What *is* "like for like"?

An assessment of tree replacement rates needed to maintain carbon sequestration parity within the city of Leeds

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Executive summary

Leeds City Council (LCC) have committed to plant 5.8 million trees over the next 25 years as part of the city's contribution to the UK net-zero targets (LCC, 2020). To ensure that the intended emissions reductions are achieved, in addition to planting more trees, the current level of carbon sequestration from the city's existing urban forest needs to be retained.

The LCC *Natural Resources and Waste Local Plan* (LCC, 2013) set out strategies for the management of local resources and waste within the city. The plan called for increased protection of trees affected by development activity. The plan set a requirement for three trees to be planted for every tree felled (LCC, 2013). This replacement policy does not account for the differences between trees, such as size, species and condition, and lacks the flexibility to address variations in carbon sequestration potential.

This report provides a method for estimating the number of trees that are required to replace a tree of a given condition, species and size, in order to achieve parity in carbon sequestration. This specific focus on carbon sequestration formed the brief for this research, however climate change mitigation is just one of the many environmental benefits provided by the urban forest (Nowak and Dwyer, 2007).

In this study, field data for 1,045 trees were used as a representative sample of the trees in Leeds. A mathematical model was used to estimate the rate of carbon sequestration for each tree as determined by species, condition, and size. This was compared with the rate of sequestration expected from typical replacements, at the point of planting, to estimate the number of replacements required to compensate for any removal.

Depending on the condition, species, and stature of the tree to be replaced, we found that calculated replacement rates were highly variable and could be more than 38:1 in the case of some very large trees, with the LCC 3:1 rate only applicable for replacing the smallest trees.

Based on this work we make six recommendations, summarised below:

1. The current policy of a 3:1 replacement rate should be amended. Trees should be replaced on a rate defined by the size, condition, and species (referring to Table 1) of the tree to be felled as described in this report.
2. Trees with large diameters are particularly valuable, delivering a range of environmental benefits on a large scale. These should have an assumption of retention applied unless there is a substantial case for

removal. LCC may wish to specify a bespoke number of trees on a case-by-case basis. Alternatively, further research could be commissioned for a focused study on trees of these greater DBH values.

3. Using this system of classification, there may be an incentive for developers to underestimate both tree health and tree size. We recommend that LCC adopt a risk-based approach, to independently audit a number of surveys every year.
4. The replacement rates here assume that replacement trees (conforming to British Standard 8545:2014) will remain healthy and continue to grow. We suggest that LCC should add provision in the framework for tree inspections up to 5 years after planting to ensure that replacement trees are properly established and have the ability to reach maturity.
5. In the event of a mixture of tree statures being planted to replace the removed tree, the smallest category of tree used will determine the replacement rate.
6. This study is bespoke to the specific brief of considering carbon sequestration of the trees. We recommend that the metric presented is considered in the wider context of the environmental benefits provided by the urban forest.

Contents

Introduction

In 2018, the Intergovernmental Panel on Climate Change highlighted the importance of limiting global temperature rise to 1.5°C above pre-industrial levels to avoid some of the most severe impacts of climate change (IPCC, 2018). As well as a rapid and substantial reduction in carbon emissions associated with global activities, we can look to urban forests to help us limit rising levels of carbon dioxide in the atmosphere. Trees provide a range of intrinsic benefits to people, often referred to as ecosystem services (Millenium Ecosystem Assessment, 2005). Sequestering and storing carbon is just one of the ecosystem services trees provide. There are many other environmental benefits, such as the removal of air pollution and benefits for both human physical and mental health (Nowak and Dwyer, 2007).

The Committee on Climate Change advise in their net-zero report (CCC, 2019) that the UK needs to plant a minimum of 30,000 hectares of woodland annually to achieve net-zero greenhouse gas emissions by the year 2050. If Leeds contributes to this target in line with its share of national greenhouse gas emissions, the planting would be equivalent to doubling the current tree canopy cover from 17.1% to approximately 33% (United Bank of Carbon, 2019).

In July 2020, Leeds City Council (LCC) launched their initiative to plant 5.8 million trees over the next 25 years to contribute to these targets (LCC, 2020). If plans to boost canopy cover are to be successful in contributing to carbon neutrality in the city, they must also seek to protect existing trees and avoid reducing the current rate of carbon sequestration (LCC, 2020).

In 2013, Leeds City Council adopted the Natural Resources and Waste Local Plan, which set out strategies and aims for the management of natural resources and waste up to the year 2026 (LCC, 2013). The document identified the need to use natural resources efficiently, and to protect and enhance the natural environment. In particular, the plan recognised the need for additional measures to protect trees within the framework for planning and development activity and said that 'where removal of existing trees is agreed in order to facilitate approved development, suitable tree replacement should be provided on a minimum *three for one replacement to loss*' (LCC, 2013 p.64 emphasis added).

A recent i-Tree Eco survey carried out by the University of Leeds (UoL) and the United Bank of Carbon (UBoC) demonstrated the importance of protecting and maintaining existing trees to support the delivery of climate change mitigation (Gugan et al., 2019). One of the findings of the study was that of 1,450 trees, the top 100 trees [for the delivery of environmental benefits] were delivering over one third of the total carbon storage and sequestration (attributed to the large size and good condition of those trees).

The study demonstrates that larger trees which are well established can be proportionally more valuable than a greater number of smaller trees in the same location.

There is a large variation in the methods and criteria used to devise tree replacement policies elsewhere in the world. These range from the simple 3:1 replacement rate currently in use in Leeds, to variable rates used by the City of Vienna (2:1 to 21:1; Schwitzer and Bonduel, 2016) and the Council of Tree and Landscape Appraisers (CTLA) method (1:1 to 59:1; CTLA, 2000).

In line with the net-zero commitments of the city, in this report we attempt to inform an updated tree replacement policy for LCC which ensures zero net loss of carbon sequestration in the city attributed to the required felling of trees in planned development works. Our analysis utilises the best available local estimates for rates of carbon sequestration of urban trees outside of woodlands, within the Leeds area, and uses this data to calculate tree replacement rates based on tree condition, size, and species in a new Leeds4Trees method, to provide a scientific underpinning for a revised LCC replacement rate policy.

Research question
How many replacement trees should be planted to compensate for the loss of carbon sequestration incurred when an existing tree is felled in the city of Leeds?

Method

Overview

In brief, the study compares the estimated rates of carbon sequestration of a sample of trees in Leeds, to that which would be expected for replacement trees. This allows the calculation of estimates of the number of trees which would need to be planted in order to compensate for the carbon sequestration capacity lost by the removal of existing trees.

Data collection

Over the summers of 2017 and 2018, a full inventory of the trees on the University of Leeds (UoL) campus was carried out by a core team of trained staff, along with volunteer staff and students. i-Tree Eco v6 (i-Tree Eco, 2020) was used to analyse the field data and to assess the delivery of ecosystem services (Gugan et al., 2019). i-Tree Eco is a peer reviewed software designed to analyse the functional and structural services provided by trees in urban areas, based on a range of measurements (Nowak et al. 2008). In collecting data for the analysis, information for 1,450 trees on campus was collected, including:

- Species
- DBH ("diameter at breast height" tree diameter in cm, measured at 1.3 m from ground)
- Total tree height (m)
- Live height of the tree (m)
- Height of canopy base (m)
- Canopy width (m), east to west and north to south
- Tree condition (expressed as a percentage: 0% being dead and 100% being excellent health)
- Percentage crown missing (%)
- Crown light exposure (number of sides of the tree (0-5) receiving sunlight from above)

Data analysis

The data from the UoL campus survey was first sorted into three stature groups (1, 2, and 3) based on the typical size at maturity of a healthy example of the species as defined by Hand et al. (2019a, 2019b) described in Table 1.

Table 1. Definition of species stature grouping. Note that these definitions refer to the species stature and not that of an individual tree.

Group	Definition as used by Hand et al. (2019a, 2019b).	Number of UoL sample trees in group
Group 1- small stature species	"A species in which a healthy, isolated 20-year-old specimen growing in good soil conditions typically attains a height of less than 6 m (Stokes et al., 2005; RHS, 2016)" - Hand et al. (2019a)	112
Group 2- medium stature species	"A species in which a healthy, isolated 20-year-old specimen growing in good soil conditions typically attains a height of between 6 and 12 m (Stokes et al., 2005; RHS, 2016)" - Hand et al. (2019a)	262
Group 3- large stature species	"A species for which a healthy, isolated 20-year-old specimen growing in good soil conditions is typically over 12 m high (Stokes et al., 2005)" - Hand et al. (2019b)	671
Not categorised	Species not referred to by Hand et al. (2019a, 2019b) or disqualified as being in very poor health, or coppiced etc.	405

Tree species identified during the University of Leeds campus survey were allocated to groups 1 to 3 based on species as described in Table 2 below.

Table 2. A list of species and stature group.

Common name	Scientific name	Group (stature)
Apple spp.	*Malus spp.*	Group 1 (small stature species)
Plum spp.	*Prunus spp.*	Group 1 (small stature species)
Hawthorn	*Crataegus monogyna*	Group 1 (small stature species)
Holly	*Ilex aquifolium*	Group 1 (small stature species)
Elder	*Sambucus nigra*	Group 1 (small stature species)
Bird cherry	*Prunus padus*	Group 1 (small stature species)
Common hazel	*Corylus avellana*	Group 1 (small stature species)
Goat willow	*Salix caprea*	Group 1 (small stature species)
Callery pear	*Pyrus calleryana*	Group 2 (medium stature species)
Yew	*Taxus baccata*	Group 2 (medium stature species)
Common alder	*Alnus glutinosa*	Group 2 (medium stature species)

Common name	Scientific name	Group (stature)
Common hornbeam	*Carpinus betulus*	Group 2 (medium stature species)
Field maple	*Acer campestre*	Group 2 (medium stature species)
Lawson's cypress	*Chamaecyparis lawsoniana*	Group 2 (medium stature species)
Rowan	*Sorbus aucuparia*	Group 2 (medium stature species)
Silver birch	*Betula pendula*	Group 2 (medium stature species)
Wild cherry	*Prunus avium*	Group 2 (medium stature species)
Common ash	*Fraxinus excelsior*	Group 3 (large stature species)
Sycamore	*Acer pseudoplatanus*	Group 3 (large stature species)
Leyland cypress	*X Cupressocyparis leylandii*	Group 3 (large stature species)
London plane	*Platanus x hispanica*	Group 3 (large stature species)
Common beech	*Fagus sylvatica*	Group 3 (large stature species)
Scots pine	*Pinus sylvestris*	Group 3 (large stature species)
Norway maple	*Acer platanoides*	Group 3 (large stature species)
Elm spp.	*Ulmus spp.*	Group 3 (large stature species)
Oak spp.	*Quercus spp.*	Group 3 (large stature species)
Lime spp.	*Tilia spp.*	Group 3 (large stature species)

Modelling

For each group of trees, a mathematical model was developed to identify the maximum and minimum boundaries of the relationship between tree diameter and the i-Tree predicted annual rate of carbon sequestration (see Appendix 1, Figures a1-a3 for more details). These boundaries were then used to generate curves (where the middle is the mean of the middle of the boundary lines) to predict the rate of sequestration of trees of different size (DBH) and condition (categories A, B and C as defined in British Standard 5837:2012 *Trees in Relation to Design, Demolition and Construction [BSI, 2012]* shown in Figure 1 and Table 3 (Please note Figure 1 is for group 3 only, the equivalent graph for group 1 and group 2 can be found in appendices a4 and a5)).

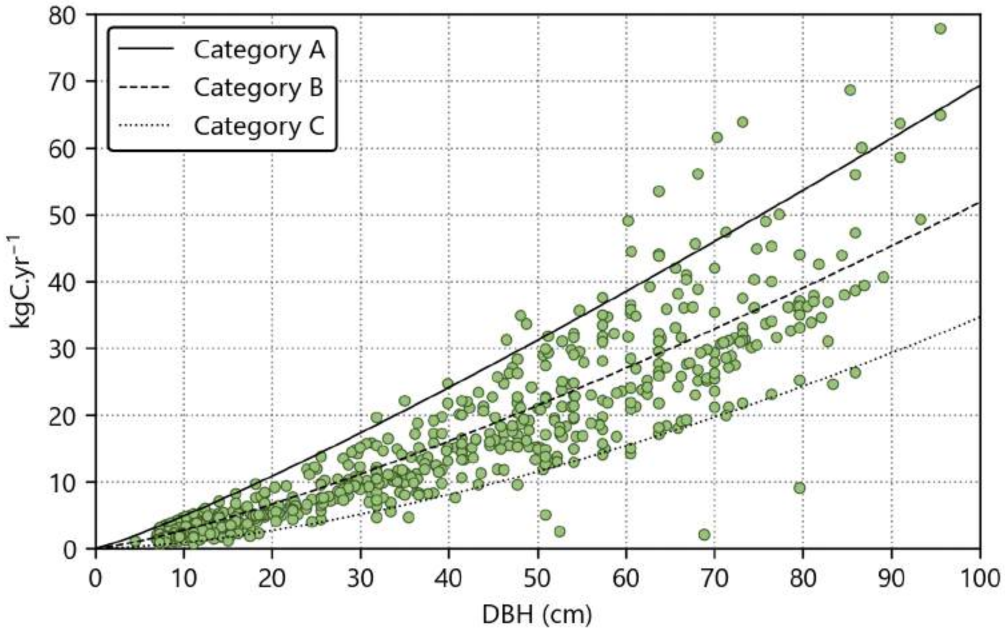

Figure 1. All group 3 (large) tree species from the UoL campus, showing fitted curves of annual carbon sequestration for trees of BS Categories A, B and C.

Table 3. Tree condition definitions.

Category	Definition according to BS 5837: 2012
A (upper line in Figure 1)	"Trees of high quality with an estimated remaining life expectancy of at least 40 years. Trees that are particularly good examples of their species, especially if rare or unusual; or those that are essential components of groups or formal or semi-formal arboricultural features (e.g. the dominant and/or principal trees within an avenue)."
B (mean line in Figure 1)	"Trees of moderate quality with an estimated remaining life expectancy of at least 20 years. Trees that might be included in category A, but are downgraded because of impaired condition (e.g. presence of significant though remediable defects, including unsympathetic past management and storm damage), such that they are unlikely to be suitable for retention for beyond 40 years; or trees lacking the special quality necessary to merit the category A designation."
C (lower line in Figure 1)	"Trees of low quality with an estimated remaining life expectancy of at least 10 years, or young trees with a stem diameter below 150 mm. Unremarkable trees of very limited merit or such impaired condition that they do not qualify in higher categories."

The generated curves were then checked against UoL inventory data. By carrying out site visits we were able to check the current conditions of sample trees in each category and compare our observations to the condition defined by the curves. This enabled us to ensure that the trees did indeed represent a good fit with the condition categories.

Very few mature trees are present in the UoL inventory, therefore, our calculated values become less certain at diameters of >50 cm in the case of group 1 species, >60 cm in group 2 species and >100 cm in group 3 species. This can in part be attributed to the limited size of our sample, and the rarity of trees in urban forests reaching these larger sizes.

Reference replacement trees

From the sample trees in each of the three stature groups, a subset of 'young' trees, defined by Hand et al. (2019a, 2019b: all trees <8 cm DBH in group 1, and all trees <15 cm DBH in groups 2 and 3), were used to calculate mean carbon sequestration rates of young trees within each group. These results are shown in Table 4 below. Due to minimum size requirements of trees analysed in i-Tree Eco, the UoL sample was already restricted to trees with a DBH greater than 7 cm. Therefore, our subset includes trees of between 7 and 15 cm DBH for groups 2 and 3, and between 7 and 8 cm DBH for group 1. i-Tree Eco analysis demonstrates that carbon sequestration rates for young trees are largely similar across these DBH ranges (see Figure 1 and Appendices a4-a6). In this method, the subset of young trees serves as a proxy for typical replacement trees.

Table 4. Annual mean rate of carbon sequestration of young trees grouped by expected stature at maturity (to the nearest kg).

	Annual rate of carbon sequestration (kgC yr $^{-1}$)
Small stature young trees (Group 1)	1
Medium stature young trees (Group 2)	3
Large stature young trees (Group 3)	3

Replacement rates

Replacement rates were calculated by dividing the annual carbon sequestration rate of a tree of known size by the sequestration rate of a young replacement tree (as shown in Table 4 above). This exercise was carried out for a matrix of different replacements (shown in Table 5) to account for the replacement of existing trees of varying size and condition with trees belonging to different stature groups. All the results were rounded up to the nearest whole number of trees and defined based on DBH increments of 10cm as shown in Figure 2.

Table 5. Matrix of tree replacement options.

Group	Replaced with trees from		
Group 1 (small stature species)	Group 1 (small stature species)	Group 2 (medium stature species)	Group 3 (large stature species)
Group 2 (medium stature species)	Group 1 (small stature species)	Group 2 (medium stature species)	Group 3 (large stature species)
Group 3 (large stature species)	Group 1 (small stature species)	Group 2 (medium stature species)	Group 3 (large stature species)

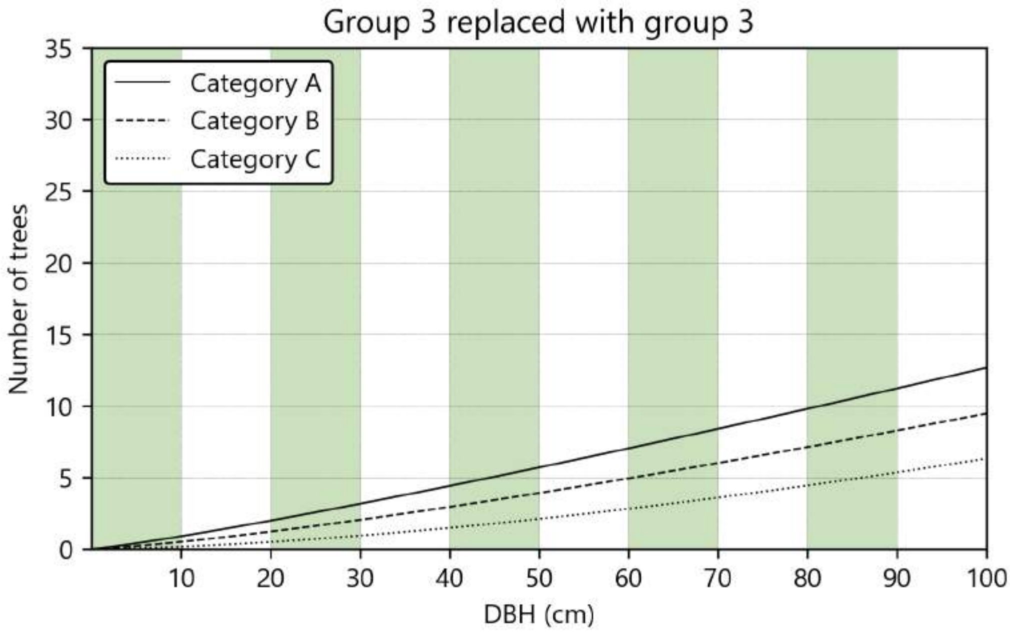

Figure 2. An example of calculated replacement rates of a tree in group 3, replaced by young trees in the same group.

As model uncertainty increases (due to the nature of the trees available in our dataset) when DBH is above the thresholds shown in Table 6, we have set the replacement rates to constant, which represents a minimum number of replacements based on the rate for the next increment (i.e., 60 cm, 70 cm, and 110 cm; see tables 7, 8 and 9). It is important to note that these levels, while high, do not represent the full value of very large trees (Gugan et al., 2019) and these trees should be treated with special care (which we have included in our recommendations).

Table 6. Model uncertainty points for stature groups.

Group (stature)	Threshold of uncertainty (DBH in cm)
Group 1 (small stature species)	50
Group 2 (medium stature species)	60
Group 3 (large stature species)	100

Results and discussion

Tree replacement rates

Our calculated replacement rates are described in Tables 7 – 9. Replacement rates vary from one single tree (i.e., when a group 3 tree of smallest DBH category is replaced with a group 3 tree) to >38 (i.e., when a group 3 tree of >100 cm DBH is replaced with group 1 trees). Greater numbers of replacement trees are required where the tree to be felled is of good condition, larger DBH and the chosen replacement trees are from a smaller stature group. Trees in poorer condition require fewer replacement trees, as this factor limits the tree's ability to sequester carbon to the degree that a healthier tree might.

Table 7. Replacement rates for trees in different stature groups based on their current DBH (stem diameter at 1.3 m) and condition category (from Table 3).

Group 1 (small stature species) replaced with:	Diameter of tree to be removed (cm)				
	<20	20 - 29.9	30 - 39.9	40 - 49.9	50+
Group 1 (small stature species) replacement rates (number of trees)	5	8	11	16	>20
	4	6	9	13	>16
	3	5	7	10	>13
Group 2 (medium stature species) replacement rates (number of trees)	2	4	5	7	>9
	2	3	4	6	>8
	1	2	3	5	>6
Group 3 (large stature species) replacement rates (number of trees)	2	3	5	6	>8
	2	3	4	5	>6
	1	2	3	4	>5

Legend
Category A
Category B
Category C

Table 8. Replacement rates for trees in different groups based on their current DBH (stem diameter at 1.3 m) and condition category (from Table 3).

Group 2 (medium stature species) replaced with:	Diameter of tree to be removed (cm)					
	<20	20 - 29.9	30 - 39.9	40 - 49.9	50 - 59.9	60+
Group 1 (small stature species) replacement rates (number of trees)	5	9	13	17	22	>27
	4	7	11	14	19	>23
	3	5	8	11	15	>20
Group 2 (medium stature species) replacement rates (number of trees)	3	4	6	8	10	>13
	2	3	5	7	9	>11
	2	3	4	5	7	>9
Group 3 (large stature species) replacement rates (number of trees)	2	4	5	7	9	>10
	2	3	4	6	7	>9
	1	2	3	5	6	>8

Legend
Category A
Category B
Category C

Table 9. Replacement rates for trees in different groups based on their current DBH (stem diameter at 1.3 m) and condition category (from Table 3).

Group 3 (large stature species) replaced with:	Diameter of tree to be removed (cm)									
	<20	20 - 29.9	30 - 39.9	40 - 49.9	50 - 59.9	60 - 69.9	70 - 79.9	80 - 89.9	90 - 99.9	100+
Group 1 (small stature species) replacement rates (number of trees)	6	9	12	16	19	23	27	31	34	>38
	4	6	8	11	14	17	20	23	26	>29
	2	3	4	6	8	10	12	15	17	>20
Group 2 (medium stature species) replacement rates (number of trees)	3	4	6	7	9	11	12	14	16	>18
	2	3	4	5	7	8	9	11	12	>14
	1	2	2	3	4	5	6	7	8	>9
Group 3 (large stature species) replacement rates (number of trees)	2	4	5	6	8	9	10	12	13	>15
	2	3	3	4	5	7	8	9	10	>11
	1	1	2	3	3	4	5	6	7	>8

Legend
Category A
Category B
Category C

Differences between existing tree replacement policies and the methods they use for deciding tree replacement rates contributes to a large variation in tree replacement numbers across policies, ranging from a simple 3:1 replacement rate currently used by LCC, to variable rates calculated using the CTLA method which can reach 59:1 (CTLA, 2000) as shown in Table 10.

Table 10. Comparison of existing replacement rate policies with newly calculated values using the method described above.

Replacement Method	Diameter of tree to be removed (cm)									
	< 20	20 - 29.9	30 - 39.9	40 - 49.9	50 - 59.9	60 - 69.9	70 - 79.9	80 - 89.9	90 - 99.9	100 +
LCC current tree replacement policy*	3	3	3	3	3	3	3	3	3	3
Vienna Tree Replacement Act 1974†	2	4	6	8	10	13	15	17	19	21
CTLA Trunk Formula method‡	1	2	5	9	15	21	29	38	48	59
Bristol City Council's tree replacement policy§	1	2	3	4	5	6	7	8	8	8
Condition category (definition in Table 3)	Leeds4Trees method number of trees required as replacements (depending on stature group from Tables 7 - 9 above)									
Category A	2 - 6	3 - 9	5 - 13	6 - 17	8 - 20	9 - 27	10 - 27	12 - 31	13 - 34	15 - 38
Category B	2 - 4	3 - 7	3 - 11	4 - 14	5 - 19	7 - 23	8 - 20	9 - 23	10 - 26	11 - 29
Category C	2 - 3	2 - 5	2 - 8	3 - 11	3 - 15	4 - 20	5 - 12	6 - 15	7 - 17	8 - 20

* Leeds City Council Tree replacement policy (LCC, 2013).
† Vienna Tree Replacement Act (1974) is based on the circumference of the tree divided by 15cm (diameter of the replacement tree). For trees > 40cm circumference measured a 1m above ground. Should be planted within 300m of the original tree (Schweitzer and Bonduel 2016).
‡ CTLA Trunk Formula Method: Council of Tree and Landscape Appraisers method takes the surface area of the tree (in cm) at 1.4m high. Divides it by the surface area of the replacement tree (CTLA, 2000).
§ Bristol City Council tree replacement policy is based on a capitalisation method, where the number of replacements is assigned according to specific aims (increased protection for mature trees) (Bristol City Council, 2012).

Based on this comparison we suggest that while the current 3:1 policy used by LCC is a reasonable estimate of the true sequestration rates in a limited set of circumstances (i.e., when comparing trees of the same species at diameters of < 20 cm) it lacks the flexibility to handle more complex operations. Where species are substituted for one another, or where large trees are felled, the current replacement method is inadequate for recovering the loss of carbon sequestration.

Key points to note

Measurement

There is a discrepancy between the standard scientific / forestry practice of measuring tree DBH at a height of 1.3 m from the ground; the arboricultural practice of measuring DBH at 1.5 m, and the British Standard approach (measured at 1 m). All the trees in the representative sample were measured at 1.3 m, and this diameter was used by i-Tree to calculate the rates of carbon uptake. In practice this means that trees measured at 1.5 m may fall into lower size brackets than if measured at 1.3 m (due to stem taper) while trees measured at 1 m will tend to fall into higher brackets. This will only affect trees on the category boundary but may lead to under-reporting. Where DBH of trees due to be felled have been measured at 1.5 m and trees are found to be near the boundary of the two size brackets, the higher bracket should be used for calculating the replacement rate.

A detailed method for measuring trees is available in *Forest Mensuration: A Handbook for Practitioners* (Forestry Commission, 2006) which provides standard approaches to measuring trees with forked stems, epicormic growths, on slopes etc.

Stored carbon vs. rate of uptake

It is important to note that the method presented here estimates replacement values based on the rate of carbon sequestration. It does not account for the loss of stored carbon that takes place when mature trees are felled. Essentially an assumption has been made that any felled trees will be used for products which will not decompose, to release carbon, for some time. LCC should consider options for the use of the felled tree, such as for materials for park infrastructure including benches, left as deadwood, or for biofuel. We acknowledge that the carbon in the trees will not always be retained through products. Table gives three examples of replacement rates calculated using a stored carbon approach in both the removed tree and the replacement trees. The results in Table 11 highlight that the number of replacement trees increases significantly, to a level which would be extremely difficult to enforce.

Table 11. Indicative tree replacement rates for species in each stature grouping (like with like). The number of trees required to account for embodied carbon lost on felling is much higher than if we only account for loss of sequestration potential.

Group (stature)	Species	DBH (cm)	Total Height (m)	Carbon storage (kg C)	Replacement trees required (based on **carbon storage**)	Leeds4Trees method (based on **carbon sequestration rate**)
Group 1 (small stature species)	Holly	45	14	498	**63**	**21**
Group 2 (medium stature species)	Silver birch	52	22	1026	**57**	**15**
Group 3 (large stature species)	London plane	96	19	3059	**219**	**23**

Further, the method used is unable to account for any carbon expended by the replacement trees at the point of planting and establishment. This means that there is a small delay in achieving carbon sequestration parity. However, as our method is aiming for parity, the replacement trees will soon deliver additional carbon sequestration to compensate.

Replacement trees

We have assumed that felled trees will be replaced with trees in the young category (as defined by Hand et al., (2019a; 2019b). LCC currently aim to plant extra-heavy standards (as per British Standard 3936-1:1992) when replacing trees. The extra heavy standard DBH of 4-5 cm (14-16 cm girth) is below the minimum required by i-Tree Eco software. Therefore, no specimens equivalent to extra heavy standard were available in our sample. However, our analysis has demonstrated the applicability of our replacement ratios to extra heavy standard replacement trees due to the narrow range of carbon sequestration rates in young trees (see Figure 1 and Appendices a4- a6).

Location

The dataset used to train the model was developed specifically for the city of Leeds using a sample from the University of Leeds campus. It is entirely possible to adapt this method for other cities, but variation in climate, topography, geology, air quality, etc. are likely to influence estimated rates of tree growth. This means that (depending on the degree of difference in these variables) other datasets may be required to provide accurate estimates. It should not be assumed that replacement rates would remain constant if transposed to other cities without local data to support the assessment.

Recommendations

1. The current policy of a 3:1 replacement rate should be amended. Trees should be replaced by a number of young trees defined by the size, condition, and species (referring to table 1) of the tree to be felled. These rates are shown in tables 7 - 9 above.
2. Trees with a diameter greater than 50 cm (group 1), 60 cm (group 2), and 100 cm (group 3) are particularly valuable, delivering a range of environmental benefits on a large scale. These trees should have an assumption of retention applied, unless there is a substantial case for removal. LCC may wish to specify a bespoke number of trees on a case-by-case basis. Alternatively, further research could be commissioned for a focused study on trees of these greater DBH values.
3. Tree assessment is not an exact science and variation in categorisation of trees according to condition (and possible variability of the height of the DBH measurement) may lead to variable classification. It should be noted that in using this system there may be an incentive for developers to underestimate both tree health and tree size. We recommend that LCC adopt a risk-based approach, to independently audit a number of surveys every year.
4. The replacement rates here assume that replacement trees will remain healthy and continue to grow. In line with the recommendations of British Standard 8545: 2014, we make the assumption that replacement trees will reach 'independence in the landscape', to maturity and beyond. Newly planted urban trees are frequently vulnerable to drought, vandalism, and poor after-care. We suggest that LCC should add provision in the framework for tree inspections up to 5 years after planting to ensure that replacement trees are properly established.
5. In the event of a mixture of tree statures being planted to replace the removed tree (i.e., planting trees from group 1 and 2 and 3), the smallest category of tree used will determine the replacement rate.
6. This study is bespoke to the specific brief of considering carbon sequestration of the trees. We recommend that the metric presented is considered in the wider context of the environmental benefits provided by the urban forest.

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Appendix 1. Technical supplement

Modelling the relationship between DBH and carbon uptake.

The initial dataset was categorised by stature into three groups (Table 2 in the main report). For each group, Pareto frontiers (see Messac, 2003 for a complete discussion) were calculated using a general-purpose programming language (Python). These were manually amended to remove obvious outliers and prevent tangling. The result of this exercise was a dataset for each stature group showing the maximum and minimum boundaries (as shown in Figures a1 – a3).

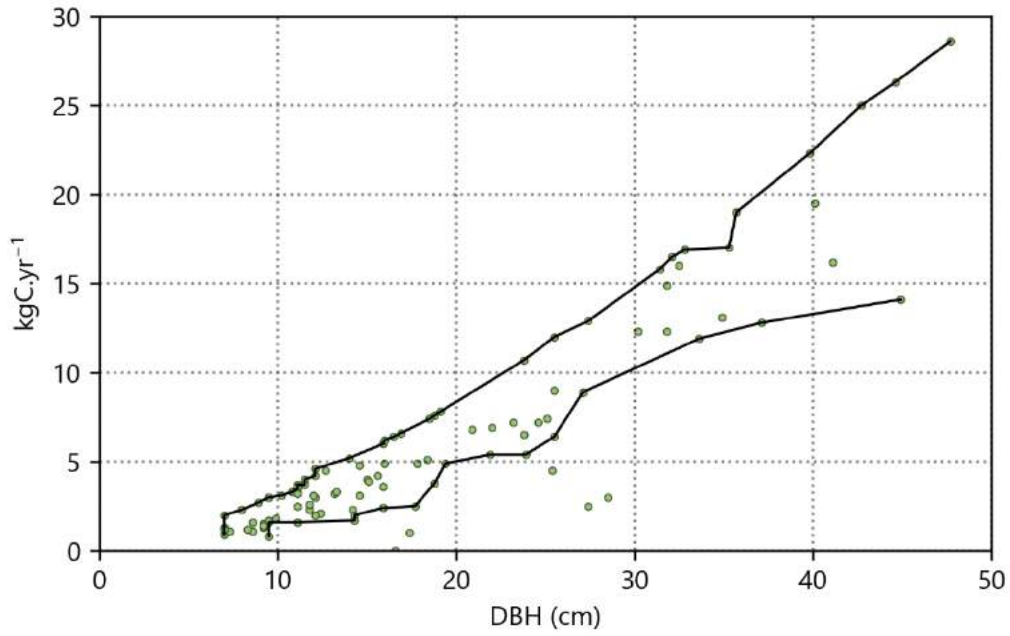

Figure a1. Values for trees in the initial dataset in group 1 (small stature). upper and lower Pareto frontiers are shown in black.

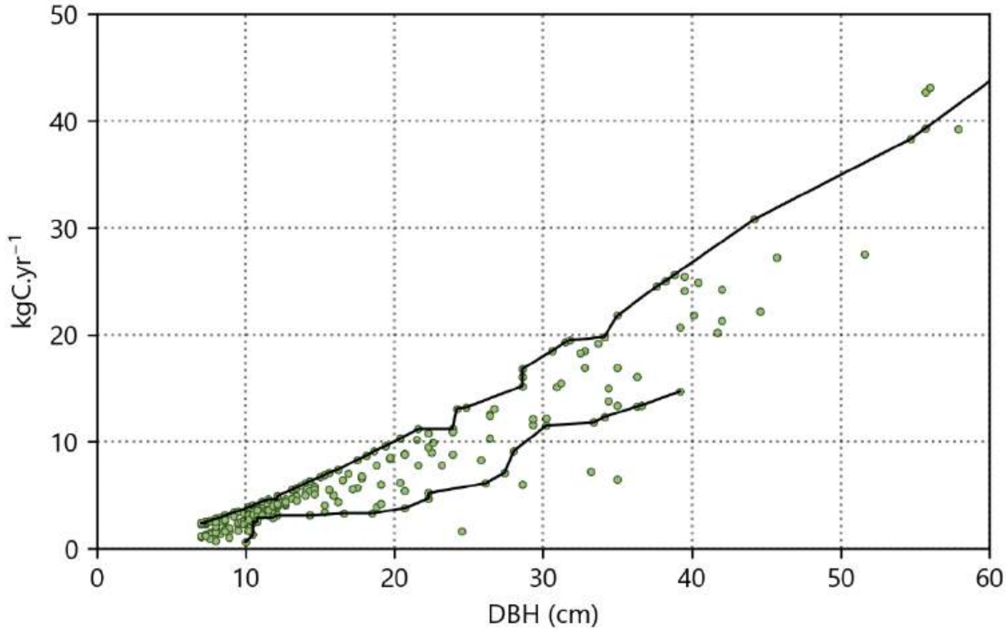

Figure a2. Values for trees in the initial dataset in group 2 (medium stature). upper and lower Pareto frontiers are shown in black.

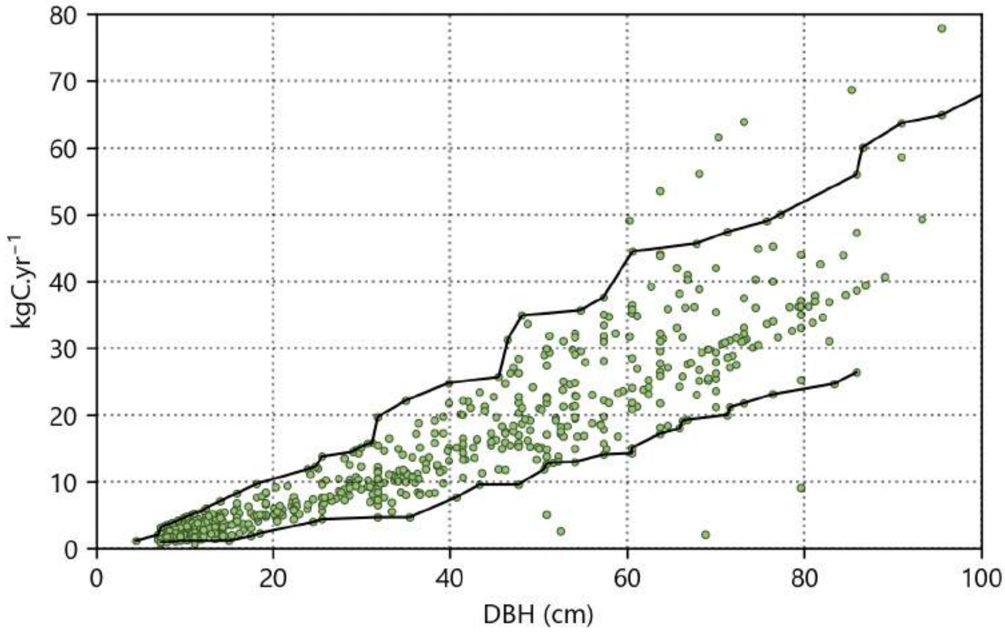

Figure a3. Values for trees in the initial dataset in group 3 (large stature). upper and lower Pareto frontiers are shown in black.

The upper and lower boundaries (and the mean of the two) were then used to fit a power curve (where $y = ax^b$) using a nonlinear least squares regression in the scipy Python library as shown below in figures a4 - a6.

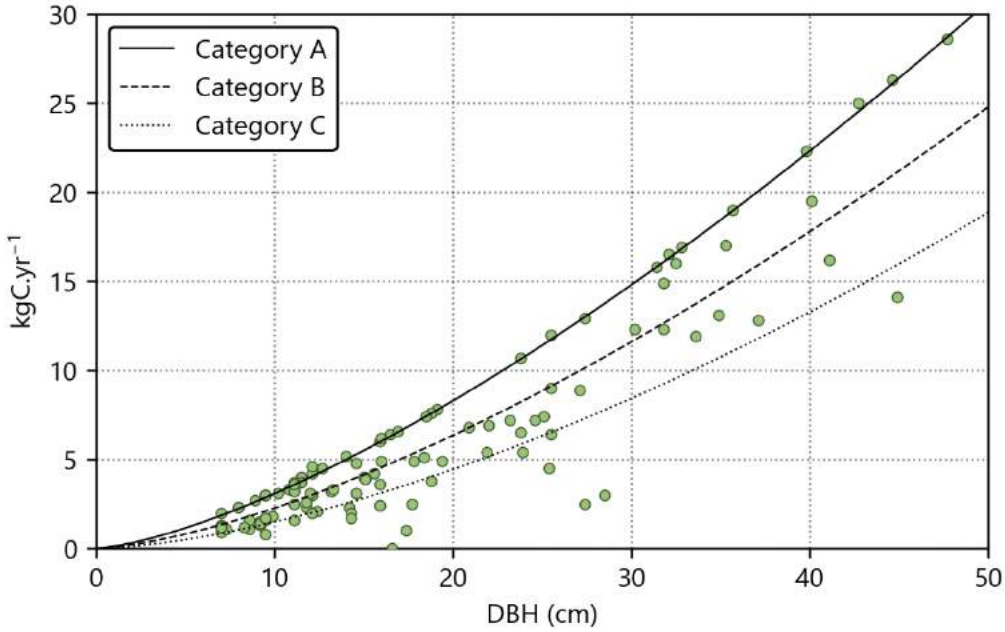

Figure a4. Fitted curves for group 1 species (small stature)

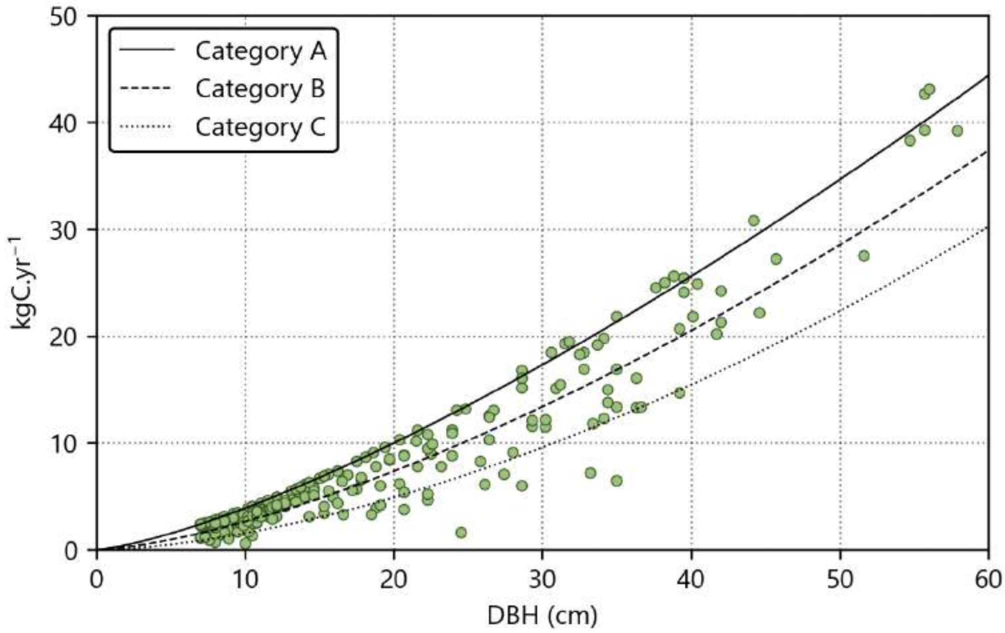

Figure a5. Fitted curves for group 2 species (medium stature)

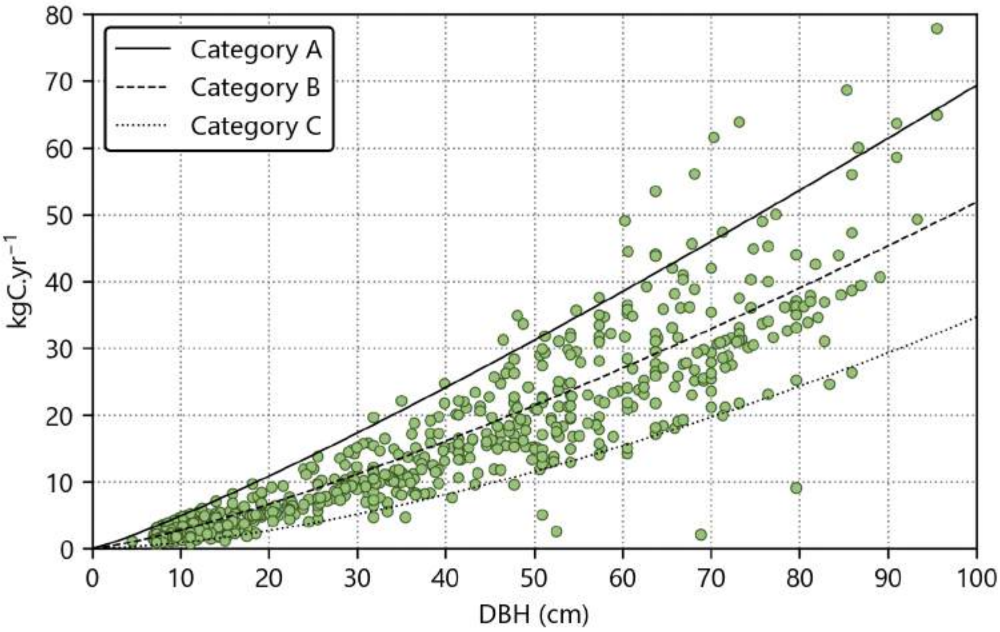

Figure a6. Fitted curves for group 3 species (large stature)

These curves were assessed based on our knowledge of the underlying data, the original tree inventory, and site visits. The curves were found to have a good correlation with trees fitting the British Standard definitions A-C as described in Table 3 in the main report.

For the upper limit of each 10 cm DBH increment (from 20 cm to 100 cm) a value was calculated equal to the rate of carbon uptake (as defined by the curve) divided by the mean rate of uptake for a "young" tree as described above. This resulted in a value describing the number of young trees required to equal the carbon uptake of a tree with a DBH at the point specified. In all cases this value was rounded up to the nearest tree.

Calculating reference tree carbon uptake

Using the fitted curves described above, reference tree carbon uptake was calculated for each stature group as the mean of ($y = ax^b$) where a and b are calculated curve parameters for category B trees and x is a range incorporating DBH values between 7 cm and 8 cm (in the case of group 1 trees) and 15 cm (in the case of trees from groups 2 and 3). For example, in group 2.

Table a7 example calculation of reference tree carbon uptake

DBH (cm)	Rate of carbon uptake (KgC.a-1) based on the function ($y = ax^b$)
7	1.55
8	1.89
9	2.25
10	2.63
11	3.03
12	3.45
13	3.88
14	4.33
15	4.80
Mean	3.09