban lawn are in closer proximity to trees (the distance ranged from 3.3 to 15.4 m, average 7.6 m), while on average the distance of soil points to the closest tree in Heaton Sports Ground is 31.6 m (nearest: 8.5 m, farthest: 75.3 m). The presence and abundance of soil microbes (Nacke et al., 2016), and soil chemical properties such as the concentration of metals (Desta et al., 2018), can be importantly influenced by the distance between soil sampling site and the tree trunk, which are all driving factors for soil carbon formation. As explained by Livesley et al. (2016), tree roots not only modify soil compaction and improve nutrient cycling, but enhance organic input to the ground, and strengthen soil carbon content. This discussion might be extended by considering land management practices and other factors, e.g. fertiliser application, frequency of grass cutting, tree ages and recreation of original soil types. Great differences in carbon storage between various land-cover classes have previously been discussed (Lal and Augustin, 2011, Lindén et al., 2020, Pouyat et al., 2002, Richter et al., 2020). In New York City, surveyed soils reported by Pouyat et al. (2002) showed a higher SOC concentration (38%) under low-density built-up lands than in commercial lands. The reasons resulting in this effect may be the differences in management frequency and lack of soil disturbance.

The mineralogy of the soils in this survey is dominated by quartz, with subsidiary kaolinite and feldspar, reflecting the mineralogical composition of the geological parent material (glacial till or alluvium derived from Carboniferous sediments). SIC was reported from all soil samples in this study, and normally the source of SIC should be calcite ($CaCO_3$) (Jorat et al., 2020). However, based on the diffraction patterns in Fig. 2, calcite ($CaCO_3$) is only reported for 2 samples, reflecting the relatively high detection limit for routine X-ray diffraction. The proportion of TIC relative to total carbon is higher for the urban soil samples reported here (24–30%) than has been observed for agricultural soils (e.g. 10%; Wang et al., 2021). This is consistent with the observations reported by Washbourne et al (2015) that carbonation of materials derived from construction and demolition is a rapid process in urban soils, and needs to be recognised as a dynamic and manageable carbon stock.

4.2 Tree growth for different species on the city campus

Amid a total of 67 different tree species, Large-Leaved Lime occurs more frequently (20.1%) than other species found in this survey. Within our dataset, a clear trend of larger DBH, tree height and tree cover area is shown with increasing age classifications. As the first and second largest population in this study, the tree height of mature Large-Leaved Lime (16.58 m) and Sycamore (14.73 m) is lower than the mean value from other 10 British cities (Lime: 18.1 m; Sycamore: 20.7 m) (2 sites in Wales, 6 sites in Southern England, 2 sites in Southern Scotland) (Hand et al., 2019); similarly, the tree heights of mature Norway Maple (11.82 m) and Ash (13.95 m) in central Newcastle are 31% and 33%, respectively, shorter than the trees growing in other British cities (Hand et al., 2019). Again, among semi-mature trees, the mean height of Large-Leaved Lime and Norway Maple summarized by Hand et al. (2019) are still 17% and 29% greater than tree parameters in this report, respectively. In some species, the tree height peaked in the early-mature age classification and remained static into the mature stage (e.g. Sycamore, Swedish Whitebeam), based on tree characteristics measurements (**Table S3**) (Liepiņš et al., 2016). Generally, Norway Maple and Sycamore from mature age classification in Greater Manchester (Scholz et al., 2016) all express a variably thicker trunk (13–40%) than their counterparts in Newcastle, while fully-grown Lime and Ash from these two cities possess similar features with respect to the diameter of trunk.

For Silver Birch, on average, the trees in Newcastle are shorter than 22-year old trees in Finland, Estonia, Latvia and Russia; whereas, regarding DBH, the Newcastle group is greater than these four Baltic groups (Viherä-Aarnio and Velling, 2017). Comparing with the study of 7,768 Silver Birch in southern Finland (Kilpeläinen et al., 2011), Silver Birch in our survey are 2–3 cm larger in diameter and 6–7 metres shorter in height. With respect to urban Ash in Newcastle, Latvia Ash from the 80–100 years-old group (Liepiņš et al., 2016) has an up to 14 cm smaller average DBH; conversely, relating to mean height. Ash in Latvia is almost double the height of trees in Newcastle (Liepiņš et al., 2016).

Mean environmental temperature, precipitation, sunlight time and air moisture, affected by differences in climate, are all vital factors for tree growth and the development of different tree dimensions (Hand et al., 2019). The reasons for the different DBH values from the same tree species between Newcastle and other European cities may lie in the tree's ability to adapt to different photoperiodic conditions caused by latitude, which in turn could explain the trunk diameter variation between Newcastle and cities in more southern regions of the UK (Hand et al., 2019, Scholz et al., 2016). The decreasing tree stem height when exposed to stronger winds seems to hold true (Kronfuss and Havranek, 1999), which may thus be related to the occurrence of taller trees in other England cities compared to Newcastle (Hand et al., 2019, Scholz et al., 2016). Although wind speed was not measured in this report, a comparable dataset can be referenced (Weather Spark): average wind speeds in London and Manchester show a 6–15% and 5–13% weaker pattern than Newcastle, respectively. High wind speed hampers the growth of tree height: not just by escalating the risks of falling down or the loss of branches, but also by cooling of air, soil, leaves and meristems which are potential drawbacks during the vegetation period (Kronfuss and Havranek, 1999). It should be emphasized that tree distribution in our project is not dense because most of the trees are planted along pathways and roads where more open spaces are provided, which also means each tree is less protected by its neighbours from strong winds.

4.3 The capacity of carbon capture for different tree species

The amounts of carbon stored by 490 trees calculated in this study by using allometric biomass equations is 223 tonnes. In Newcastle, urban tree carbon storage averages 76.6 tonnes per hectare canopy. Carbon storages in our urban campus survey varied substantially among the eight largest number of tree species from 2.94 to 14.67 $kg \cdot m^{-2}$, which influences local ecosystem functions (Lal and Augustin, 2011, Nowak et al., 2013), and can inform tree species selection for carbon accumulation (Burton et al., 2021, Edmondson et al., 2014, Ennos et al., 2020, Hand et al., 2019). In our analysis, some trees which are not of the main populations are likely to store larger quantities of carbon, such as the carbon storage per m^2 of tree cover from Ash and Swedish Whitebeam (Fig. 4). This is because tree tissues (root, stem, branch, foliage, etc) of these species may have a higher carbon density (Widagdo et al., 2021), and probably these trees also face a less suppressed growth condition caused by impervious surfaces and local climate (Richter et al., 2020).

Furthermore, tree age classifications play an imperative role in carbon stock outcome. The research from ourselves and Hand et al. (2019) demonstrated that carbon storage of newly planted trees is comparatively less than that of fully established trees in urban areas. For the eight largest population species modelled in our work, carbon stock increases with each successive age classification, slowly in some species (e.g. Norway Maple) but faster in others (e.g. Silver Birch) (Table 3). Carbon stock varies not just due to different tree species, but also the climate features of sampling sites. Greater tree carbon stock values were found in other British cities (Hand et al., 2019) than the value in Newcastle, which probably occurs as most cities surveyed in that study are in more southerly, sunnier and warmer locations with relatively more sunlight, compared with north-eastern England, which benefits enzyme activity and provides more time for photosynthesis (Hand et al., 2019). One noted point is that the choice of allometric biomass formulas can lead to a diverse range of results when evaluating carbon storage performance in vegetation, despite inputting the same dimensions (Lal and Augustin, 2011). By using three sets of biomass equations, Vorster et al. (2020) demonstrated a substantial uncertainty of up to 75% for the estimated biomass of three tree species. Zhou et al. (2015) suggested that most biomass equations were developed based on forests, probably causing a disparity on estimating carbon stock of free-standing trees, like individual trees on the Newcastle University campus.

Tree health issues, including cavities, dead or dying branches (Boa, 2003), winter burn, fungal diseases, infestation (International Society of Arboriculture, 2020), and soil impaction (Sanders et al., 2013), importantly affect whether the trees can perform well for carbon storage. The occurrence, frequency, and out-break scale of tree health problems are combined consequences of inappropriate planting locations, wrong tree species choice, and lack of adequate planning and maintenance. For example Limoges et al. (2018) have shown that 28.54% of total tree growth condition was attributed to variables associated with street levels, geographic orientation (tree position in relation to the street), type of location, or presence of an obstruction, while 65.51% of the variation was led by tree species choice. Additionally, some urban locations are characterized as impervious and so not suitable for particular trees (Morani et al., 2011). Studying 45,500 trees across cities in the USA, Sanders et al. (2013) found significantly larger tree DBH for planting strips and non-limited soil, compared with tree pits. Conversely, the damage to infrastructure like impermeable pavements, roads and kerbs containing drainage systems caused by trees is considerable (Scholz et al., 2016), and another important consideration to take into account when selecting tree species. Land use history is another key factor influencing the appearance of trees (Heusinkvelt, 2016).

4.4 Carbon stock potential of urban greenspace

Many local authorities nowadays pursue a larger urban tree cover (City of Durham, Plymouth City Council, Newcastle City Council, 2019), but as scenarios 1–4 in **Table S5-8** in **SI** show, the possibility of offsetting significant parts of annual carbon emissions at an institutional or city-scale is limited by the current availability of urban greenspace resources. Therefore, the involvement of rural areas through climate partnerships may become necessary to achieve net-zero targets of city institutions (Gebre and Gebremedhin, 2019). Previous work (Wang et al., 2021) showed that land use change at two research farms managed by Newcastle University could make a much more substantial contribution towards offsetting institutional carbon emissions (up to 50%), than the urban campus greenspace analysed in this study (up to 1%). Similarly, city councils could seek assistance with carbon offsetting from rural partners. In return for assisting city councils with carbon abatement by planting trees or restoring peatlands, rural councils could benefit from ecosystem service payments and city council expertise to improve the rural provision of transport services and infrastructures, the upgrade of healthcare and education facilities, etc.

Multiple ecosystem services operated by urban trees have been positively mentioned (De Villiers et al., 2014, Hand et al., 2019, Jenkins et al., 2003, Lindén et al., 2020). For instance, street trees reduce glare reflected from the pavement, mediate a regional urban heat island, provide shade and local cooling (Landscape Architects- Bangkok, 2018), reduce air pollution (Hand et al., 2019), and beautify cities (Newcastle City Council, 2019); conifers can form a windbreak or protect residential privacy because the needle-leaf densely grows from the bottom of the conifer stem and is evergreen (Green, 2017, Lindensmith, 2013); broadleaved trees lose leaves in the fall, which improves ground heat intake from the winter sun (International Society of Arboriculture, 2020, Nowak et al., 2013, Spengler and Ellis, 2019). Despite diverse attractions for tree plantation, considerations related to the increase of tree numbers on campus still should be balanced with other business interests (Table 5).

The limited availability of urban greenspace resources for carbon offsetting also highlights the importance and necessity of using diverse nature-based approaches (Edmondson et al., 2014, Lal and Augustin, 2011). For instance, biochar (the product of organic biomass combusted in a no or limited oxygen pyrolysis environment), as a soil amendment, potentially enhances carbon especially when using cuttings from the maintenance of urban trees or dead woods (Lal and Augustin, 2011). Furthermore, opportunities for managing soil inorganic carbon should be emphasized, as soil inorganic carbon is 24–30% of soil total carbon according to the present study. Urban brownfield land, where areas have previously been used for industrial or commercial activity and become vegetated after demolition (albeit temporarily), with or without a specific design, can promote the soil's inorganic C sink. Following the observed accumulation of 23 tonnes$\cdot$ha$^{-1}\cdot$yr^{-1} inorganic carbon at a demolition site (Washbourne et al., 2015), an accumulation of topsoil inorganic carbon of 16 tonnes$\cdot$ha$^{-1}\cdot$yr^{-1} has been reported across 20 brownfield sites in northern England, largely because of calcite precipitation, which emphasizes the importance of soil carbonation to remove CO_2 (Jorat et al., 2020). The limits to what can be achieved with nature-based carbon off-setting in urban greenspace also emphasizes the need to substantially reduce emissions when building a green city, such as switching to renewable energy systems, popularizing low carbon transport infrastructures (Newcastle City Council, 2020), deploying eco-homes (Pickerill, 2017), eco-driving and eco-charging (Ortega-Cabezas et al., 2021).

5 Conclusions

Our study comes at a time when many institutions are setting ambitious targets for achieving net zero carbon. In northeast England, Newcastle University has worked together with Newcastle City Council to build the "city community forest", and university carbon managers look forward to introducing more trees on campus. This research quantified the current soil and tree carbon storage of urban greenspace on Newcastle University's city campus as a function of land-cover classifications and tree species selection to evaluate the potential of this greenspace for carbon abatement. Based on our analysis, total carbon in urban woodland soils > carbon for urban lawn soils with free-standing trees > carbon for sports grounds in suburban areas. From 490 urban trees, the eight most common tree species were divided into different tree age classifications for assessing their carbon storage potential. As a result, for tree carbon storage per m^2 of tree cover, Ash ranked the first; while Swedish Whitebeam was the best tree type in terms of carbon stock per individual tree from each species. Overall, Newcastle University could offset no more than 1.13% of its emissions at current rates by afforestation of its entire urban campus greenspace. Choosing the carbon value from our study to be a representative of the urban ecosystem to predict the carbon stock more widely in Newcastle City, no more than 0.95% of annual carbon emissions of the city council at current rates could be offset by afforestation of its urban greenspace. This limited off-setting potential is caused by the small amount of available urban greenspace. Consequently, city institutions should first reduce their carbon emissions as much as possible before considering carbon offsetting strategies. For the hard-to-abate emissions, afforestation of urban greenspace in cities can bring many ecological and social benefits in addition to carbon offsetting, while woodland planting or peatland restoration in climate partnerships with rural councils could help city institutions achieve their net-zero carbon aims.

Declarations

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Figures

Figure 1

The location of the study areas. **a)** the location of Newcastle upon Tyne in the UK; **b)** study area locations in Newcastle upon Tyne**; c)** the area of the Heaton Sports Ground managed by Newcastle University; **d)** the central campus of Newcastle University.

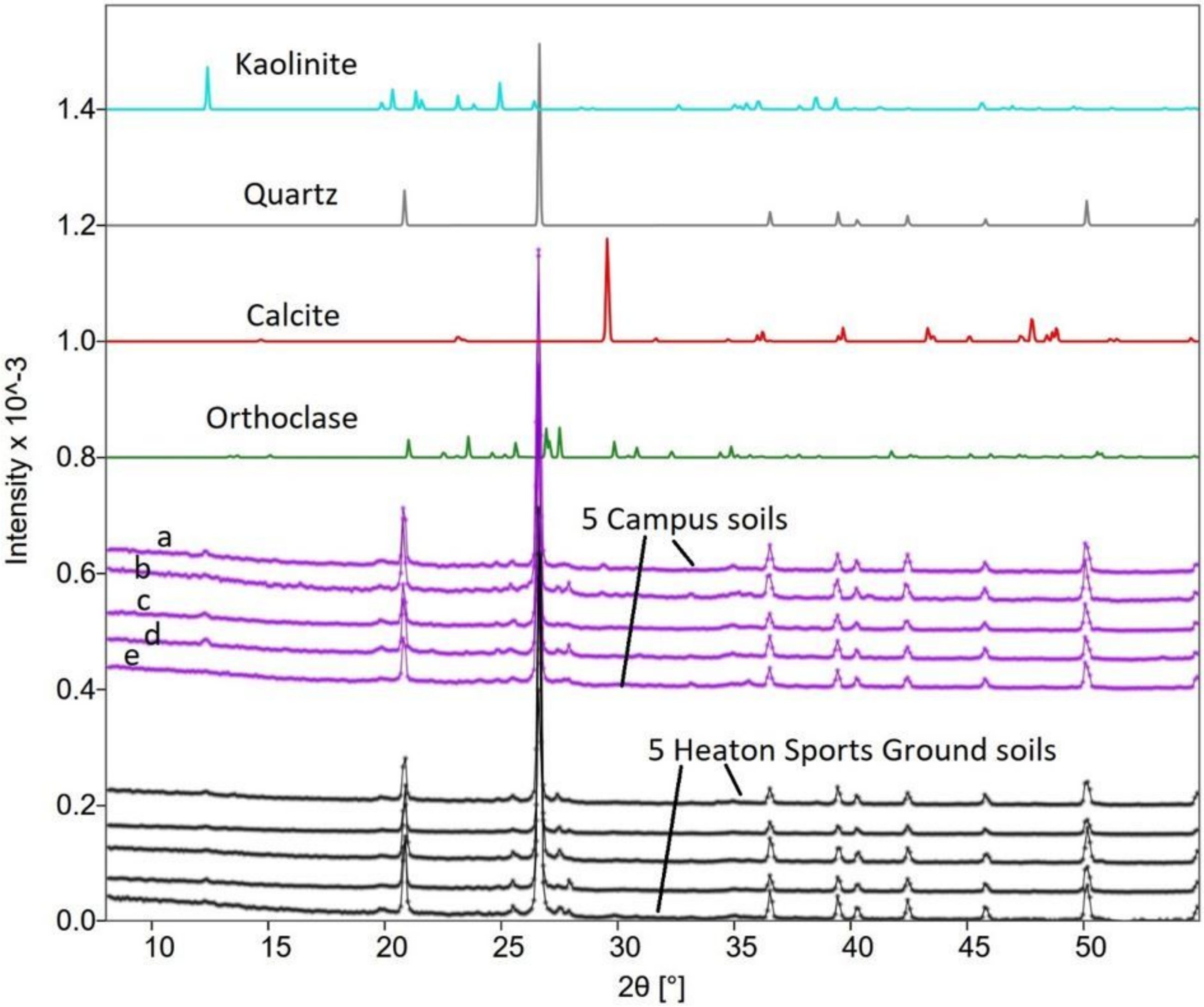

Figure 2

X-ray diffraction patterns of 10 selected soil samples. The top 4 spectra are XRD patterns of reference minerals (CrystalDiffract®, CrystalMaker Software Ltd, Oxford, England; http://crystalmaker.com/). The 5 purple XRD patterns show the soils collected in the urban campus of Newcastle University: a&b from the woodland; c&d&e from the lawned areas with free-standing trees. The 5 black patterns at the bottom are the results of soils from Heaton Sports Ground

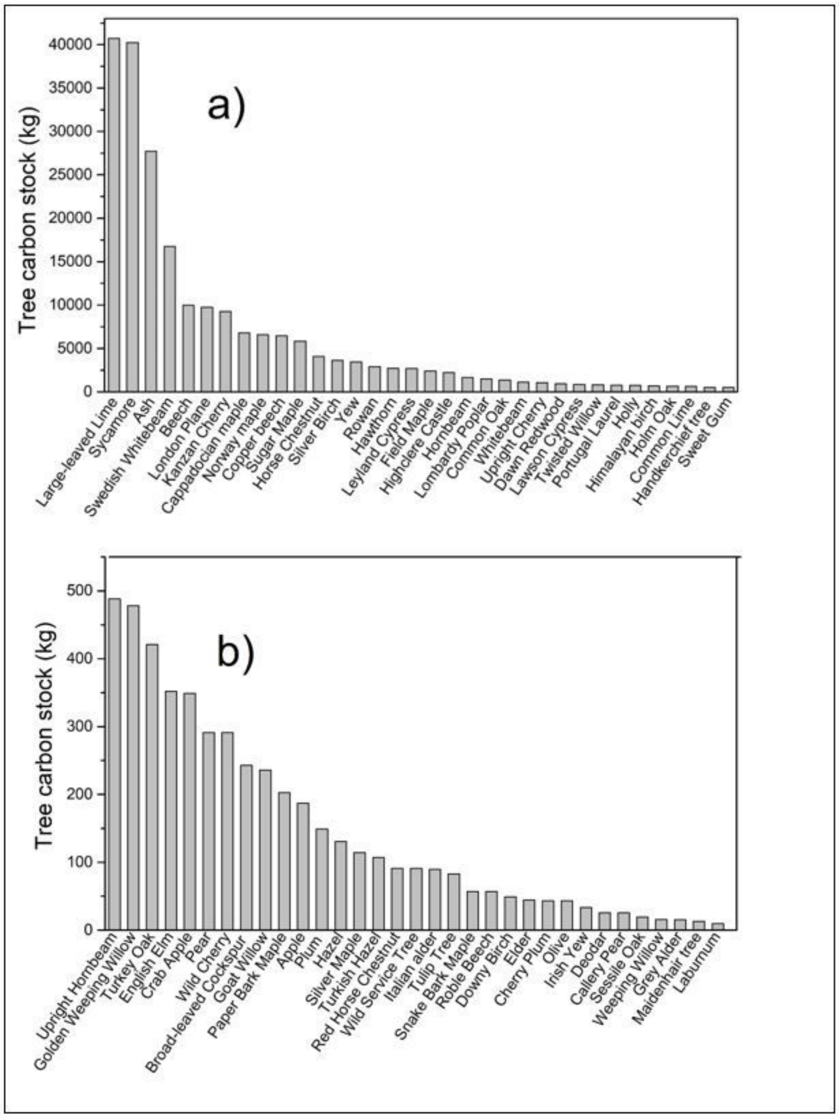

Figure 3

Total carbon stock (kg) of all trees from each tree species on the campus of Newcastle University calculated by allometric biomass equations (overall 67 tree species). **a):** the tree species with the total carbon stock≥ 500 kg; **b):** the tree species with the total carbon stock ≤500 kg

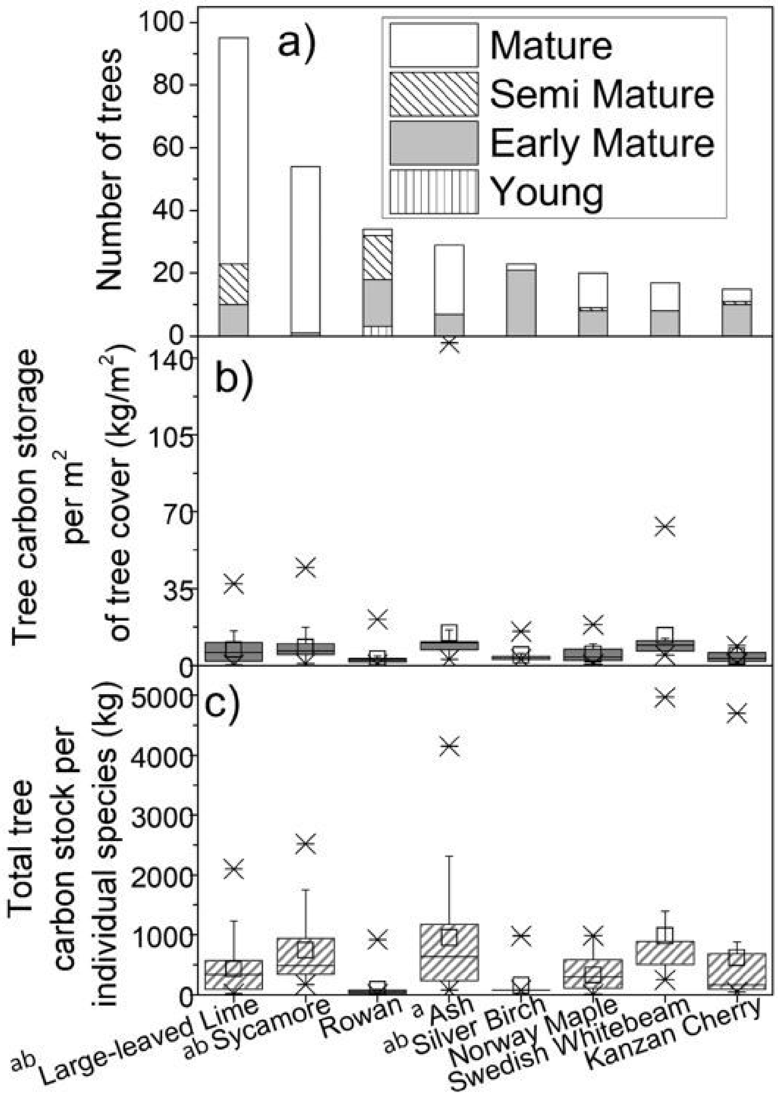

Figure 4

a) The distribution of life stage per tree species among the eight species which occur most frequently on the campus of Newcastle University; **b**) the average carbon storage per m^2 of tree cover; **c)** the carbon stock per individual tree

[a]: tree carbon stock from an individual tree of this species is significantly impacted by the tree age; [b]: tree carbon storage of this species is significantly impacted by the tree age.

Supplementary Files

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