Sheffield Street Tree Strategy Development Group

Sheffield & Rotherham

i-Tree Eco Stratified Inventory Report

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Treeco2nomics

i-Tree Eco

The Authors

James Watson - Treeconomics

Reviewed By:

Danielle Hill - Treeconomics

This assessment was carried out by Treeconomics

Executive Summary

In this report, the street trees in Sheffield have been assessed based on the benefits that they provide to society. These trees, which form part of Sheffield's natural capital, are generally recognised and appreciated for their amenity, presence and stature in the cityscape and surroundings. However, society is often unaware of the many other benefits (or ecosystem services) that trees provide to those living in our towns and cities.

The trees in and around our urban areas (together with woodlands, shrubs, hedges, open grass, green space and wetland) are collectively known as the 'urban forest'. This urban forest improves our air, protects watercourses, saves energy, and improves economic sustainability[1]. There are also many health and well-being benefits associated with being in close proximity to trees and there is a growing research base to support this[2].

Sheffield's street trees are a crucial part of the city's urban forest, rural areas and woodlands. Many of the benefits that Sheffield's urban forest provides are offered through its street trees.

Economic valuation of the benefits provided by our natural capital[3] (including the urban forest) can help to mitigate for development impacts, inform land use changes and reduce any potential impact through planned intervention to avoid a net loss of natural capital. Such information can be used to help make better management decisions. Yet, as the benefits provided by such natural capital are often poorly understood, they are often undervalued in the decision making process.

In order to produce values for some of the benefits provided by Sheffield's street trees, a state of the art, peer reviewed software system called i-Tree Eco[4] (referred to as 'Eco' throughout the report) was used.

This is a partial analysis as not all trees or ecosystem services were quantified or valued. Therefore the figures presented in this report should be regarded as a conservative estimate.

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1 Doick et al (2016)

2 http://depts.washington.edu/hhwb/

3 Natural capital can be defined as the world's stocks of natural assets which include geology, soil, air, water, trees and all living things

4 i-Tree Eco is i-Tree is a suite of open source, peer-reviewed and continuously improved software tools developed by the USDA Forest Service and collaborators to help urban foresters and planners assess and manage urban tree populations and the benefits they can provide. i-Tree Eco is one of the tools in the i-Tree suite. It is designed to use complete or sample plot inventories from a study area along with other local environmental data to: Characterise the structure of the tree population, Quantify some of the environmental functions it performs in relation to air quality improvement, carbon dioxide reduction, and stormwater control, Assess the value of the annual benefits derived from these functions as well as the estimated worth of each tree as it exists in the landscape.
I-Tree Eco is adaptable to multiple scales from a single tree to area-wide assessments.
For more information see www.itreetools.org

Highlights Include:

- **The street trees in Sheffield remove 3 tonnes of air-borne pollutants each year and store over 12,000 tonnes of carbon.**
- **These trees divert over 10,000 cubic meters of storm water runoff away from the local sewer systems each year. This is worth an estimated £18,039 each year in avoided stormwater treatment costs.**
- **The total replacement cost of all street trees in Sheffield currently stands at £41,156,000.**

Sheffield Street Tree Inventory - Headline Figures		
Total Number of Trees Measured	35,108	
Most Common Species	Sycamore (Acer pseudoplatanus), Common Lime (Tilia x europaea), Ash (Fraxinus excelsior)	
Replacement Cost	£41,156,410.00	
CAVAT Valuation	£340,746,149.00	
Species Recorded	187	
Amounts and Values		
Pollution Removal	3.0 tonnes	£39,198.00
Carbon Storage	12,313 tonnes	£3,025,104
Carbon Sequestration	302 tonnes	£74,246
Avoided Runoff	10,415m³	£18,039
Total Annual Benefits	**£131,483**	

Table 1: Headline figures

Total Number of Trees Measured: Not all records supplied were used in the analysis. For further details see the methodology section below.
Leaf Area: The area of ground covered by leaves when viewed from above (not to be confused with Leaf Area Index (LAI) which is the total surface area of leaves). This is not the total canopy cover for Sheffield as only the inventoried trees are included in the analysis and some tree canopy dimensions were conservatively estimated.
Capital Asset Value for Amenity Trees (CAVAT): A valuation method developed in the UK to express a tree's relative contribution to public amenity and its prominence in the urban landscape.
Replacement Cost: Value based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree) using the Council of Tree and Landscape Appraisers (CTLA) Methodology guidance from the Royal Institute of Chartered Surveyors
Carbon storage: The amount of carbon bound up in the above-ground and below-ground parts of woody vegetation.
Carbon sequestration: The annual removal of carbon dioxide from the air by plants
Carbon storage and carbon sequestration values are calculated based on CO_2e and the DECC figures of £67 per metric ton for 2019.
Pollution removal: This value is calculated based on the UK social damage costs for 'Transport Outer Conurbation' and the US externality prices where UK figures are not available; £0.98 per Kg (carbon monoxide - USEC), £3.96 per kg (ozone - USEC), £13.20 per Kg (nitrogen dioxide - UKSDC), £6.27 per Kg (sulphur dioxide - UKSDC), £250.22 per Kg (particulate matter less than 2.5 microns - UKSDC). Values calculated using an exchange rate of $0.75 = £1.00.
Avoided Runoff: Based on the amount of water held in the tree canopy and re-evaporated after the rainfall event. The value is calculated using Yorkshire Water 2019/2020 volumetric charge of £1.732 per cubic metre. It includes the cost of the avoided energy and associated greenhouse gas emissions in treating the water.

Data processed using i-Tree Eco Version 6.0.16.

Methodology

Sheffield's street tree inventory (which contained 35,274 records) was provided by Amey on behalf of the Sheffield Street Tree Development Group. Amongst the data collected were tree species, diameter at breast height (dbh), tree height, tree condition and tree location.

The minimum data required by Eco is tree species and the dbh. However, the more data that is available for each tree, the more accurate the Eco outputs will be.
166 records had to be removed due to insufficient data for processing.

The Eco software also requires data to be input in a format with values over 0 for all the structural data of each tree. Several estimates had to be inputted based on the information available within the provided street tree inventory.

Of the original 35,274 records, 35,108 were suitable for import and processing. Reasons for removal included no dbh or no species.

The inventory data is processed within Eco using the in-built local pollution and climate data from 2013 and the Church Fenton weather station to provide the following results (listed in Table 2 below). Please refer also to Appendix IV for further details on methodology.

Tree Structure and Composition	Species diversity. DBH size classes. Leaf area. % leaf area by species.
Ecosystem Services	Air pollution removal by urban trees for CO, NO_2, SO_2, O_3 and $PM^{2.5.}$ % of total air pollution removed by trees. Current Carbon storage. Carbon sequestered. Stormwater Attenuation (Avoided Runoff) i-Tree eco also calculates Oxygen production but this service is not valued.
Structural and Functional values	Replacement Cost in £. Carbon storage value in £. Carbon sequestration value in £. Pollution removal value in £. Avoided runoff in £

Table 2: Study Outputs.

For each category, the top ten performing species (based on the trees performance rather than their quantity or size) were used for charts and tables within this report. However, all other figures for the remaining 177 species are available within the Eco files for this project. For a more detailed description of the model calculations see Appendix IV.

Tree Characteristics

Tree Species

Sheffield's street tree inventory has a relatively high diversity of species (187). The most common tree species, with 10.8% of the 35,108 trees in the inventory are Sycamore (*Acer pseudoplatanus*). The second, third and fourth most common trees are respectively: Common Lime (*Tilia x europaea* - 8.7%), Ash (*Fraxinus excelsior* - 7.0%) and Apple (*Malus* - 4.5%). Appendix II contains a full list of species included in the inventory.

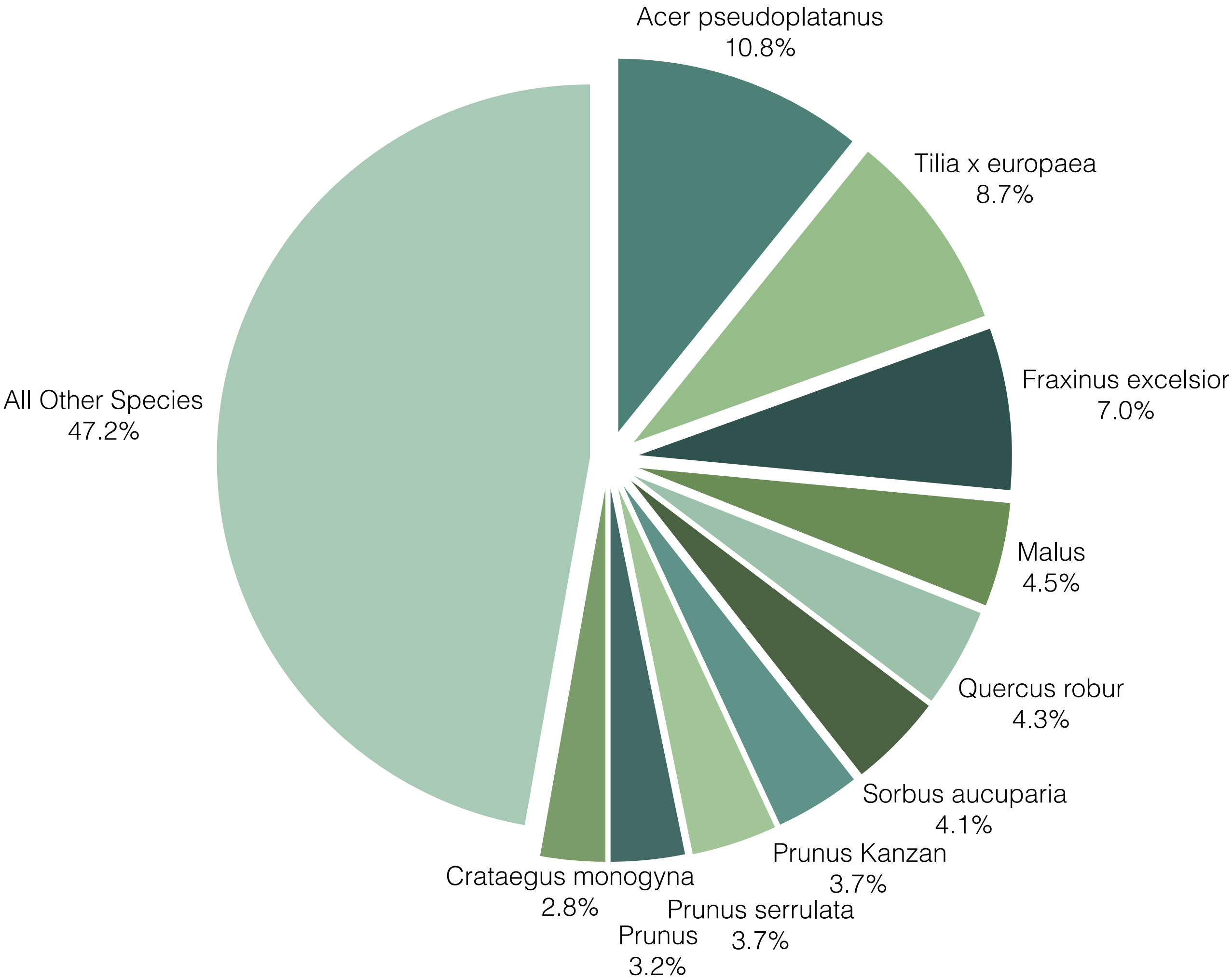

Figure 1: Percentage Population of Tree Species

Tree Diversity

Tree diversity is an important aspect of the tree population to take into account. Tree diversity increases overall resilience in the face of various environmental stress-inducing factors. Diversity includes both the individual diversity within a tree species (i.e. genetic diversity) and between different tree species in terms of different genera or families (e.g. Acer (maple family); Fraxinus (Ash family)).

Tree species which originate from more distant regions to each other may be more genetically dissimilar and their presence may therefore increase resilience to environmental perturbations. A more diverse tree-scape is better able to deal with possible changes in climate or potential pest and disease impacts. This is because with more diverse tree populations, the likelihood that they all will be vulnerable to a particular threat is lower and therefore a smaller proportion will be detrimentally affected. The tree population within Sheffield's street tree inventory represents a rich community of trees given the area, with 187 species identified. However, some of the inventory records provided are at the genus level only, indicating that species richness may actually be greater than the 187 species provided.

Tree species from 4 continents are represented in Sheffield's street tree inventory. Most of the species are native to Europe and Asia (see Figure 2 below). However, further work would be required to assess the condition, size and populations of these trees and to provide recommendations on the best species to choose for any future plantings.

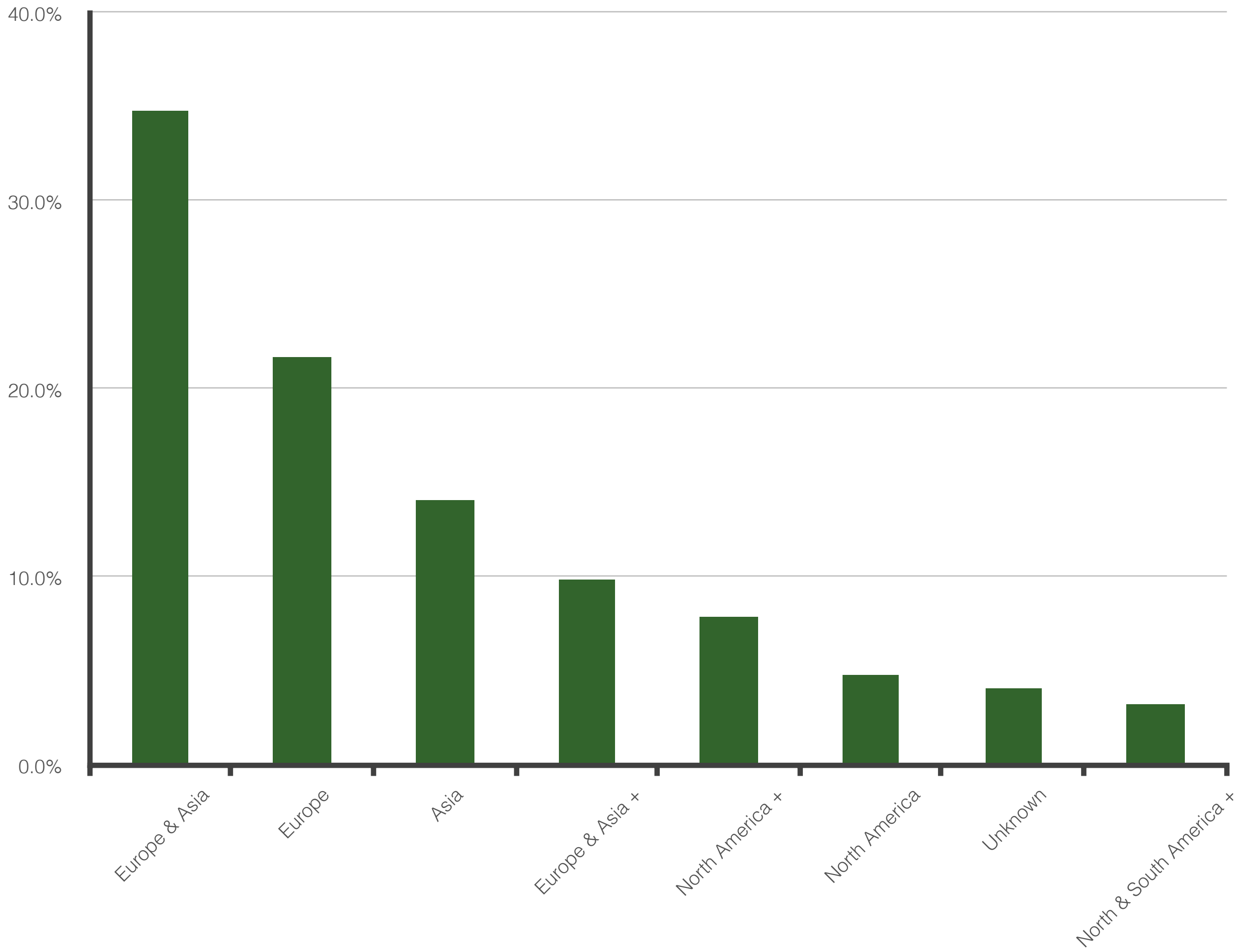

Figure 2: Origin of Tree Species

Note: The + sign indicates that the species is native to another continent other than the continents listed in the grouping. For example, Europe & Asia + would indicate that the species is native to Europe, Asia, and one other continent.

Size Distribution

Size class distribution is also an important aspect to consider in managing a sustainable and diverse tree population, as this will ensure that there are enough young trees to replace those older specimens that are eventually lost through old age or disease.

In this inventory, trees were sized by their stem diameter taken at 1.5m, or, breast height (dbh). Figure 3 (below) shows the percentage of the tree population for the ten most common trees by dbh class.

The chart below represents a fairly typical size class contribution for an urban area, displaying a negative correlation (with percentage composition declining as size increases). There is, however, some variation between species. If new plantings are made up of smaller stature species there will be a definite lack of larger trees in the future. To maintain or increase canopy cover and tree benefits at or above current levels then more trees capable of attaining a larger size will need to be planted and maintained in areas where their presence can be guaranteed to ensure that there is no shortfall in the future.

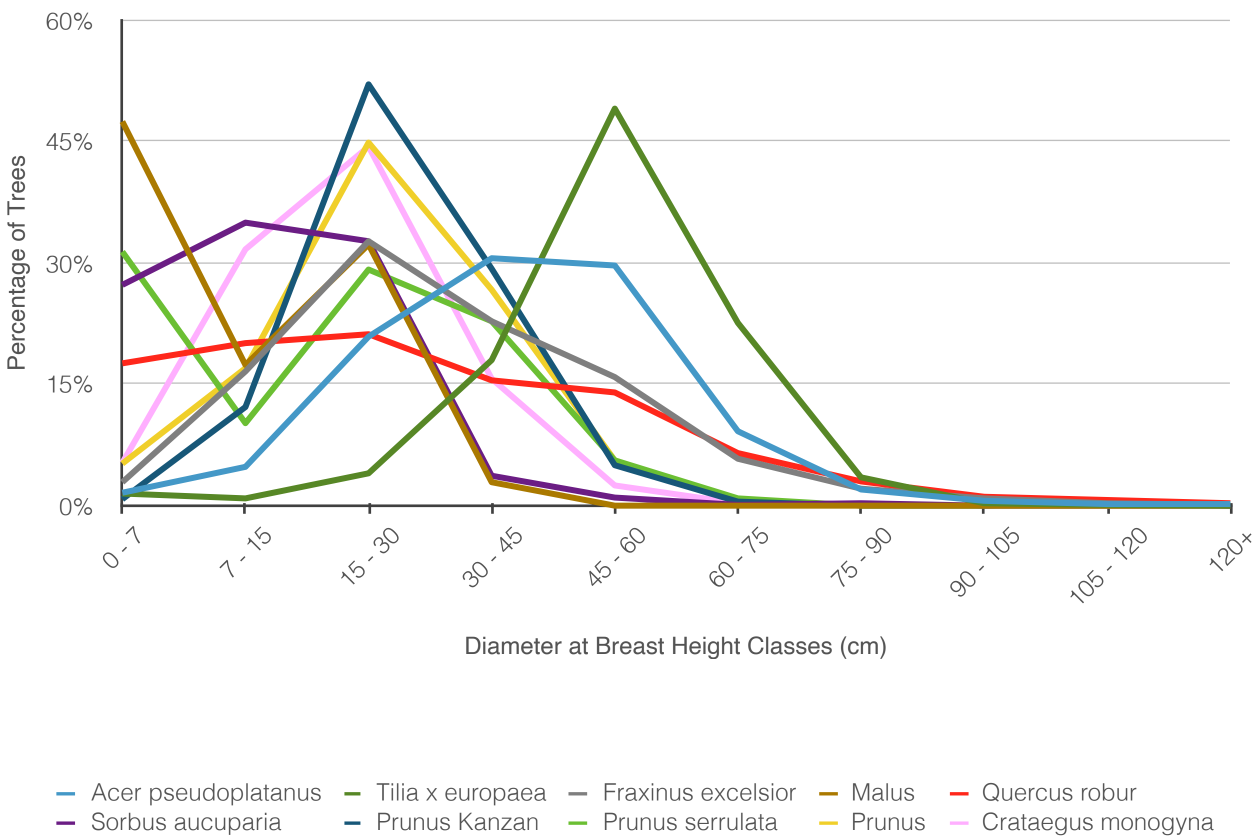

Figure 3: Percentage of Tree Population by DBH Class

Leaf Area and Population

Leaf area is an important metric because the total photosynthetic area of a trees canopy is directly related to the amount of benefit provided. The larger the canopy and its surface area, the greater the amount of air pollution or rainfall which can be held in the canopy of the tree.

Within Sheffield's street tree inventory, total leaf area is estimated at 6,453,800m². If all the layers of leaves within the tree canopies were spread out, they would cover an area over 800 times the size of the pitch at Bramall Lane!

The three most dominant species in terms of leaf area are *Sycamore (Acer pseudoplatanus)* (which has 20.9% of the total leaf area for all trees), Common Lime (*Tilia x europaea)* (19.4%) and Ash (*Fraxinus excelsior)* (8.9%).

Figure 4 (below) shows the top ten dominant trees' contributions to total leaf area. In total these ten species, representing 48.2% of the tree population, contribute almost 76.2% of the total leaf area.

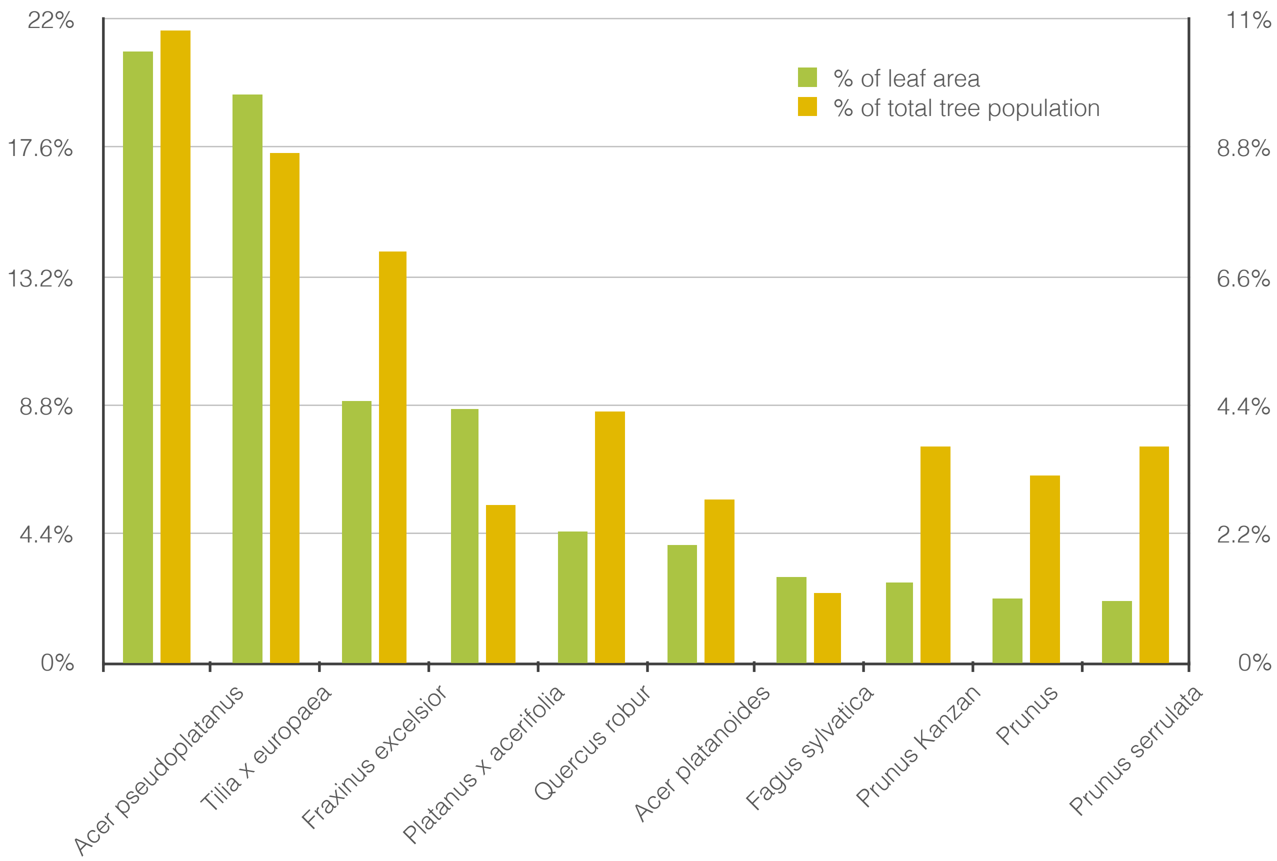

Figure 4: Percentage Leaf Area and Population of the Ten Most Dominant Trees

Leaf Area by Ward

Figure 5 (below) shows the leaf area in Sheffield by ward. Stannington has the largest leaf area (912,200m²) followed by Firth Park (479,200m²) and Fulwood (435,900m²).

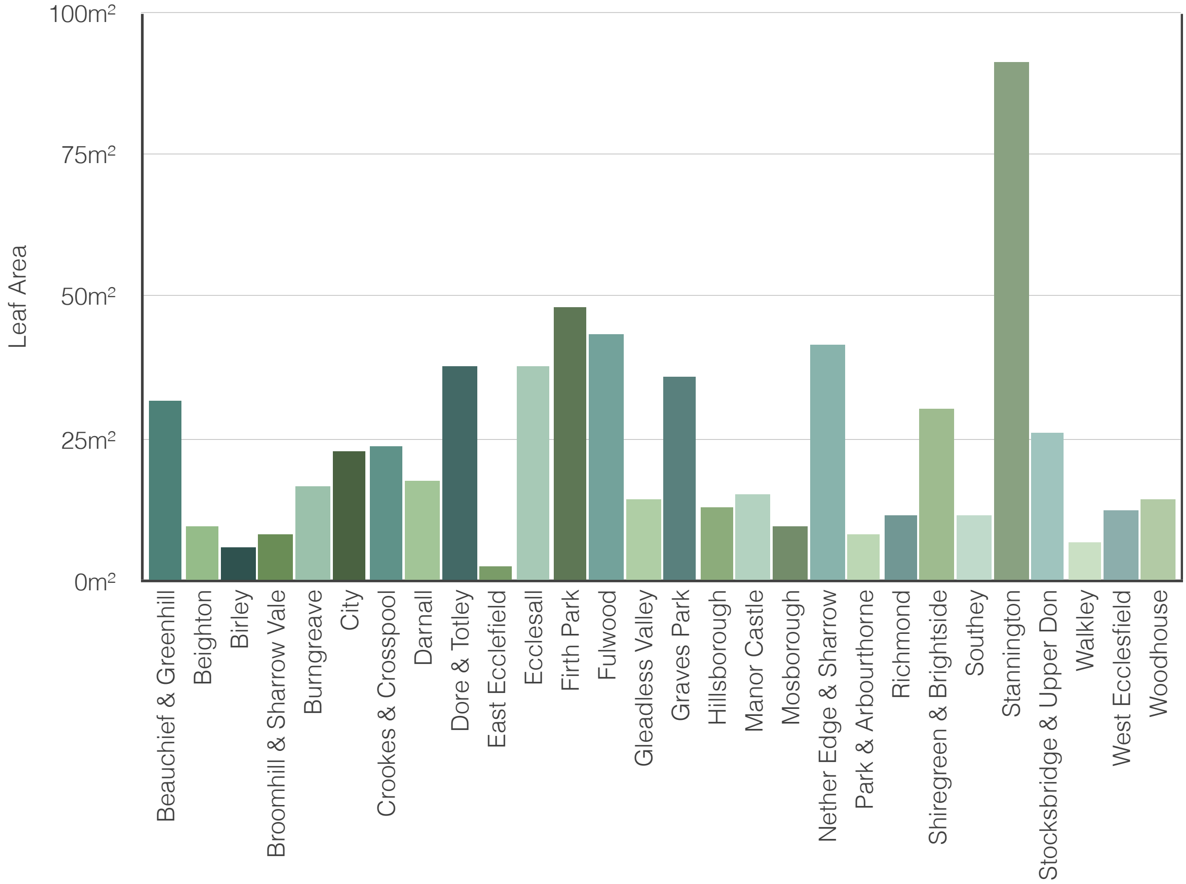

Figure 5: Leaf Area by ward

Results - Ecosystem Services Resource

Air Pollution Removal

Poor air quality is a common problem in many urban areas, in particular along the road network. Air pollution caused by human activity has become a problem since the beginning of the industrial revolution. With the increase in population and industrialisation, large quantities of pollutants have been produced and released into the urban environment. The problems caused by poor air quality are well known, ranging from severe health problems in humans to damage to buildings.

Urban trees can help to improve air quality by reducing air temperature and directly removing pollutants[5]. Trees intercept and absorb airborne pollutants on to the leaf surface[6]. In addition, by removing pollution from the atmosphere, trees reduce the risks of respiratory disease and asthma, thereby contributing to reduced health care costs[7].

Trees also emit volatile organic compounds (VOCs) that can contribute to low-level ozone formation which is detrimental to human health. However, integrated studies have revealed that an increase in tree cover leads to a general reduction in ozone through a reduction in air temperature. Eco accounts for both reduction of ozone and production of VOCs within its algorithms and, as shown in Figure 6, Eco estimated that the inventoried trees in Sheffield remove more ozone than they produce.

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[5] Tiwary et al., 2009

[6] Nowak et al., 2000

[7] Peachey et al., 2009. Lovasi et al., 2008

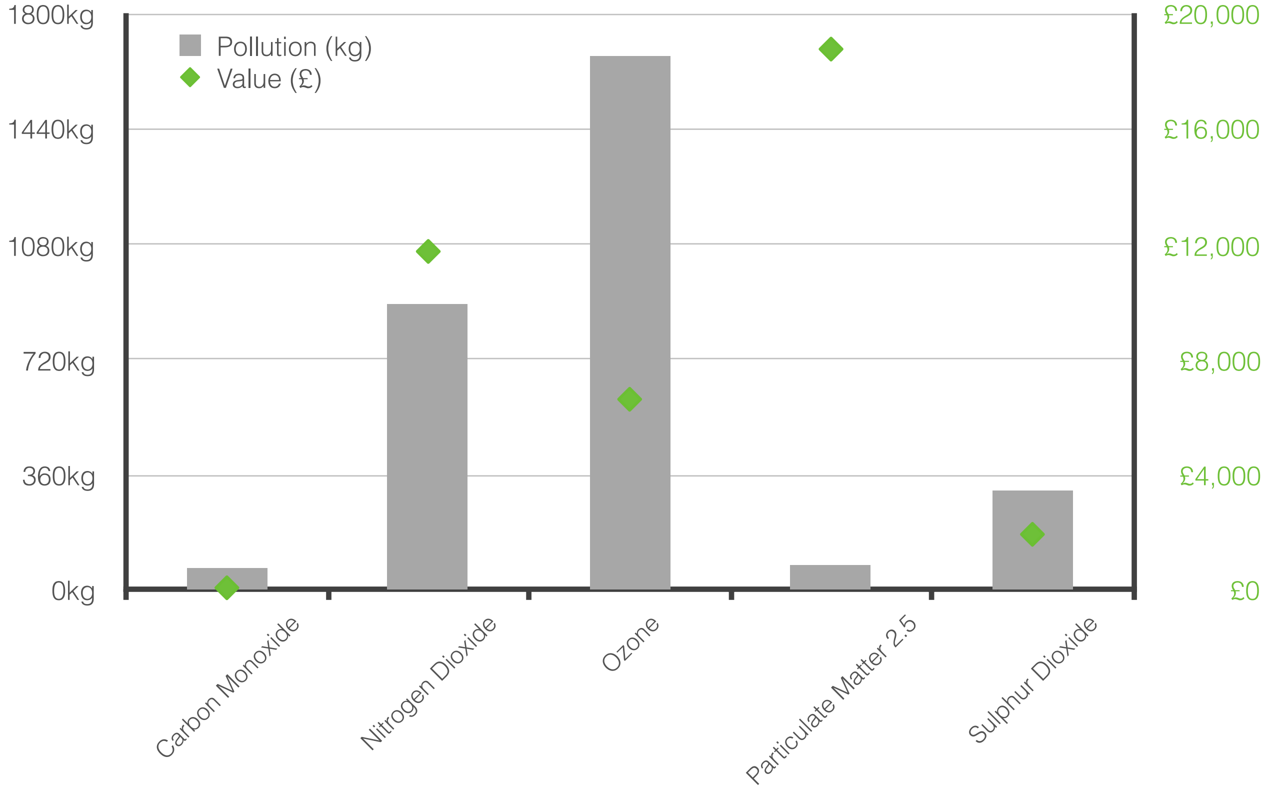

Figure 6: Value of the Pollutants Removed and Quantity Per-Annum within Sheffield

The valuation method uses, where available, UK social damage costs (UKSDC). Where there are no UK figures, the US externality cost (USEC) is used as a substitution.

Greater tree cover, pollution concentrations and leaf area are the main factors influencing pollution filtration and therefore increasing areas of tree planting have been shown to make further improvements to air quality. Furthermore, because filtering capacity is closely linked to leaf area it is generally the trees with larger canopy potential that provide the most benefits.

Figure 7 (below) shows the breakdown for the top ten pollution removing tree species in Sheffield's street tree inventory. As different species can capture different sizes of particulate matter,[8] it is recommended that a broad range of species should be considered for planting in any air quality strategy.

[8] Freer-Smith et al. 2005

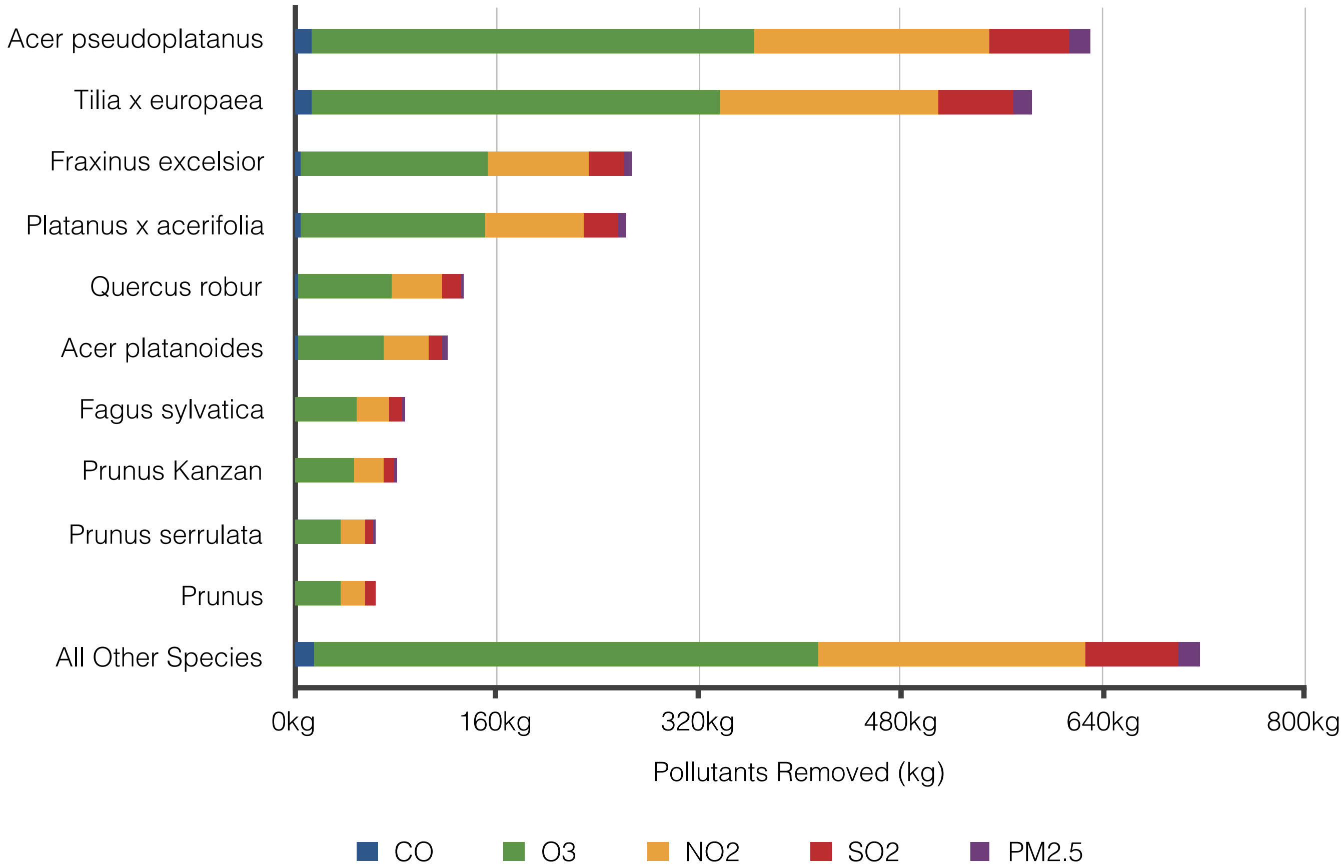

Figure 7: Pollution Removal by Tree Species

It is interesting to note that despite being the 4th most common species, 'Apple (*Malus)*' is the 17th highest pollutant removing species. Likely this is due to its generally smaller size and leaf area. This demonstrates that larger trees provide more benefits when compared with smaller specimens. To further support this, London Plane (*Platanus x acerifolia)*, a particularly large-leaved species, is not within the the top ten by percentage composition (it is 12th, with 2.7%) but it is 4th for pollution removal.

Pollution Removal by Ward

Table 3 (below) shows the pollution removal by pollutant in Sheffield by ward. The Stannington removes the highest concentration of pollutants, removing 425.64kg per annum.

Ward Name	CO Removed (kg)	O3 Removed (kg)	NO2 Removed (kg)	SO2 Removed (kg)	PM2.5 Removed (kg)	Total of all pollutants (kg)
Beauchief & Greenhill	3.18	82.16	43.80	15.07	3.69	147.91
Beighton	0.97	25.14	13.40	4.61	1.13	45.26
Birley	0.59	15.15	8.08	2.78	0.68	27.28
Broomhill & Sharrow Vale	0.79	20.42	10.88	3.74	0.92	36.75
Burngreave	1.65	42.67	22.75	7.83	1.92	76.82
City	2.28	58.73	31.30	10.76	2.64	105.72
Crookes & Crosspool	2.38	61.46	32.77	11.28	2.76	110.65
Darnall	1.76	45.35	24.18	8.32	2.04	81.64
Dore & Totley	3.77	97.37	51.90	17.86	4.38	175.29
East Ecclefield	0.27	6.93	3.70	1.27	0.31	12.48
Ecclesall	3.81	98.47	52.50	18.06	4.43	177.28
Firth Park	4.81	124.21	66.21	22.79	5.58	223.60
Fulwood	4.38	112.97	60.23	20.73	5.08	203.40
Gleadless Valley	1.43	37.00	19.73	6.79	1.66	66.61
Graves Park	3.60	92.87	49.51	17.04	4.18	167.20
Hillsborough	1.26	32.61	17.39	5.98	1.47	58.70
Manor Castle	1.52	39.17	20.88	7.19	1.76	70.52
Mosborough	0.94	24.36	12.99	4.47	1.09	43.86
Nether Edge & Sharrow	4.16	107.36	57.23	19.69	4.83	193.27
Park & Arbourthorne	0.80	20.79	11.08	3.81	0.94	37.43
Richmond	1.15	29.74	15.85	5.46	1.34	53.54
Shiregreen & Brightside	3.03	78.39	41.79	14.39	3.52	141.13
Southey	1.13	29.09	15.51	5.33	1.31	52.37
Stannington	9.17	236.44	126.03	43.37	10.64	425.64
Stocksbridge & Upper Don	2.60	67.09	35.77	12.30	3.02	120.78
Walkley	0.68	17.61	9.38	3.23	0.79	31.70
West Ecclesfield	1.24	32.09	17.11	5.89	1.45	57.77
Woodhouse	1.44	37.17	19.82	6.82	1.67	66.93

Table 3: Removal of each pollutant by ward

Carbon Storage and Sequestration

The main driving force behind climate change is the concentration of carbon dioxide (CO_2) in the atmosphere. Trees can help mitigate climate change by storing and sequestering atmospheric carbon as part of the carbon cycle. Since about 50% of wood by dry weight is comprised of carbon, tree stems and roots can store up to several tonnes of carbon for decades or even centuries[9].

Overall the trees in the Sheffield street tree inventory store an estimated 12,313 tonnes of carbon with a value of £3.03 million.

Figure 8 (below) illustrates the carbon storage of the top ten tree species.

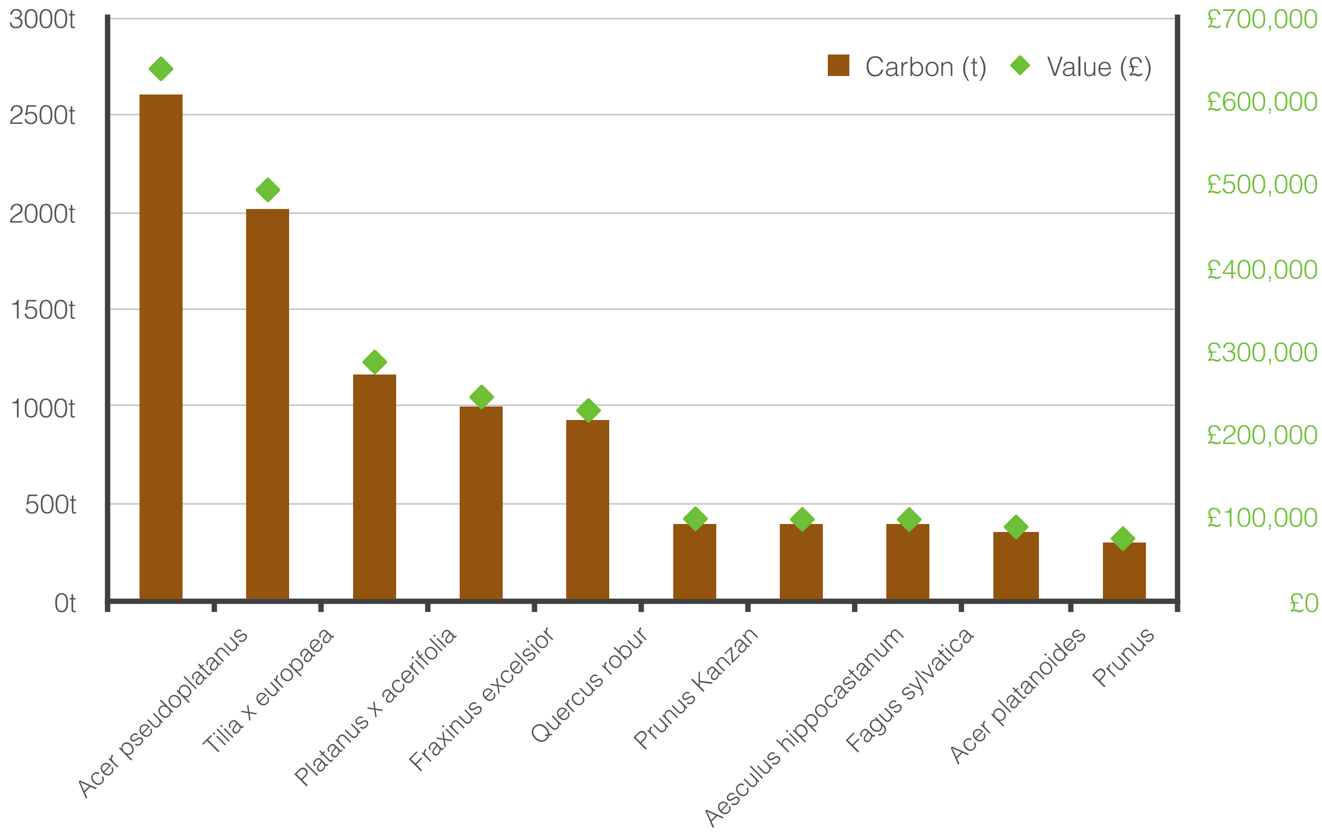

Figure 8: Carbon Storage (tonnes) for Top Ten Tree Species in Sheffield

As trees die and decompose they release this carbon back into the atmosphere. Therefore, the carbon storage of trees and woodland is an indication of the amount of carbon that could be released if all the trees died.

[9] Kuhns 2008, Mcpherson 2007

Maintaining a healthy tree population will ensure that more carbon is stored than released. Utilising the timber in long term wood products, in energy production or to help heat buildings will also help to reduce carbon emissions from other sources, such as power plants.

Carbon Storage by Ward

The highest quantity of carbon is stored in Stannington (1,851 tonnes) which is 15% of the total storage in Sheffield (see figure 9 below). The second and third highest carbon storage wards are Firth Park (891 tonnes) and Fulwood (846 tonnes).

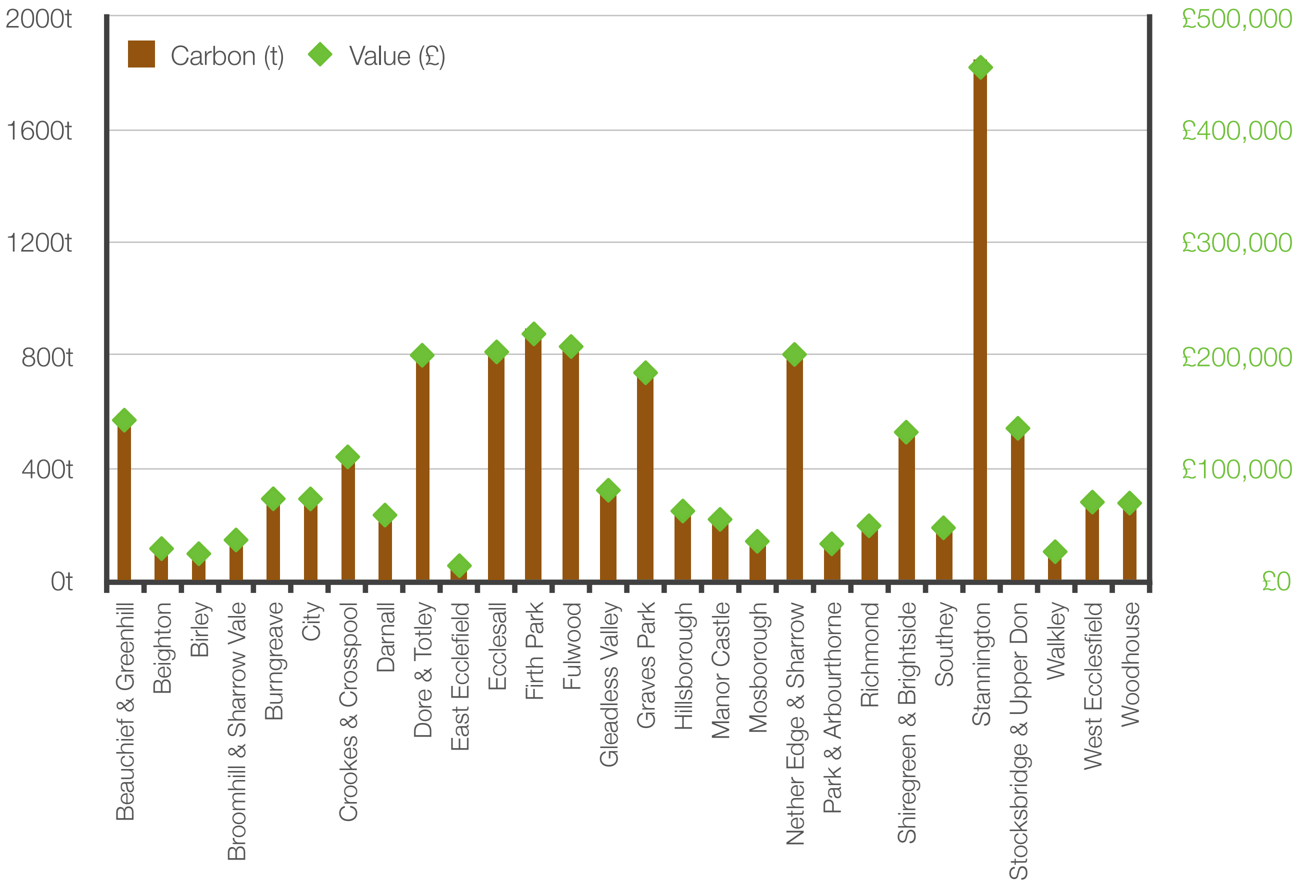

Figure 9: Carbon Stored by Ward

Carbon Sequestration

Carbon sequestration is calculated from the predicted growth of trees based on field measurements of individual trees, climate data and genera specific growth rates within Eco. This provides a measure of tree growth (converted volume). The volume is converted into tonnes of carbon based on species specific conversion factors. Following this, the volume is converted to CO_2 equivalent before being multiplied by the unit cost for carbon. The current (2019) UK social cost for carbon is £67/tonne.

Sheffield's inventory trees sequester an estimated 302 tonnes of carbon per year, with a value of £74,246. Table 4 (below) shows Sheffield's top ten trees in terms of carbon sequestration (annually), and the value of the benefit derived from the sequestration of this atmospheric carbon.

Species	**Common Name**	**Carbon Sequestration (tonnes/yr)**	**CO² Equivalent (Tonnes/yr)**	**Carbon Sequestration (£/yr)**
Acer pseudoplatanus	Sycamore	55.13	202.16	£13,545
Tilia x europaea	Common Lime	40.23	147.54	£9,885
Fraxinus excelsior	Ash	22.50	82.51	£5,528
Platanus x acerifolia	London Plane	20.70	75.90	£5,085
Quercus robur	English Oak	19.55	71.70	£4,804
Prunus Kanzan	Kanzan Cherry	13.29	48.74	£3,266
Prunus	Cherry	10.37	38.04	£2,549
Prunus serrulata	Japanese Cherry	10.05	36.85	£2,469
Acer platanoides	Norway Maple	9.45	34.67	£2,323
Fagus sylvatica	Beech	7.45	27.31	£1,830
All Other Species	All Other Species	93.47	342.73	£22,963
Total		**302.19**	**1,108.15**	**£74,246**

Table 4: Top Ten Carbon Sequestration by Species

Of the tree species inventoried, Sycamore (*Acer pseudoplatanus)* store and sequester the most carbon. They add approximately 55 tonnes in the study year to the current Sycamore (*Acer pseudoplatanus)* carbon storage of 2,600 tonnes.

For comparison, the average newly registered car in the UK produces 34.3g carbon per km[10]. Carbon sequestration in Sheffield's street tree inventory therefore corresponds to around 1,603,499 'new' vehicle km per year, equivalent to 49 people driving a car over 10 years[11].

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[10] http://naei.beis.gov.uk/data/emission-factors
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/454981/veh0150.csv/preview

[11] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/823068/national-travel-survey-2018.pdf

Carbon Sequestration by Ward

Trees remove four million tonnes of Carbon from the UK atmosphere each year[12].

Stannington has the largest carbon sequestration value at 41.7 tonnes/yr (table 5 below). The second and third highest are Fullwood (21.2 tonnes) and Ecclesall (19.4 tonnes).

Ward Name	Gross Carbon Sequestration (metric ton/yr)	CO_2 Equivalent (metric ton/yr)	Value (£)
Beauchief & Greenhill	14.49	53.15	£3,561
Beighton	4.74	17.40	£1,166
Birley	3.45	12.65	£848
Broomhill & Sharrow Vale	3.18	11.64	£780
Burngreave	7.27	26.67	£1,787
City	9.44	34.61	£2,319
Crookes & Crosspool	11.43	41.91	£2,808
Darnall	8.46	31.03	£2,079
Dore & Totley	19.38	71.07	£4,762
East Ecclefield	1.48	5.44	£364
Ecclesall	20.36	74.68	£5,004
Firth Park	19.88	72.89	£4,884
Fulwood	21.23	77.86	£5,217
Gleadless Valley	6.32	23.17	£1,552
Graves Park	17.40	63.79	£4,274
Hillsborough	5.60	20.54	£1,376
Manor Castle	6.81	24.97	£1,673
Mosborough	4.48	16.43	£1,101
Nether Edge & Sharrow	16.37	60.01	£4,021
Park & Arbourthorne	4.19	15.36	£1,029
Richmond	5.47	20.04	£1,343
Shiregreen & Brightside	12.93	47.42	£3,177
Southey	5.47	20.07	£1,345
Stannington	41.66	152.76	£10,235
Stocksbridge & Upper Don	14.16	51.93	£3,479
Walkley	3.09	11.32	£758
West Ecclesfield	6.59	24.18	£1,620
Woodhouse	6.86	25.16	£1,686

Table 5: Carbon Sequestration in each ward

12 Forestry Commission England (2010)

Hydrology (Avoided Runoff)

Surface runoff can be a cause for concern in many areas as it can contribute to flooding and is a source of pollution in streams, wetlands, waterways, lakes and oceans. During precipitation events, a proportion is intercepted by vegetation (trees and shrubs) while the remainder reaches the ground. Precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff[13].

In urban areas, the large extent of impervious surfaces increases the amount of runoff. However, trees are very effective at reducing surface runoff[14]. The trees' canopy intercepts precipitation, while the root system promotes infiltration and storage of water in the soil.

Annual avoided surface runoff in Eco is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. The trees within Sheffield's street tree inventory reduce runoff by an estimated 10,415m³ a year with an associated value of £18,039[15].

Figure 10 (below) shows the volumes and values for the ten most important species for reducing runoff.

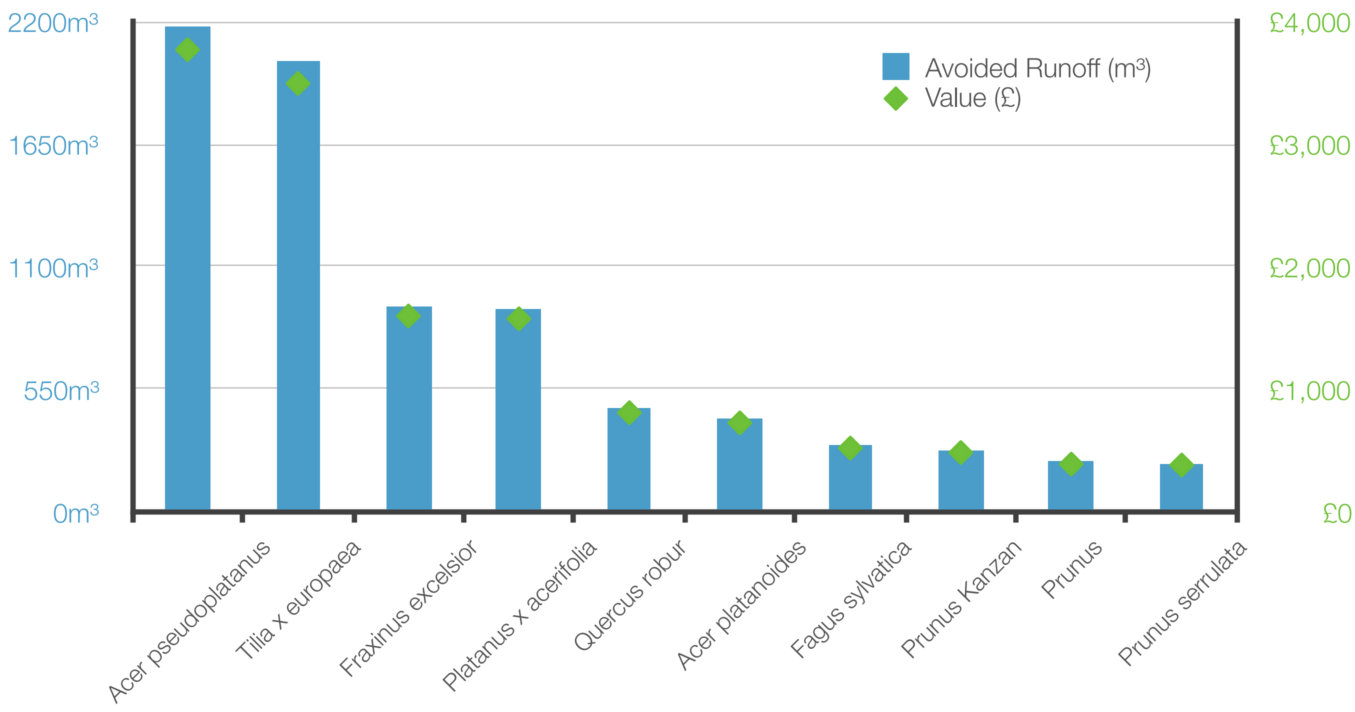

Figure 10: Avoided Runoff by Top Ten Species

13 Hirabayashi 2012

14 Trees in Hard Landscapes (TDAG) 2014

15 Yorkshire Water Charges 2019/20

The trees in Sheffield's street tree inventory play an important role in reducing runoff: Sycamore (*Acer pseudoplatanus)* intercepts the largest proportion of precipitation for a species, and is the most important species in this category. This is due to the trees' population, canopy size and leaf morphology.

10,415m³ is equivalent to over 4 Olympic swimming pools of stormwater being averted every single year.

Avoided Runoff by Ward

Figure 12 shows that Stannington has the highest avoided runoff value, preventing 1,472m³ of stormwater each year from entering sewerage systems which has an associated saving of £2,550; this is 14.1% of the total runoff value for the Sheffield Inventory. The second and third highest are Firth Park (773m³) and Fulwood (703m³).

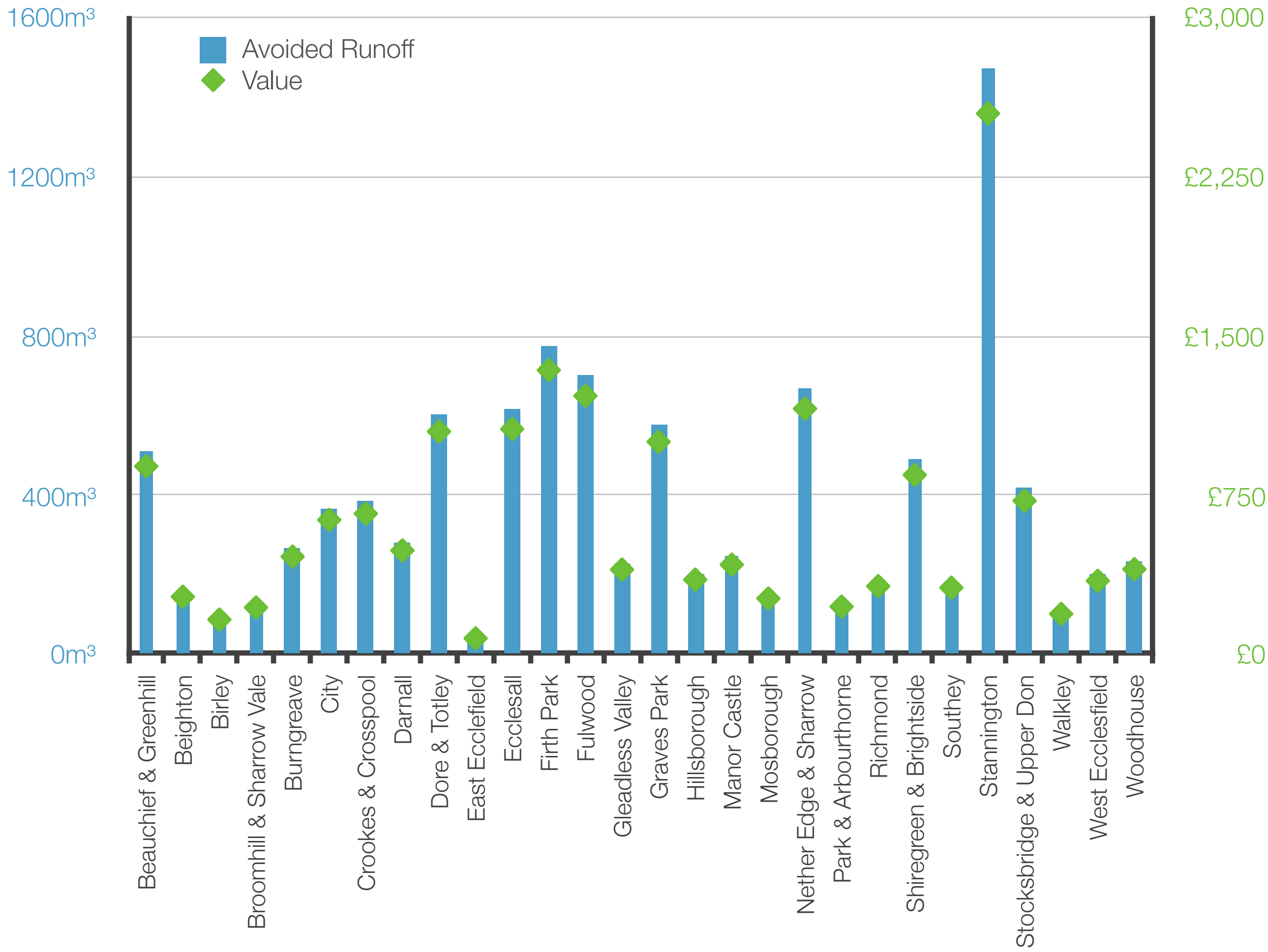

Figure 11: Avoided Runoff for each ward

Potential Pests and Diseases

Various pests and diseases can affect trees, reducing both their health and value, and therefore the sustainability of our urban forests. As most pests generally tend to have a specific range of tree hosts, the potential damage that can be caused by each pest will differ.

In this instance Phytophthora (*Phytophthora spp*) and Xyella (*Xyella fastidiosa*) have been selected to illustrate how the results from this survey can be used to estimate the potential impacts on the trees in Sheffield.

These pathogens have the potential to reduce the performance of or even potentially kill a number of trees that are present in Sheffield's tree population. Figure 12 (below) illustrates the potential impact of these pathogens, the potential percentage of population that could become infected and those which are resistant.

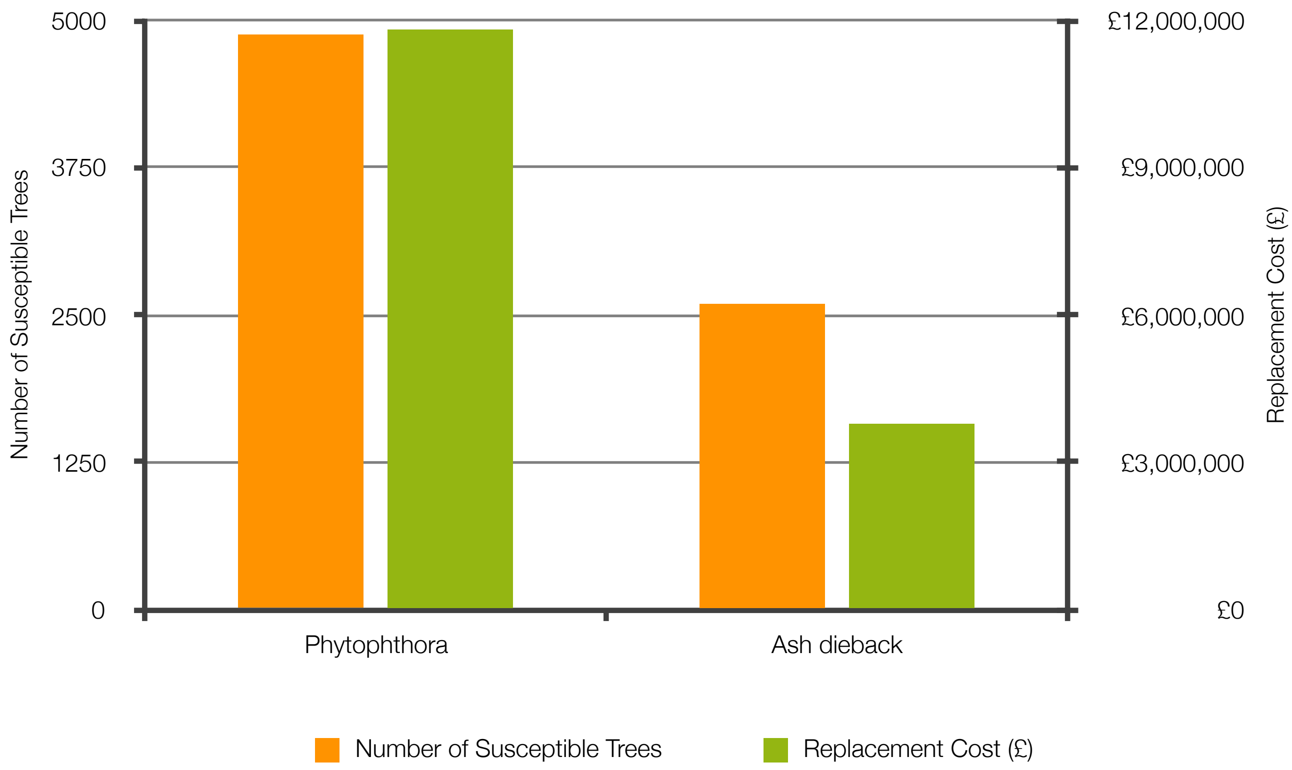

Figure 12: Potential Pest Impacts on Species

Ash dieback (*Hymenoscyphus fraxineus*) is harmless in its native range in Asia, associating with native ash species including *Fraxinus mandshurica*. However, European ash (*Fraxinus excelsior*) has shown to be highly susceptible to the pathogenicity of *H fraxineus*. *F excelsior* is one of the most common species and alongside the other ash species, provide the high ecosystem benefits within the inventory to Sheffield, such as pollution removal, avoided runoff, carbon storage and sequestration. They currently account for 7.4% of the population (or 2,589 trees). Ash trees can be large in stature and within Sheffield, provide significant amount of ecosystem service benefits. Therefore their replacement, should they perish, would be costly.

Phytophthora Bleeding Canker (*Pytophthora spp)* is an infection of the bark of several trees by a number of different species of the fungus-like (Oomycete) micro-organism *Phytophthora*, causing the affected bark to bleed a dark sticky fluid. Cankers may be present at any time of year.
Trees affected in the UK include Aesculus (horse chestnut), Tilia (lime) and Alnus (alder).

For the purpose of this study all species of Ash including, *Fraxinus, Fraxinus Excelsior, Fraxinus Augustifolia, Fraxinus Augustifolia 'Raywood', Fraxinus Ornus,* and *Fraxinus Pennsylvanica and Fraxinus velutina* have been included. According to the Defra Management Plan for Chalara (Ash Dieback) many species of Ash can be infected but the intensity and appearance of symptoms varies. Common Ash (*Fraxinus Excelsior)* is the most severely affected[16]. This information should be considered when reviewing the impacts of Ash Dieback on Sheffield's trees.

[16] Defra, 2013

Replacement Cost

In addition to estimating the environmental benefits provided by trees, Eco also provides a structural valuation, which in the UK is termed the 'Replacement Cost'. It must be stressed that the way in which this value is calculated means that it does not constitute a benefit provided by the trees. The valuation is a depreciated replacement cost, based on the Council of Tree and Landscape Appraisers (CTLA) formulae[17].

Replacement Cost is intended to provide a useful management tool, as it is able to value what it might cost to replace any or all of the trees (taking account of species suitability, depreciation and other economic considerations) should they become damaged or diseased for instance. The replacement costs for the ten most valuable tree species are shown in Figure 13, below.

The total value of all trees in the study area, as estimated by Eco, currently stands at over £41 million. Common Lime (*Tilia x europaea*) is the most valuable species of tree, on account of both its size and population, followed by Sycamore (*Acer pseudoplatanus*) and Ash (*Fraxinus excelsior*). These three species (or genera) account for £22 million (53%) of the total replacement cost of the trees in Sheffield's street tree inventory, with the Lime alone accounting for 24% of the total replacement cost.

A full list of trees with the associated replacement cost is given in Appendix III.

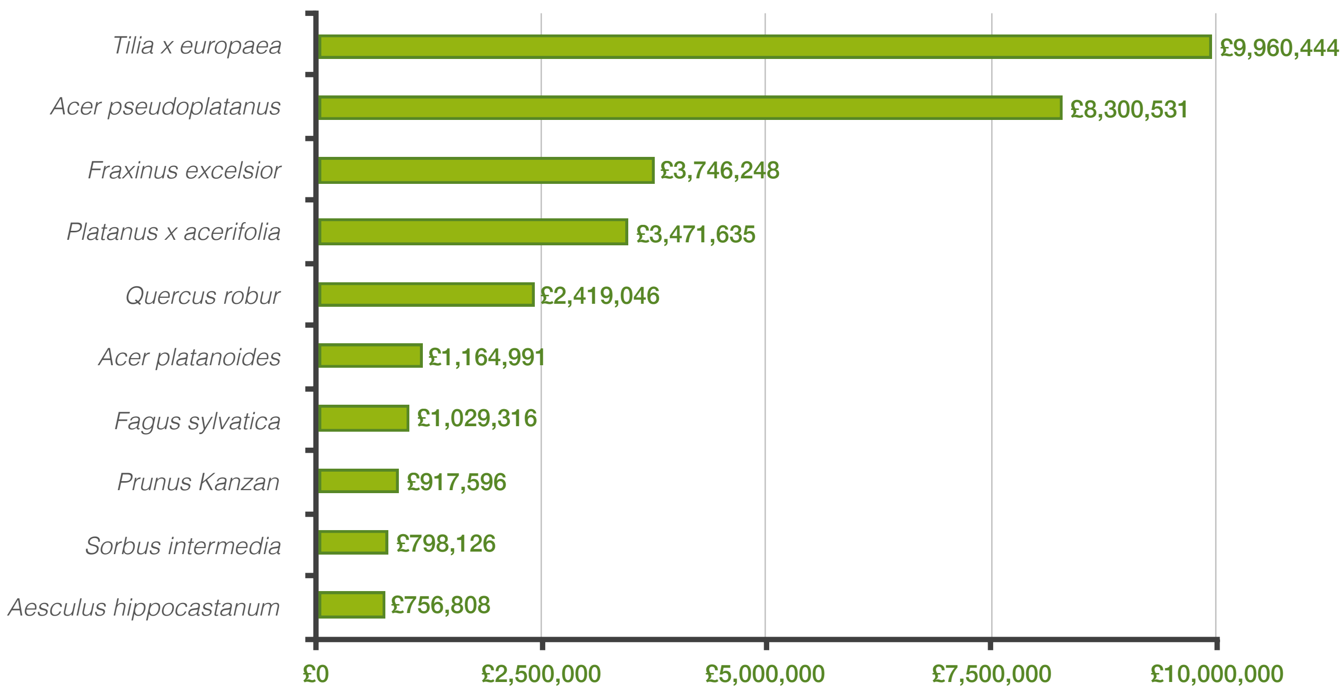

Figure 13: Replacement Cost for Top Ten Trees in Sheffield

17 Hollis, 2007

Replacement Cost by Ward

Stannington has the highest Replacement Cost value at £6.48 million (Figure 14) which is 15.8% of the total replacement cost in Sheffield (£41,156,410). The second and third highest are Firth Park (£3,152,878) and Nether Edge & Sharrow (£3,136,480).

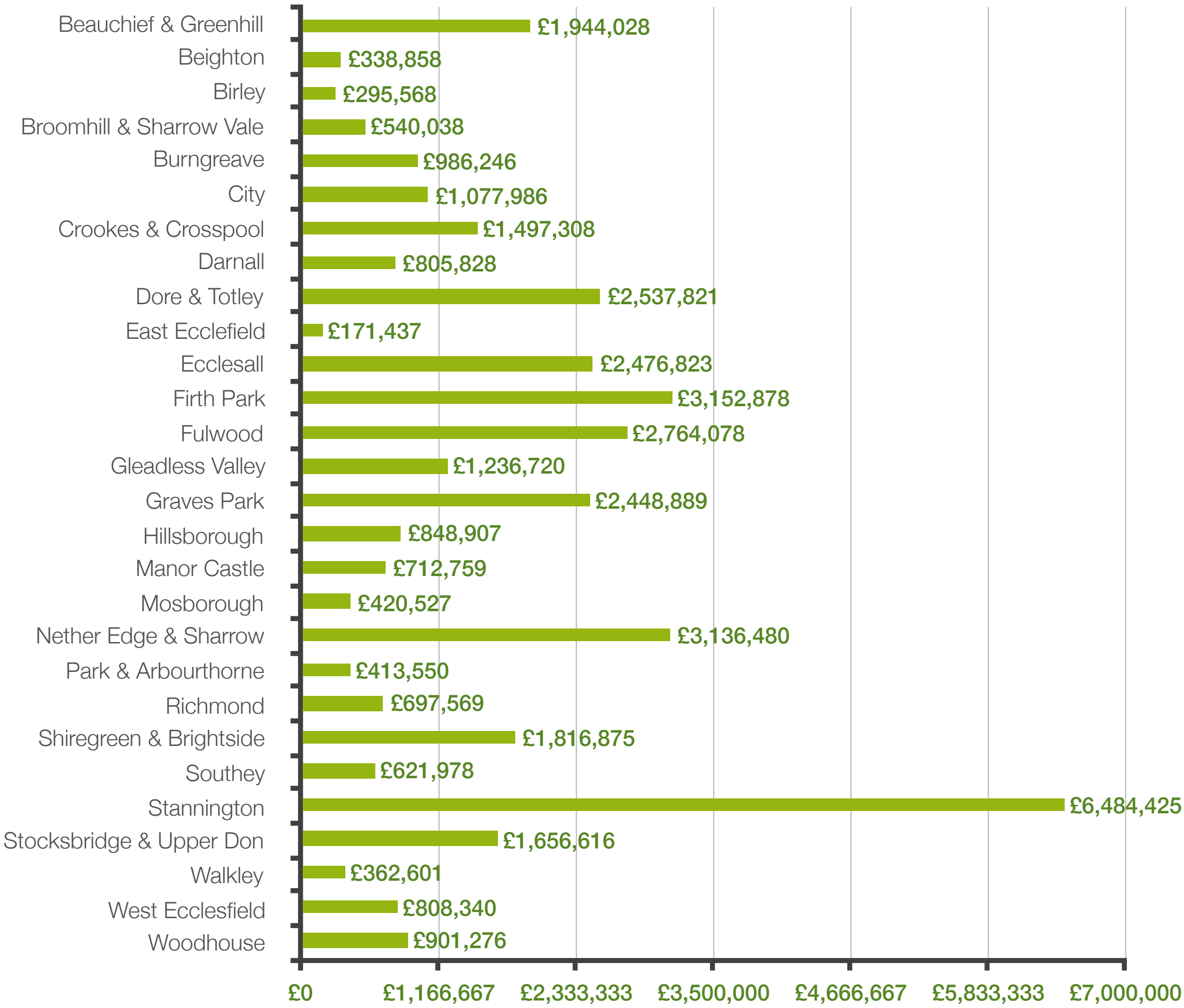

Figure 14: Replacement Cost in each Ward

CAVAT - The amenity value of trees

Capital Asset Valuation for Amenity Trees (CAVAT) is a method developed in the UK to provide a value for the public amenity that trees provide. The CTLA (Council of Tree and Landscape Appraisers) valuation method does not take into account the health or amenity value of trees, and is a management tool rather than a benefit valuation.

Particular differences to the CTLA valuation include the Community Tree Index (CTI) value, which adjusts the CAVAT assessment to take account of the greater benefits of trees in areas of higher population density, using official population figures. CAVAT allows the value of Sheffield's trees to include a social dimension by valuing the visual accessibility and prominence within the overall urban forest.

For the street trees of Sheffield, the estimated total public amenity asset value is over £340 million.

Given the particular nature of local street trees, local factors and choices could not be taken into account as part of this study. The value should reflect the reality that street trees have to be managed for safety. They are frequently crown lifted and reduced (to a greater or lesser extent) and are generally growing in conditions of greater stress than their open grown counterparts. As a result, they may have a significantly reduced functionality under the CAVAT system.

This study also included assumptions of condition based on the Safe Useful Life Expectancy (SULE), as this was not included in the Sheffield street tree inventory information.

The Common Lime (*Tilia x europaea*) of Sheffield holds the highest CAVAT value (Table 6, below), although the Sycamore (*Acer pseudoplatanus*) is the most numerous tree, representing 10.8% of the total tree population.

Species	Common Name	CAVAT Value	Percent of Total Population	Replacement Cost
Tilia x europaea	*Common Lime*	£75,366,587.37	8.7%	£9,960,444
Acer pseudoplatanus	*Sycamore*	£66,125,383.93	10.8%	£8,300,531
Fraxinus excelsior	*Ash*	£29,709,366.34	7.0%	£3,746,248
Platanus x acerifolia	*London Plane*	£26,587,541.61	2.7%	£3,471,635
Quercus robur	*Oak*	£20,254,380.42	4.3%	£2,419,046
Acer platanoides	*Norway Maple*	£9,703,710.29	2.8%	£1,164,991
Prunus Kanzan	*Kanzan Cherry*	£9,309,112.71	3.7%	£917,596
Fagus sylvatica	*Beech*	£8,483,383.79	1.2%	£1,029,316
Aesculus hippocastanum	*Horse Chestnut*	£8,356,741.42	0.8%	£756,808
Prunus	*Cherry*	£7,125,571.15	3.2%	£700,932
All Other Species	*All Other Species*	£79,724,370.28	54.7%	£8,688,865
Total		£340,746,149.31	100%	£41,156,410

Table 6: The ten species with the highest CAVAT valuation

Using this study

The results and data from previous i-Tree studies have been used in a variety of ways to improve management of trees and inform decision making. With better information we can make better decisions about how trees are managed to provide long term benefits to communities and this is one of the key outcomes of undertaking a project such as this.

For example:

- Data can be used to inform species selection for increased tree diversity thereby lessening the impacts from potential threats like *Hymenoscyphus fraxineus* (formerly *Chalara fraxinea*), more commonly known as Ash Dieback.

- Data can be used to produce educational information about Sheffield's trees (e.g. informational tree tags).

- Using the data for cost benefit analysis to inform decision making.

- Undertake a gap analysis to help inform where to plant trees to optimise ecosystem services and maximise the benefits, to align to the objectives and priorities of Sheffield's tree management plan.

- Inform species selection. Size does matter! Identify trees that can grow on to full maturity and reach their optimal canopy size (given any site specific restrictions) and contribute the most benefits to the surrounding urban communities. Review together with an ancient tree management plan to include non-natives and heritage trees to broaden the potential for Sheffield's inventory trees to build resilience to future change.

Conclusions

The tree population within Sheffield's street tree inventory generally has a good species and age diversity. It is acknowledged that there are a number of constraints on urban planting, however that can hinder planting of larger-growing species. Additional larger-growing species provide some resilience from possible future influences such as climate change and pest and disease outbreaks. The role of Sheffield's trees in complementing people's health is clear, through air pollution removal especially. Sheffield's trees provide a valuable benefit of over £131,000 in ecosystem services each year.

In terms of structural diversity, the Lime (*Tilia x europaea*) has the largest proportion of trees in the larger size classes within the top ten populated species but other tree species such as Sycamore (*Acer pseudoplatanus*) and Ash (*Fraxinus excelsior)* are also well represented. Larger-growing trees are important because they provide greater canopy cover and therefore ecosystem service provision. They also tend to have higher amenity value than their smaller counterparts.

Sheffield has a rich species diversity, with 187 species within the street tree inventory. However, there is a slight reliance on Sycamore (*Acer pseudoplatanus) and* Lime (*Tilia x europaea)* to provide ecosystem services, including 37.4% of all carbon stored, 31.6% of annual carbon sequestration, and 26.6% of annual avoided runoff. Like many urban areas, Sheffield would benefit from having a greater proportion of larger trees, of a more diverse range of species, in order to build resilience into its tree population and reduce reliance on a small number of species.

The values presented in this study should be seen as conservative estimates, as only a proportion of the total benefits have been evaluated. Trees confer many other benefits, such as contributions to our health and well-being, reducing urban temperatures, providing amenity value and habitats for wildlife.

The extent of these benefits needs to be recognised. Strategies and policies that will conserve this important resource (through education for example) would be one way to address this. Targets to increase canopy cover through planting larger trees, protecting large and veteran trees and where possible, diversify the urban forest through planting climate adaptable species should also be investigated through the production of an 'Urban Forest Masterplan'.

As the amount of healthy leaf area equates directly to the provision of benefits, future management of the tree stock is important to ensure canopy cover levels continue to be maintained or increased.

New tree planting can contribute to the growth of canopy cover. However, the most effective strategy for increasing average tree size and the extent of tree canopy is to preserve and adopt a management approach that enables the existing trees to develop a stable, healthy, age and species diverse, multi-layered population.

Climate change could affect the tree stock in Sheffield's street tree inventory in a variety of ways and there are great uncertainties about how this may manifest. Some species may be less able to survive under new climatic conditions. New conditions may also allow different pests and diseases to become prevalent. Further studies into this area would be useful in informing any long-term tree strategies or urban forest masterplans, such as species choice for example.

The challenge now is to ensure that policy makers and practitioners take full account of Sheffield's trees in decision making. Not only are trees a valuable functional component of our landscape, they also make a significant contribution to peoples quality of life.

Appendix I. Relative Tree Effects

The trees in the Sheffield's inventory provide benefits that include carbon storage and sequestration and air pollutant removal. To estimate the relative value of these benefits, tree benefits were compared to estimates of average carbon emissions and average family car emissions. These figures should be treated as a guideline only as they are largely based on US values (see footnotes).

Carbon storage is equivalent to:

- Amount of carbon emitted in Sheffield Inventory in 2 days
- Annual carbon (C) emissions from 9,600 family cars
- Annual C emissions from 3,940 single-family houses

Nitrogen dioxide removal is equivalent to:

- Annual nitrogen dioxide emissions from 141 family cars
- Annual nitrogen dioxide emissions from 63 single-family houses

Sulphur dioxide removal is equivalent to:

- Annual sulphur dioxide emissions from 3,640 family cars
- Annual sulphur dioxide emissions from 10 single-family houses

Carbon sequestration is equivalent to:

- Annual carbon (C) emissions from 200 family cars
- Annual C emissions from 100 single-family houses

Oxygen Production is equivalent to:

- Annual Oxygen intake from 2,808 people

Municipal carbon emissions are based on 2010 U.S. per capita carbon emissions (Carbon Dioxide Information Analysis Center 2010). Per capita emissions were multiplied by city population to estimate total city carbon emissions.

Light duty vehicle emission rates (g/mi) for CO, NOx, VOCs, PM, SO2 for 2010 (Bureau of Transportation Statistics 2010; Heirigs et al 2004), PM2.5 for 2011-2015 (California Air Resources Board 2013), and CO_2 for 2011 (U.S. Environmental Protection Agency 2010) were multiplied by average miles driven per vehicle in 2011 (Federal Highway Administration 2013) to determine average emissions per vehicle.

Household emissions are based on average electricity kWh usage, natural gas Btu usage, fuel oil Btu usage, kerosene Btu usage, LPG Btu usage, and wood Btu usage per household in 2009 (Energy Information Administration 2013; Energy Information Administration 2014)

- CO_2, SO2, and NOx power plant emission per KWh are from Leonardo Academy 2011. CO emission per kWh assumes 1/3 of one percent of C emissions is CO based on Energy Information Administration 1994. PM emission per kWh from Layton 2004.
- CO_2, NOx, SO2, and CO emission per Btu for natural gas, propane and butane (average used to represent LPG), Fuel #4 and #6 (average used to represent fuel oil and kerosene) from Leonardo Academy 2011.
- CO_2 emissions per Btu of wood from Energy Information Administration 2014.
- CO, NOx and SOx emission per Btu based on total emissions and wood burning (tons) from (British Columbia Ministry 2005; Georgia Forestry Commission 2009).

Oxygen production figures are based on the total oxygen produced by the trees within the inventory divided by the average intake of oxygen for each person per year - https://ntrs.nasa.gov/search.jsp?R=20060005209

Appendix II. Species Dominance Ranking List

Species	Percent Population	Percent Leaf Area	Dominance Value
Acer pseudoplatanus	10.80	20.90	31.70
Tilia x europaea	8.70	19.40	28.10
Fraxinus excelsior	7.00	8.90	15.90
Platanus x acerifolia	2.70	8.70	11.50
Quercus robur	4.30	4.50	8.80
Acer platanoides	2.80	4.00	6.80
Prunus Kanzan	3.70	2.70	6.30
Prunus serrulata	3.70	2.10	5.80
Malus	4.50	1.30	5.70
Sorbus aucuparia	4.10	1.30	5.40
Prunus	3.20	2.20	5.30
Fagus sylvatica	1.20	2.90	4.10
Acer campestre	2.60	1.10	3.70
Crataegus monogyna	2.80	0.80	3.60
Sorbus intermedia	1.60	1.50	3.10
Prunus avium	1.60	1.30	2.90
Betula pendula	2.00	0.90	2.80
Sorbus aria	1.50	1.20	2.70
Aesculus hippocastanum	0.80	1.80	2.60
Tilia	1.10	1.20	2.30
Tilia cordata	1.50	0.60	2.10
Malus sylvestris	1.30	0.60	1.90
Prunus padus	1.20	0.60	1.80
Liquidambar styraciflua	1.30	0.20	1.50
Pyrus calleryana 'Chanticleer'	1.40	0.10	1.50
Crataegus laevigata	1.40	0.10	1.50
Betula ermanii	1.20	0.10	1.40

Species	Percent Population	Percent Leaf Area	Dominance Value
Prunus x hiliieri	1.10	0.20	1.30
Populus x canadensis	0.80	0.40	1.20
Salix caprea	0.70	0.40	1.10
Prunus serrula	0.60	0.40	1.00
Prunus serrulata 'Umineko'	0.80	0.10	0.90
Tilia platyphyllos	0.50	0.40	0.80
Carpinus betulus 'Fastigiata'	0.50	0.30	0.80
Corylus colurna	0.70	0.10	0.80
Sorbus	0.70	0.10	0.80
Carpinus betulus	0.40	0.30	0.70
Alnus cordata	0.40	0.30	0.70
Ilex aquifolium	0.60	0.10	0.70
Ginkgo biloba	0.60	0.10	0.70
Alnus glutinosa	0.40	0.20	0.60
Betula pubescens	0.40	0.20	0.60
Quercus petraea	0.20	0.30	0.50
Ulmus	0.30	0.20	0.50
Crataegus x lavallei	0.50	<0.10	0.50
Ulmus glabra	0.20	0.30	0.40
Acer	0.20	0.20	0.40
Ulmus procera	0.20	0.20	0.40
Sambucus nigra	0.40	0.10	0.40
Pinus sylvestris	0.30	0.10	0.40
Betula utilis	0.30	0.10	0.40
Pinus	0.30	0.10	0.40
Betula utilis ssp. jacquemontii	0.30	0.10	0.40
Malus tschonoskii	0.20	0.10	0.40
Corylus avellana	0.20	0.10	0.40
Populus nigra v. italica	0.10	0.20	0.30
Crataegus	0.30	0.10	0.30
Quercus palustris	0.20	0.10	0.30

Species	Percent Population	Percent Leaf Area	Dominance Value
Malus floribunda	0.20	0.10	0.30
Pinus nigra ssp. Nigra	0.20	0.10	0.30
Pyrus	0.20	0.10	0.30
Gleditsia triacanthos v. inermis 'Sunburst'	0.30	<0.10	0.30
Ulmus 'New Horizon'	0.20	<0.10	0.30
Betula	0.20	<0.10	0.30
Tilia cordata 'Greenspire'	0.20	0.10	0.20
Malus x purpurea	0.20	0.10	0.20
Prunus cerasus	0.10	0.10	0.20
Metasequoia glyptostroboides	0.10	0.10	0.20
Fraxinus angustifolia	0.10	0.10	0.20
Taxus baccata	0.10	0.10	0.20
Prunus pissardii	0.10	0.10	0.20
Acer saccharinum	0.10	0.10	0.20
Fraxinus	0.10	0.10	0.20
Quercus	0.10	0.10	0.20
Aesculus x carnea	0.10	0.10	0.20
Prunus spinosa	0.10	0.10	0.20
Prunus x yedoensis 'Akebono'	0.10	0.10	0.20
Prunus serrulata 'Amanogawa'	0.10	0.10	0.20
Populus nigra	0.10	0.10	0.20
Cotoneaster	0.10	0.10	0.20
Alnus	0.10	0.10	0.20
Gleditsia triacanthos	0.20	<0.10	0.20
Acer rubrum 'October glory'	0.20	<0.10	0.20
Acer rubrum	0.10	<0.10	0.20
Populus canescens	0.10	<0.10	0.20
Quercus cerris	0.10	0.10	0.10
Robinia pseudoacacia	0.10	0.10	0.10
Populus	0.10	0.10	0.10

Species	Percent Population	Percent Leaf Area	Dominance Value
Salix fragilis	0.10	0.10	0.10
Quercus rubra	0.10	0.10	0.10
Tilia euchlora	<0.10	0.10	0.10
Castanea sativa	<0.10	0.10	0.10
Larix decidua	0.10	<0.10	0.10
Tilia americana 'Redmond'	0.10	<0.10	0.10
Liriodendron tulipifera	0.10	<0.10	0.10
Picea abies	0.10	<0.10	0.10
Chamaecyparis lawsoniana	0.10	<0.10	0.10
Prunus cerasifera	0.10	<0.10	0.10
Populus alba	0.10	<0.10	0.10
Corylus	0.10	<0.10	0.10
Fraxinus ornus	0.10	<0.10	0.10
Alnus incana	0.10	<0.10	0.10
Malus domestica	0.10	<0.10	0.10
Celtis australis	0.10	<0.10	0.10
Laburnum anagyroides	0.10	<0.10	0.10
Populus tremula	0.10	<0.10	0.10
Pyrus communis	0.10	<0.10	0.10
Sorbus x thuringiaca	0.10	<0.10	0.10
Zelkova carpinifolia	0.10	<0.10	0.10
Tilia mongolica	0.10	<0.10	0.10
Betula albosinensis	0.10	<0.10	0.10
Pinus nigra	<0.10	<0.10	0.10
Aesculus	<0.10	<0.10	0.10
Salix	<0.10	<0.10	0.10
Salix babylonica	<0.10	<0.10	0.10
Acer cappadocicum	<0.10	<0.10	0.10
Prunus dulcis	<0.10	<0.10	0.10
Amelanchier canadensis	<0.10	<0.10	0.10
Cupressocyparis leylandii	<0.10	<0.10	0.10
Juglans nigra	<0.10	<0.10	<0.10

Species	Percent Population	Percent Leaf Area	Dominance Value
Acer saccharum	<0.10	<0.10	<0.10
Fraxinus angustifolia 'Raywood'	<0.10	<0.10	<0.10
Salix x chrysocoma	<0.10	<0.10	<0.10
Ulmus x hollandica	<0.10	<0.10	<0.10
Amelanchier	<0.10	<0.10	<0.10
Prunus laurocerasus	<0.10	<0.10	<0.10
Zelkova serrata	<0.10	<0.10	<0.10
Fagus	<0.10	<0.10	<0.10
Prunus subhirtella v. autumnalis	<0.10	<0.10	<0.10
Prunus domestica	<0.10	<0.10	<0.10
Pinus nigra ssp. salzmannii	<0.10	<0.10	<0.10
Quercus robur 'Fastigiata'	<0.10	<0.10	<0.10
Ailanthus altissima	<0.10	<0.10	<0.10
Salix alba	<0.10	<0.10	<0.10
Amelanchier laevis	<0.10	<0.10	<0.10
Magnolia kobus	<0.10	<0.10	<0.10
Crataegus crus-galli	<0.10	<0.10	<0.10
Abies alba	<0.10	<0.10	<0.10
Malus John Downie	<0.10	<0.10	<0.10
Cedrus deodara	<0.10	<0.10	<0.10
Tilia tomentosa	<0.10	<0.10	<0.10
Malus x robusta	<0.10	<0.10	<0.10
Quercus/live ilex	<0.10	<0.10	<0.10
Ilex	<0.10	<0.10	<0.10
Prunus serotina	<0.10	<0.10	<0.10
Sorbus commixta	<0.10	<0.10	<0.10
Malus x soulardii	<0.10	<0.10	<0.10
Prunus sargentii	<0.10	<0.10	<0.10
Cedrus atlantica v. glauca	<0.10	<0.10	<0.10
Pinus wallichiana	<0.10	<0.10	<0.10
Fraxinus pennsylvanica	<0.10	<0.10	<0.10

Species	Percent Population	Percent Leaf Area	Dominance Value
Sorbus thibetica 'John Mitchell'	<0.10	<0.10	<0.10
Cupressus	<0.10	<0.10	<0.10
Koelreuteria paniculata	<0.10	<0.10	<0.10
Acer davidii	<0.10	<0.10	<0.10
Betula papyrifera	<0.10	<0.10	<0.10
Syringa vulgaris	<0.10	<0.10	<0.10
Pyrus salicifolia	<0.10	<0.10	<0.10
Fraxinus velutina	<0.10	<0.10	<0.10
Tsuga heterophylla	<0.10	<0.10	<0.10
Ostrya carpinifolia	<0.10	<0.10	<0.10
Ilex x altaclarensis	<0.10	<0.10	<0.10
Laburnum	<0.10	<0.10	<0.10
Acer pensylvanicum	<0.10	<0.10	<0.10
Abies	<0.10	<0.10	<0.10
Nothofagus	<0.10	<0.10	<0.10
Sorbus latifolia	<0.10	<0.10	<0.10
Crataegus prunifolia	<0.10	<0.10	<0.10
Alnus viridis	<0.10	<0.10	<0.10
Sorbus vilmorinii	<0.10	<0.10	<0.10
Cornus mas	<0.10	<0.10	<0.10
Sorbus torminalis	<0.10	<0.10	<0.10
Parrotia persica	<0.10	<0.10	<0.10
Cedrus atlantica	<0.10	<0.10	<0.10
Prunus serrulata 'Accolade'	<0.10	<0.10	<0.10
Magnolia	<0.10	<0.10	<0.10
Picea	<0.10	<0.10	<0.10
Buddleja davidii	<0.10	<0.10	<0.10
Sophora japonica	<0.10	<0.10	<0.10
Crataegus laciniata	<0.10	<0.10	<0.10
Alnus rubra	<0.10	<0.10	<0.10
Pinus pinea	<0.10	<0.10	<0.10

Species	Percent Population	Percent Leaf Area	Dominance Value
Cercis siliquastrum	<0.10	<0.10	<0.10
Picea sitchensis	<0.10	<0.10	<0.10
Picea omorika	<0.10	<0.10	<0.10
Cercidiphyllum japonicum	<0.10	<0.10	<0.10
Eucalyptus gunnii	<0.10	<0.10	<0.10

Appendix III. Tree Values by Species

Species	Trees	Carbon Storage (Tonnes)	Gross Carbon Seq (Tonnes/Yr)	Avoided Runoff (m^3/Yr)	Pollution Removal (Tonne/Yr)	Replacement Cost (£)
Tilia x europaea	3057	2007.72	40.23	2017.38	0.58	£ 9960443.63
Acer pseudoplatanus	3801	2599.50	55.13	2176.47	0.63	£ 8300530.67
Fraxinus excelsior	2469	995.64	22.50	921.95	0.27	£ 3746247.74
Platanus x acerifolia	961	1166.58	20.70	908.95	0.26	£ 3471634.64
Quercus robur	1520	929.76	19.55	466.42	0.13	£ 2419046.12
Acer platanoides	967	360.78	9.45	418.59	0.12	£ 1164990.94
Fagus sylvatica	437	396.85	7.45	299.71	0.09	£ 1029315.57
Prunus Kanzan	1290	400.47	13.29	278.60	0.08	£ 917595.73
Sorbus intermedia	565	238.52	6.50	157.74	0.05	£ 798125.77
Aesculus hippocastanum	277	397.59	6.51	183.68	0.05	£ 756807.95
Prunus serrulata	1287	297.78	10.05	219.90	0.06	£ 727470.05
Prunus	1117	303.45	10.37	224.10	0.06	£ 700932.33
Prunus avium	566	195.37	6.21	130.56	0.04	£ 526049.85
Sorbus aria	538	151.39	4.96	126.35	0.04	£ 497498.31
Tilia	374	95.10	2.52	128.46	0.04	£ 462450.83
Crataegus monogyna	976	155.05	6.04	83.40	0.02	£ 440928.43
Sorbus aucuparia	1438	113.68	5.14	131.84	0.04	£ 350788.46
Betula pendula	686	124.64	5.09	91.18	0.03	£ 334419.62
Malus	1572	89.60	4.89	130.81	0.04	£ 314164.05
Tilia cordata	528	52.29	1.41	58.26	0.02	£ 272604.71
Populus x canadensis	284	57.63	1.75	44.00	0.01	£ 205507.95
Prunus padus	405	70.51	2.87	66.88	0.02	£ 189978.50
Quercus petraea	68	72.36	1.47	30.10	0.01	£ 188180.76
Malus sylvestris	461	60.82	2.76	65.74	0.02	£ 179186.73
Salix caprea	239	56.86	1.82	41.28	0.01	£ 172570.38
Prunus serrula	202	75.62	2.11	41.46	0.01	£ 167233.23
Acer campestre	917	50.13	2.64	109.67	0.03	£ 161591.85
Tilia platyphyllos	161	25.10	0.81	39.77	0.01	£ 123477.69

Species	Trees	Carbon Storage (Tonnes)	Gross Carbon Seq (Tonnes/Yr)	Avoided Runoff (m^3/Yr)	Pollution Removal (Tonne/Yr)	Replacement Cost (£)
Populus nigra v. italica	46	30.84	0.66	18.23	0.01	£ 113125.83
Pinus nigra ssp. Nigra	54	13.09	0.30	15.02	<0.01	£ 92645.31
Alnus glutinosa	143	28.19	0.87	25.09	0.01	£ 85685.57
Alnus cordata	140	24.45	0.90	27.70	0.01	£ 80060.13
Carpinus betulus	140	23.39	0.89	31.02	0.01	£ 78123.93
Ilex aquifolium	204	23.12	0.92	14.66	<0.01	£ 74513.77
Pinus nigra	15	10.97	0.18	4.68	<0.01	£ 69076.81
Corylus avellana	82	20.38	0.51	12.62	<0.01	£ 65238.46
Pyrus calleryana 'Chanticleer'	486	11.59	0.80	14.12	<0.01	£ 62171.94
Prunus x hiliieri	390	17.97	0.94	24.40	0.01	£ 59746.75
Populus nigra	26	19.99	0.31	9.10	<0.01	£ 59127.54
Malus tschonoskii	86	18.14	0.71	15.61	<0.01	£ 57056.13
Acer	70	17.08	0.53	22.43	0.01	£ 53430.79
Carpinus betulus 'Fastigiata'	184	15.97	0.79	31.30	0.01	£ 52508.56
Castanea sativa	8	17.99	0.27	7.55	<0.01	£ 50080.31
Populus	19	15.74	0.31	7.59	<0.01	£ 49680.74
Aesculus x carnea	18	14.57	0.34	12.68	<0.01	£ 47267.32
Betula pubescens	132	17.02	0.75	18.89	0.01	£ 46840.93
Pinus sylvestris	121	5.95	0.19	8.54	<0.01	£ 45302.90
Crataegus laevigata	475	7.17	0.55	11.66	<0.01	£ 44469.53
Sambucus nigra	133	13.61	0.54	6.50	<0.01	£ 43052.18
Ulmus glabra	67	30.70	0.66	26.89	0.01	£ 40858.26
Taxus baccata	34	6.07	0.15	10.57	<0.01	£ 40629.01
Prunus cerasus	50	16.93	0.50	10.45	<0.01	£ 36509.49
Quercus	40	13.11	0.33	6.88	<0.01	£ 34051.83
Betula ermanii	433	1.60	0.38	13.02	<0.01	£ 33543.04
Prunus x yedoensis 'Akebono'	30	14.14	0.39	8.51	<0.01	£ 33365.79
Pyrus	77	10.55	0.47	8.06	<0.01	£ 33167.11
Crataegus	96	10.51	0.48	6.32	<0.01	£ 31342.17

Species	Trees	Carbon Storage (Tonnes)	Gross Carbon Seq (Tonnes/ Yr)	Avoided Runoff (m³/Yr)	Pollution Removal (Tonne/ Yr)	Replacement Cost (£)	
Liquidambar styraciflua	449	5.43	0.40	19.44	0.01	£	29647.71
Alnus	29	8.85	0.26	7.31	<0.01	£	28519.80
Acer saccharinum	32	8.28	0.21	9.97	<0.01	£	28285.63
Salix fragilis	24	9.82	0.24	5.55	<0.01	£	28051.98
Quercus cerris	30	11.45	0.27	5.66	<0.01	£	26678.17
Ulmus procera	60	17.34	0.50	22.19	0.01	£	26335.24
Corylus colurna	249	4.14	0.36	14.51	<0.01	£	25790.09
Populus alba	25	6.45	0.18	4.45	<0.01	£	25255.13
Salix babylonica	8	7.54	0.17	3.79	<0.01	£	25026.99
Ulmus	105	19.51	0.49	21.30	0.01	£	24264.60
Tilia euchlora	15	4.49	0.12	6.31	<0.01	£	23217.52
Populus canescens	41	6.54	0.20	4.67	<0.01	£	22860.32
Malus floribunda	76	7.92	0.39	9.58	<0.01	£	22401.82
Sorbus	245	2.21	0.25	7.63	<0.01	£	21883.95
Fraxinus angustifolia	44	5.55	0.20	7.82	<0.01	£	20590.08
Prunus serrulata 'Umineko'	295	0.99	0.25	8.12	<0.01	£	19233.70
Fraxinus	40	4.86	0.18	7.46	<0.01	£	19119.15
Chamaecyparis lawsoniana	29	4.05	0.12	4.27	<0.01	£	18886.14
Robinia pseudoacacia	27	6.25	0.21	5.85	<0.01	£	18760.71
Betula utilis	108	6.34	0.43	10.07	<0.01	£	17263.16
Salix x chrysocoma	6	5.23	0.12	2.75	<0.01	£	17196.61
Tilia cordata 'Greenspire'	66	2.74	0.12	6.12	<0.01	£	16829.09
Ginkgo biloba	208	2.87	0.29	7.50	<0.01	£	16182.65
Prunus serrulata 'Amanogawa'	37	6.49	0.27	6.40	<0.01	£	15577.00
Quercus rubra	24	5.05	0.19	5.35	<0.01	£	15407.57
Malus x purpurea	61	5.62	0.30	7.51	<0.01	£	15034.86
Acer cappadocicum	8	4.67	0.10	3.77	<0.01	£	14978.66
Prunus pissardii	44	6.47	0.31	7.08	<0.01	£	14395.49
Aesculus	7	5.42	0.12	4.51	<0.01	£	14325.05
Alnus incana	19	4.80	0.16	4.83	<0.01	£	14290.63

Species	Trees	Carbon Storage (Tonnes)	Gross Carbon Seq (Tonnes/ Yr)	Avoided Runoff (m^3/Yr)	Pollution Removal (Tonne/ Yr)	Replacement Cost (£)	
Tilia tomentosa	2	4.02	0.04	1.36	<0.01	£	13613.34
Prunus spinosa	41	5.14	0.24	5.75	<0.01	£	13368.75
Metasequoia glyptostroboides	49	2.83	0.13	6.95	<0.01	£	12595.31
Pinus	115	2.51	0.16	6.78	<0.01	£	12420.86
Salix	12	3.93	0.12	2.96	<0.01	£	12218.79
Cotoneaster	36	4.92	0.24	6.09	<0.01	£	11521.72
Crataegus x lavallei	160	0.68	0.13	4.28	<0.01	£	11308.32
Quercus palustris	83	4.63	0.32	8.05	<0.01	£	10809.51
Betula utilis ssp. jacquemontii	99	3.71	0.30	7.49	<0.01	£	10790.16
Cedrus deodara	3	1.53	0.03	1.15	<0.01	£	10346.02
Malus domestica	24	3.19	0.14	3.33	<0.01	£	9658.63
Fraxinus ornus	22	2.67	0.11	4.32	<0.01	£	9438.35
Cupressocyparis leylandii	11	1.96	0.06	2.05	<0.01	£	9293.56
Sorbus x thuringiaca	18	2.48	0.09	2.23	<0.01	£	8678.13
Gleditsia triacanthos v. inermis 'Sunburst'	93	1.73	0.15	2.92	<0.01	£	8288.04
Betula	80	1.95	0.16	4.29	<0.01	£	8091.00
Populus tremula	23	1.88	0.09	2.24	<0.01	£	7543.32
Corylus	26	2.33	0.11	3.57	<0.01	£	7392.26
Laburnum anagyroides	20	3.66	0.12	3.45	<0.01	£	7278.53
Prunus cerasifera	28	3.77	0.18	3.96	<0.01	£	7225.85
Acer saccharum	7	2.74	0.09	2.79	<0.01	£	7215.73
Salix alba	6	1.99	0.05	1.15	<0.01	£	6564.66
Gleditsia triacanthos	64	2.43	0.18	3.73	<0.01	£	6472.19
Pyrus communis	22	1.95	0.10	1.68	<0.01	£	6341.75
Juglans nigra	6	1.83	0.06	3.21	<0.01	£	6157.58
Malus x soulardii	3	1.93	0.04	0.67	<0.01	£	6109.84
Acer rubrum	52	1.09	0.09	3.36	<0.01	£	5278.41
Prunus subhirtella v. autumnalis	6	2.09	0.07	1.71	<0.01	£	5237.85

Species	Trees	Carbon Storage (Tonnes)	Gross Carbon Seq (Tonnes/ Yr)	Avoided Runoff (m³/Yr)	Pollution Removal (Tonne/ Yr)	Replacement Cost (£)	
Fraxinus angustifolia 'Raywood'	10	1.32	0.04	1.59	<0.01	£	5184.52
Larix decidua	35	2.13	0.08	5.13	<0.01	£	4935.79
Picea abies	36	1.33	0.06	3.09	<0.01	£	4643.17
Ulmus x hollandica	5	3.07	0.07	2.67	<0.01	£	4344.13
Acer rubrum 'October glory'	55	0.17	0.04	1.80	<0.01	£	4221.56
Ailanthus altissima	5	1.22	0.05	1.61	<0.01	£	3637.54
Tilia americana 'Redmond'	46	0.09	0.02	1.17	<0.01	£	3553.13
Celtis australis	19	1.37	0.08	4.52	<0.01	£	3411.49
Liriodendron tulipifera	39	0.34	0.04	2.48	<0.01	£	3079.12
Sorbus latifolia	1	0.82	0.02	0.47	<0.01	£	2912.37
Fagus	7	3.71	0.03	1.63	<0.01	£	2827.46
Ulmus 'New Horizon'	87	0.23	0.06	2.81	<0.01	£	2329.28
Malus x robusta	4	0.66	0.03	0.68	<0.01	£	2123.49
Acer pensylvanicum	1	0.60	0.01	0.57	<0.01	£	2070.97
Prunus domestica	8	1.26	0.05	1.09	<0.01	£	1898.12
Ilex x altaclarensis	2	0.56	0.02	0.33	<0.01	£	1879.95
Sorbus thibetica 'John Mitchell'	2	0.48	0.02	0.51	<0.01	£	1580.38
Tsuga heterophylla	1	0.18	<0.01	0.67	<0.01	£	1575.76
Crataegus crus-galli	7	0.43	0.02	0.35	<0.01	£	1494.74
Zelkova carpinifolia	21	0.50	0.05	1.24	<0.01	£	1491.03
Betula albosinensis	18	0.05	0.01	0.52	<0.01	£	1440.00
Tilia mongolica	18	0.10	0.02	0.68	<0.01	£	1388.44
Prunus dulcis	14	0.87	0.06	1.26	<0.01	£	1361.98
Nothofagus	1	0.56	0.02	0.47	<0.01	£	1293.64
Fraxinus pennsylvanica	2	0.20	0.01	0.56	<0.01	£	1201.24
Amelanchier canadensis	16	0.34	0.03	0.61	<0.01	£	1176.69
Ilex	5	0.30	0.02	0.32	<0.01	£	1062.00
Prunus laurocerasus	10	0.49	0.04	0.82	<0.01	£	1017.50
Cupressus	3	0.25	0.01	0.18	<0.01	£	960.43

Species	Trees	Carbon Storage (Tonnes)	Gross Carbon Seq (Tonnes/ Yr)	Avoided Runoff (m^3/Yr)	Pollution Removal (Tonne/ Yr)	Replacement Cost (£)	
Amelanchier	12	0.16	0.02	0.40	<0.01	£	908.44
Pinus nigra ssp. salzmannii	11	0.02	<0.01	0.16	<0.01	£	897.19
Malus John Downie	5	0.41	0.02	0.63	<0.01	£	880.93
Zelkova serrata	11	0.16	0.02	0.50	<0.01	£	784.45
Crataegus prunifolia	2	0.27	0.01	0.16	<0.01	£	754.05
Quercus robur 'Fastigiata'	10	0.13	0.02	0.40	<0.01	£	750.00
Prunus sargentii	4	0.23	0.01	0.30	<0.01	£	694.27
Syringa vulgaris	3	0.22	0.01	0.13	<0.01	£	630.97
Magnolia kobus	8	0.02	0.01	0.27	<0.01	£	629.06
Prunus serrulata 'Accolade'	1	0.25	0.01	0.25	<0.01	£	609.76
Amelanchier laevis	8	0.12	0.01	0.28	<0.01	£	605.63
Sorbus commixta	4	0.22	0.01	0.39	<0.01	£	598.31
Acer davidii	2	0.25	0.01	0.45	<0.01	£	567.84
Fraxinus velutina	2	0.18	0.01	0.38	<0.01	£	499.09
Prunus serotina	4	0.25	0.02	0.41	<0.01	£	495.26
Quercus/live ilex	5	0.20	0.02	0.32	<0.01	£	479.03
Magnolia	1	0.14	0.01	0.23	<0.01	£	432.70
Cedrus atlantica v. glauca	4	0.09	0.01	0.17	<0.01	£	424.04
Abies	2	0.11	0.01	0.20	<0.01	£	423.38
Picea	1	0.12	0.01	0.18	<0.01	£	399.39
Laburnum	2	0.18	0.01	0.31	<0.01	£	399.05
Pinus wallichiana	4	0.01	<0.01	0.05	<0.01	£	307.50
Abies alba	6	0.15	0.01	0.38	<0.01	£	304.42
Crataegus laciniata	1	0.12	0.01	0.08	<0.01	£	304.33
Pyrus salicifolia	3	0.07	0.01	0.10	<0.01	£	241.33
Betula papyrifera	3	0.05	0.01	0.14	<0.01	£	230.62
Ostrya carpinifolia	3	<0.01	<0.01	0.05	<0.01	£	207.55
Koelreuteria paniculata	3	0.04	0.01	0.18	<0.01	£	203.42
Alnus viridis	2	0.04	<0.01	0.16	<0.01	£	169.14
Cedrus atlantica	2	0.02	<0.01	0.04	<0.01	£	158.44

Species	Trees	Carbon Storage (Tonnes)	Gross Carbon Seq (Tonnes/ Yr)	Avoided Runoff (m^3/Yr)	Pollution Removal (Tonne/ Yr)	Replacement Cost (£)
Buddleja davidii	1	0.08	0.01	0.16	<0.01	£ 157.65
Sophora japonica	1	0.08	0.01	0.12	<0.01	£ 157.65
Sorbus vilmorinii	2	0.03	<0.01	0.08	<0.01	£ 153.75
Sorbus torminalis	2	0.02	<0.01	0.08	<0.01	£ 153.75
Parrotia persica	2	0.02	<0.01	0.05	<0.01	£ 139.75
Cornus mas	2	0.02	<0.01	0.08	<0.01	£ 101.47
Pinus pinea	1	0.02	<0.01	0.05	<0.01	£ 87.58
Picea sitchensis	1	0.01	<0.01	0.03	<0.01	£ 76.88
Cercis siliquastrum	1	0.01	<0.01	0.05	<0.01	£ 67.81
Cercidiphyllum japonicum	1	<0.01	<0.01	0.02	<0.01	£ 67.81
Alnus rubra	1	0.04	<0.01	0.08	<0.01	£ 66.22
Picea omorika	1	0.01	<0.01	0.02	<0.01	£ 50.74
Eucalyptus gunnii	1	0.02	<0.01	0.01	<0.01	£ 50.74
Total	35,108	12,312.74	302.19	10,415.04	3.01	£41,156,409.84

Appendix IV. Notes on Methodology

Data Formatting

Tables 7 to 10, below show the list of edits which were made for this project, to enable the street tree inventory to be processed.

In total 35,274 records were provided.

Reason for Removal	Details	Number of records removed
No Species	There is no data in this field (a minimum requirement for Eco)	31
No DBH	There is no data in this field (a minimum requirement for Eco)	135
	NUMBER OF RECORDS REMOVED	**166**

Table 7: Inventory Records removed for use in Eco

Condition Text	Eco Condition Text	Eco Equivalent
Good	Good	87%
Fair	Fair	82%
Poor	Poor	62%
Dead	Dead	0%
N/A	Fair	82%
Senescent	Fair	82%
Terminal Decline	Poor	62%
Vandalised	Poor	62%

Table 8: Condition Ratings for use in Eco

DBH Band Provided (cm)	Height (m)	Number of Records
2 -10	3	316
16 - 20	10	2
21 - 40	15	30
40 +	20	2

Table 9: Missing Height Regression table for use in Eco

Crown Condtion	SLE Value	SLE Percentage
92%	80+	100%
87%	40 - 80	95%
82%	20 - 40	80%
62%	10 - 20	55%
0	0	0%

Table 10: CAVAT Safe Life Expectancy Estimates

i-Tree Methodology

i-Tree Eco is designed to use standardised field data and local hourly air pollution and meteorological data to quantify forest structure and its numerous effects, including:

- Forest structure (e.g., species composition, tree health, leaf area, etc.).
- Amount of pollution removed hourly by trees, and its associated percent air quality improvement throughout a year. Pollution removal is calculated for ozone, sulphur dioxide, nitrogen dioxide, carbon monoxide and particulate matter (<2.5 microns).
- Total carbon stored and net carbon annually sequestered by trees.
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power plants.
- Structural value of the forest, as well as the value for air pollution removal and carbon storage and sequestration.
- Potential impact of infestations by pests, such as Asian Longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease.

To calculate current carbon storage, biomass for each tree was calculated using equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations[18]. To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8. No adjustment was made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

To estimate the gross amount of carbon sequestered annually, average diameter growth from the appropriate genera and diameter class and tree condition was added to the existing tree diameter (year x) to estimate tree diameter and carbon storage in year x+1.

The amount of oxygen produced is estimated from carbon sequestration based on atomic weights: net O2 release (kg/yr) = net C sequestration (kg/yr) × 32/12. To estimate the net carbon sequestration

[18] Nowak 1994

rate, the amount of carbon sequestered as a result of tree growth is reduced by the amount lost resulting from tree mortality. Thus, net carbon sequestration and net annual oxygen production of trees account for decomposition[19].

Recent updates (2011) to air quality modelling are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values.

Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulphur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models[20]. As the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average measured values from the literature[21] [22] that were adjusted depending on leaf phenology and leaf area. Particulate removal incorporated a 50 percent resuspension rate of particles back to the atmosphere[23].Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Although tree leaves, branches and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis. The value of avoided runoff is based on estimated or user-defined local values. The local values include the cost of treating the water as part of a combined sewage system from Yorkshire Water.

Replacement Costs were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition and location information[24] [25].

For a full review of the model see UFORE (2010) and Nowak and Crane (2000).
For UK implementation see Rogers et al (2014).
Full citation details are located in the bibliography section

CAVAT

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19 Nowak, David J., Hoehn, R., and Crane, D. 2007.

20 Baldocchi 1987, 1988

21 Bidwell and Fraser 1972

22 Lovett 1994

23 Zinke 1967

24 Hollis, 2007

25 Rogers et al (2012)

An amended CAVAT method was chosen to assess the trees in this study, in conjunction with the CAVAT steering group (as done with previous i-Tree Eco studies in the UK).
In calculating CAVAT the following data sets are required:

- The current Unit Value,
- Diameter at Breast Height (DBH),
- The CTI (Community Tree Index) rating, reflecting local population density
- An assessment of accessibility,
- An assessment of overall functionality, (that is the health and completeness of the crown of the tree);
- An assessment of Safe Life Expectancy.

The current Unit Value is determined by the CAVAT steering group and is currently set at £15.88 (LTOA 2012).

DBH is taken directly from the field measurements.

The CTI rating is determined from the approved list (LTOA 2012) and is calculated on a borough by borough basis. The CTI for Sheffield is 1.00, thereby increasing the basic CAVAT value.

Accessibility, i.e. the ability of the public to benefit from the amenity value of trees, was generally judged to be 100% for trees in Parks, street trees and other open areas, and was generally reduced for residential areas and transportation networks to 60% (increased to 100% if the tree was on the street), to 80% on institutional land uses and to 40% on Agricultural plots. For this study, park trees and street trees only were included, with 100% accessibility therefore assumed.

The Safe Useful Life Expectancy (SULE) was based upon the condition assessment. This therefore may not be fully accurate, especially for each individual tree.

For full details of the method refer to Doick, et al (2018)26

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26 Doick, *et al* (2018)

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