Valuing Exeter's Urban Forest

Treeconomics

Exeter City Council

devontreeservices

i-Tree

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The project was carried out by Treeconomics with fieldwork support from Devon Tree Services. Field survey data was collected by volunteers and surveyors during the summers of 2019 and 2020.

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Executive Summary

The urban forest of Exeter is a vital resource, providing numerous benefits to the people who live, work and visit the city. The ecosystem services highlighted within this report are just some of the benefits the urban forest provides; work is ongoing to value and report additional ecosystem services relating health, wellbeing and biodiversity. This study captures an immediate snapshot of the urban forest at the time the data was collected, in relation to the plots sampled.

The purpose of this report is to provide clear, concise information on the urban forest resource as a means to assist decision making on urban forest management.

Key findings include:

- There are approximately 179,000 trees across Exeter - equivalent to 1.4 trees per person and 38 trees per hectare. Tree cover was estimated at 20.2% with shrub cover at an estimated 11.2%.

- 59 species of tree were recorded across the Exeter study area. The most common tree species are; Ash with an estimated 26,900 trees, English oak with an estimated 18,400 trees, and Sycamore and Silver birch both with an estimated 13,000 trees.

- Exeter's trees and shrubs have the potential to remove approximately 4 tonnes of air pollution every year with an associated value of £279,000. These pollutants include sulphur dioxide (SO_2), particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2).

- Exeter's trees reduce surface water runoff by over 82,000 m^3 per year. This volume is equivalent to nearly 33 Olympic swimming pools of surface runoff being averted every single year, a service worth an estimated £257,000 in avoided water treatment costs.

- In total, the trees store around 61,200 tonnes of carbon and sequester 1,510 tonnes of carbon annually, with associated values of around £56.6 million and £1.4 million respectively.

- The amenity value of the trees was calculated to be £1.32 billion, as determined using a CAVAT valuation approach.

- There is a good distribution of both semi-mature and mature trees, however there are very few large senescent (ancient) trees. Managing trees to ensure they reach their full potential, namely in their stature is important, as large trees provide far more benefits than small trees. However, the planting of young trees is also required to replace dying or removed trees and to further enhance the urban forest.

The recommendations from this study include:

- Continue to plant a wide diversity of species (with due consideration to local site factors) to replace the future loss of ash, and reduce the likelihood of severe impact from any given pest or disease outbreak.
- Aim to retain large, mature trees wherever possible, as large trees provide the most benefits - make them part of developments rather than lose them.
- Continue new planting to maintain a healthy size diversity within Exeter to avoid significant losses in ecosystem service provisions in the future and to address lack of canopy and unequal distribution of the urban forest.
- Carry out a Tree Planting Opportunity Mapping study to target prioritised areas and optimise resources. This can facilitate additional planting alongside main roads, and joining up/filling in gaps within the existing urban forest to enhance wildlife corridors and the connectivity of pathways and cycle lanes through green infrastructure. Tree equity analysis at neighbourhood level can be incorporated to target areas that lack canopy cover, particularly areas with high deprivation and which experience high pollution, surface flooding, limited green space, or lack of shade.
- Set up community tree care schemes to encourage engagement by local people and help to ensure the good health of young trees, particularly new plantings as they are at the most risk from external factors such as drought, disease and even vandalism.
- Consider developing an Urban Forest Master Plan to follow on from this study providing a vision of what the city would like to achieve with its urban forest and step to realise those goals.

Headline Figures

Exeter's Structure and Composition Headline Figures		
Number of Trees (estimate)	179,000	
Tree Density (trees/hectare)	38	
Tree Canopy Cover	20.2% (950 ha)	
Shrub Cover	11.2%	
Most Common Tree Species	European ash (14%), English oak (10.3%), Sycamore (7.3%) & Silver birch (7.3%)	
Replacement Cost (CTLA)	£111 million	
Amenity Valuation (CAVAT)	£1.32 billion	
Proportion of Trees in Good or Excellent Condition	45.1%	
Exeter's Ecosystem Services Headline Figures		
Total Carbon Storage	61,200 tonnes	£56.6 million
Annual Carbon Sequestration	1,510 tonnes	£1,390,000
Annual Pollution Removal	4 tonnes	£279,000
Annual Avoided Runoff	82,000 m^3	£257,000
Total Annual Benefits	£1,926,000	

Table 1: Headline Figures

Reference Values and Methodology Notes for Calculations:

Number of Trees: The sample inventory figures are estimated by extrapolation from the sample plots. For further details see the methodology section.

Tree Canopy/Shrub Cover: The area of ground covered by the leaves of trees and shrubs when viewed from above (not to be confused with leaf area which is the total surface area of leaves). As shrubs can be underneath trees these two figures 'overlap' and have not been added together.

Replacement Cost: The cost of having to replace a tree with a similar tree using the Council of Tree and Landscape Appraisers (CTLA) methodology from the Royal Institute of Chartered Surveyors.

Capital Asset Value for Amenity Trees (CAVAT): A valuation method with a similar basis to the CTLA Trunk Formula Method, but one developed in the UK to express a tree's contribution to public amenity and its prominence in the urban landscape. For i-Tree Eco studies the amended quick method is used.

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 the CO_2 equivalent multiplied by the Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy figures for the non-traded central estimate cost of CO_2. This is currently £252 per metric ton for 2023.

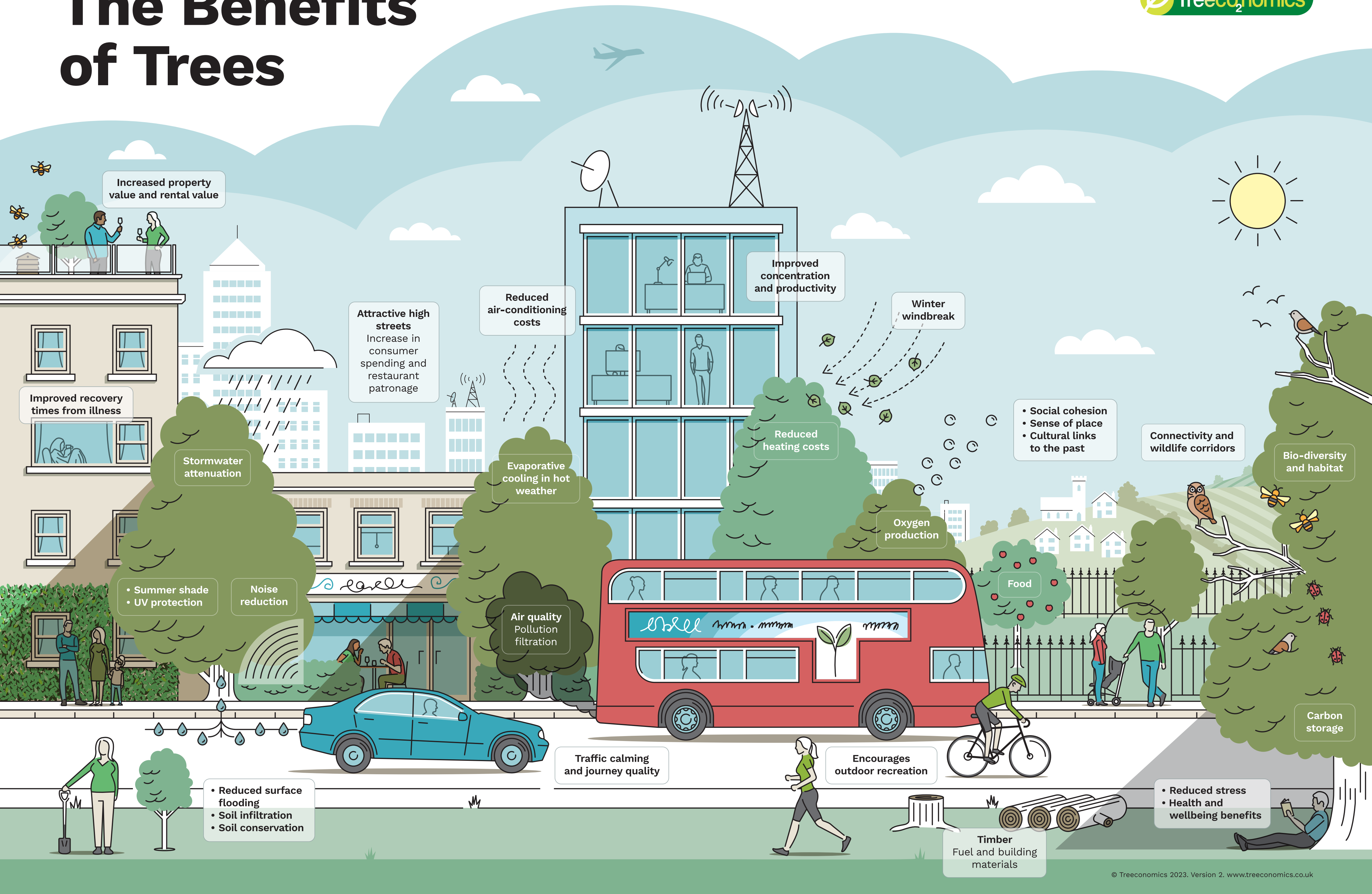
Pollution Removal: This value is calculated based on the 2020 UK social damage costs for 'Road Transport Urban Large'; nitrogen dioxide - £14.633 per kg, sulphur dioxide - £7.064 per kg, particulate matter less than 2.5 microns - £278.213 per kg.

Avoided Run-off: Based on the amount of water held in the tree canopy and re-evaporated after the rainfall event. The value is based on a volumetric charge from South West Water of £3.13 per cubic metre and includes the cost of avoided energy and associated greenhouse gas emissions.

Total Annual Benefits: Sum of the annual monetary values of carbon sequestration, pollution removal and avoided run-off. Carbon storage is not included since it is not an annual benefit, rather it is a portion of all of the carbon that has been sequestered over the lifespan of the tree.

Data was processed using iTree Eco Version 6.0.32.

The Benefits of Trees



Introduction and Background

Exeter, the county seat of Devon, is an ancient city in southwest England. With a rich history dating back to the Roman era, the city is known for its iconic Cathedral, significant role in the wool trade, and more recently its status stemming from a vibrant cultural scene and university. With a population of 128,900 people Exeter remains a relatively small city. The city of Exeter covers an area of 4,705 ha.

This i-Tree Eco study was commissioned by Exeter City Council and provides detailed information on the scale of benefits provided by the urban forest in Exeter, expressing the value of some of those benefits in monetary terms. This study shows how the perception of trees, shrubs and green spaces which make up the urban forest can move from the historic view of a costly liability to an asset for the council and the local community.

The objectives of the study were to:

- Illustrate the structure of the urban forest, including the species composition, diversity, and condition.
- Calculate the ecosystem service and economic values provided by the urban forest using the i-Tree Eco software.
- Promote the urban forest and emphasise the benefits it provides.
- Conduct a risk analysis of the susceptibility of the trees to pests and diseases.
- Explore the urban forest's potential to influence carbon net-zero balances.
- Forecast possible scenarios based on the current composition of the urban forest and future management strategies.

Report Scope

This study investigates the structure and composition of Exeter's urban forest and the benefits it delivers. The report provides baseline information which can be used to inform future decision making and strategy. Understanding the structure and composition of the urban forest is vital to its conservation and development. By showcasing the economic value of benefits provided by Exeter's urban forest, increased awareness can be used to encourage investment in Exeter's natural capital and wider environment.

The assessment presented in this report is fundamental in understanding factors which are critical to a resilient urban forest including:

- Maintaining and improving the current tree canopy cover in Exeter.
- Identifying areas vulnerable to loss of tree cover (e.g. as a result of pests and diseases, or development) which would benefit from new planting or enhanced protection.

This report can be used by:

- Those writing policy.
- Those interested in the conservation of local nature.
- Those involved in strategic planning to build resilience or planning the sustainable development and resilience of Exeter.
- Those who are interested in local trees for improving their own and others' health, wellbeing, and enjoyment across Exeter.

Methodology

To gather a collective representation of Exeter's urban forest across both public and private land, an i-Tree Eco plot-based assessment was undertaken. 260 randomly allocated plots of 0.04ha (400m²) were surveyed in Exeter. This equates to 1 plot every 18.1 ha.

The field data was submitted to the i-Tree server which, combined with local hourly pollution and meteorological data, calculates outputs, some of which are listed in Table 2 below. There are in excess of 100 reports that can be generated by i-Tree Eco and not all are listed here or referenced in this report. As part of this project Exeter City Council's tree management team were provided training in how to use the i-Tree tool and therefore will be able to access all available reports.

Structure and Composition	Species diversity; Tree canopy cover; Age class; Leaf area; Ground cover types; % leaf area by species.
Ecosystem Services	Air pollution removal by trees for NO_2, SO_2, and $PM_{2.5}$; % of total air pollution removed by trees; Current carbon storage; Carbon sequestration; Stormwater attenuation.
Structural and Functional Values	Replacement cost (£); Carbon storage value (£); Carbon sequestration value (£); Pollution removal value (£).
Additional Information	Potential insect and disease impacts; Oxygen production; Forest food production; UV Screening values.

Table 2: Study outputs

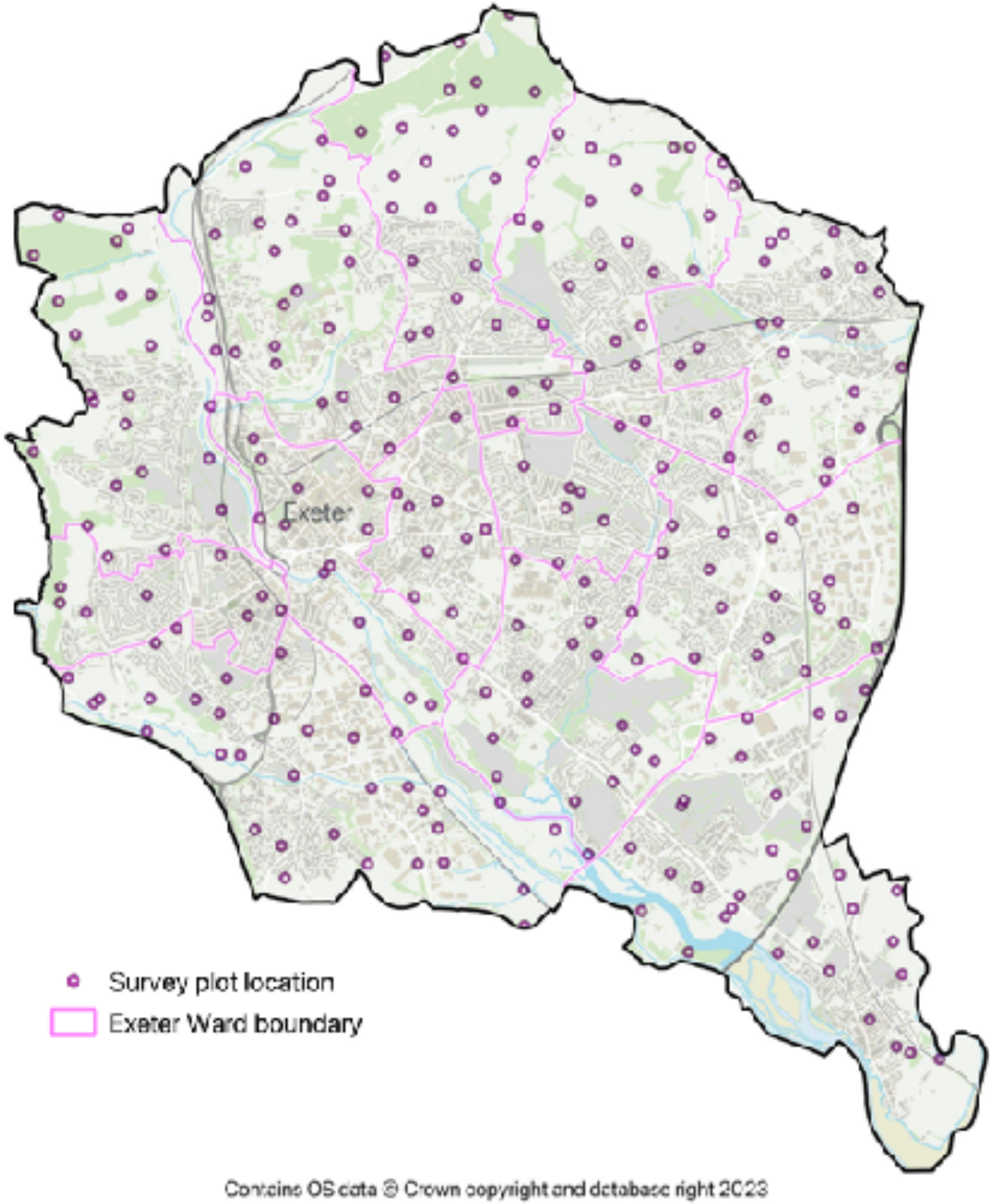


Figure 1: Map of Exeter showing ward boundaries and locations of survey plots

Plots were randomly allocated to ensure a statistically significant distribution across Exeter, as such, they fall on both public and private land. While most areas could be accessed with permission, some could not. In the event plots were inaccessible, back-up plots were used. These were randomly allocated within the same grid square as the original.

Data Limitations

While Exeter's trees provide a plethora of benefits, i-Tree Eco does not quantify all of the services that trees provide; hence, the value of the ecosystem services provided in this report are a conservative estimate. The methodology has been devised to provide a statistically reliable representation of Exeter's urban forest at the time of measurement. This report is concerned with the trees and shrubs within Exeter. It should be used only for generalised information on the urban forest structure, function, and value. Where detailed information for a specific area is required, further detailed survey work should be carried out.

The Urban Forest - The Structural Resource

Tree Canopy Cover

Canopy cover is a basic metric for measuring the extent to which we share our space with trees. Canopy cover can be defined as the area of leaves, branches, and stems of trees covering the ground when viewed from above.

It is a two-dimensional metric indicating the spread of tree canopy across an area, and it can be used to gain a basic understanding of the ecosystem services provided by the urban forest.

A lot of the ecosystem services a tree can provide - such as carbon sequestration, pollution removal and avoided runoff - depends on how healthy and widespread the canopy is. It should be considered that over time the associated benefits of the trees will increase as the trees grow to a larger size, if there are extensive thinning or felling operations or significant damage to the tree population the benefits may fall accordingly.

i-tree Eco has estimated that Exeter has a tree canopy cover of 20.2%. The average for the UK is 16%, though coastal and rural areas are often lower, and peri-urban areas are often higher.

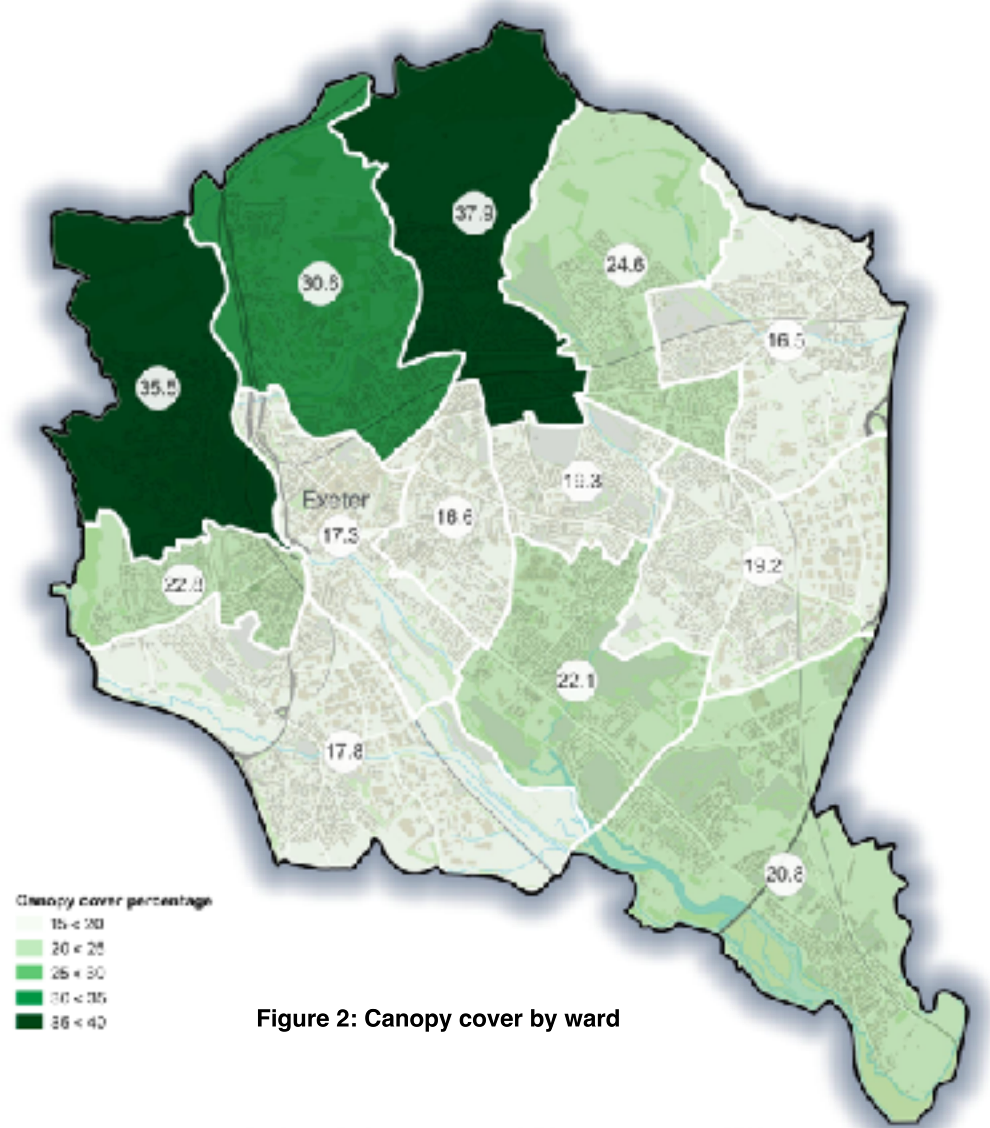


Figure 2: Canopy cover by ward

The data used to create the map above is from Exeter's previous canopy surveys. It estimates an average canopy cover of 23.2%. This data is based on aggregating information from open source satellite imagery and remote sensing surveys through i-Tree Canopy. Previous studies therefore had the capacity to measure significantly higher number of plots or total canopy cover at high resolution. It is important to note that the different approaches will yield different results and a plot based sample project such as this is known to underestimate canopy cover.

Forecasting Tree Canopy cover

Canopy cover and leaf area are often the best measures as proxies for ecosystem services provided by an urban forest. i-Tree Eco includes a powerful forecasting tool that uses structural estimates, environmental and location variables and species characteristics along with growth and mortality rates to predict changes to the urban forest and its benefits over time[1].

The forecasting tool allows adjustment of many variables that impact urban forests. Therefore the diagram in Figure 3 is an illustrative example only. It is based on Exeters current canopy cover and 3 potential scenarios of urban forestry management - the ‘Do Nothing’, the ‘Business as usual’ and the ‘Ideal’ scenarios. To achieve accurate numbers of levels of tree planting required to increase canopy cover to over 30%, a full model would need to run, accounting for other variables such as 100-year storm events, tree mortality rates and pests and disease outbreaks. This is beyond the scope of this report.

Figure 3 demonstrates both the time required for effective urban forestry management and the substantial difference successful and neglectful management can result in.

Canopy growth from new planting won’t become significant until the trees mature. This factor, combined with the need to replace dead or diseased trees, means increased canopy from new planting alone can take a very long time to develop.

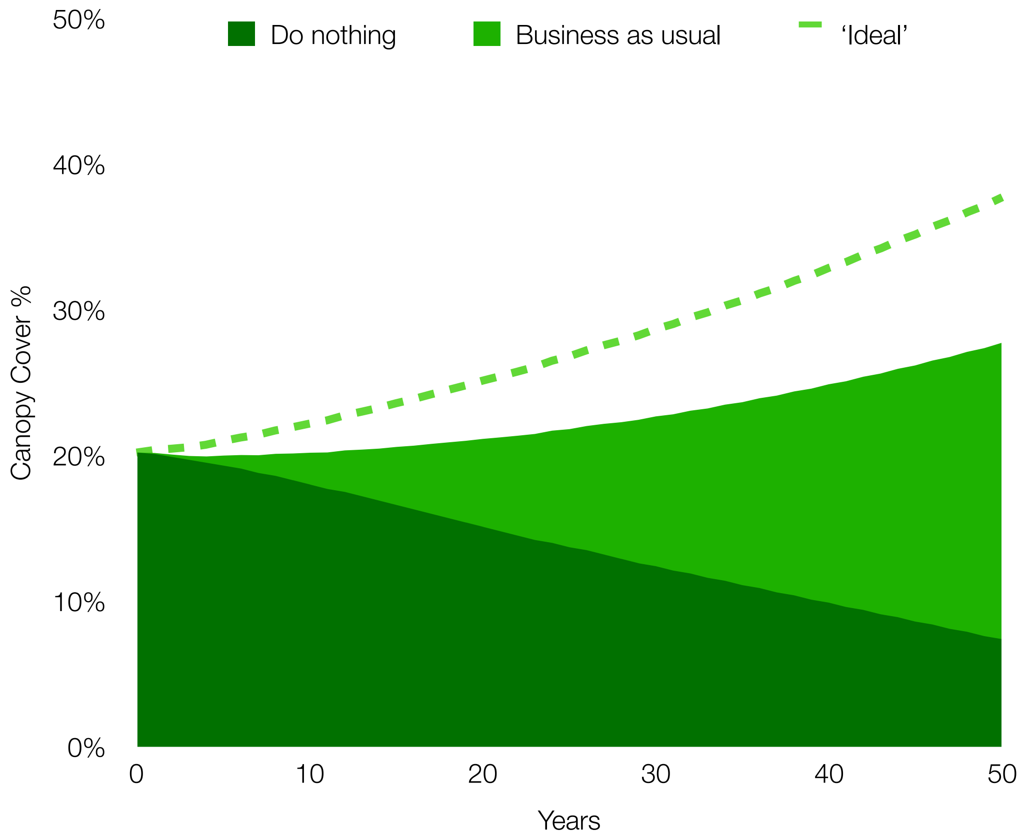


Figure 3: Differing scenarios of urban forest management to achieve increased canopy cover and leaf area.
(based on Exeter’s canopy data)

Scenarios:
Do nothing - no more tree planting takes place
Business as usual - continue tree planting at the same rate as in the past
‘Ideal’ - a conceptual model to achieve 30% canopy cover

Source: Treeconomics

[1] i-Tree (2023)

Ground Cover

Ground cover refers to the types of surface or vegetation within each plot. Within Exeter the most common ground cover types are maintained grasses (25.9%), buildings (13.9%), tar (13.9%) and bare soil (12%).

Of the surveyed area, 20.2% of Exeter is under tree canopy cover, with 11.2% under shrub cover (note that shrubs are also present under tree cover and so these two figures ‘overlap’).

The survey also showed that a further 34.5% of land within the plots could (in theory) be planted with trees. Utilising available space to increase the tree canopy cover is one way to reduce air and noise pollution, and increase carbon sequestration.

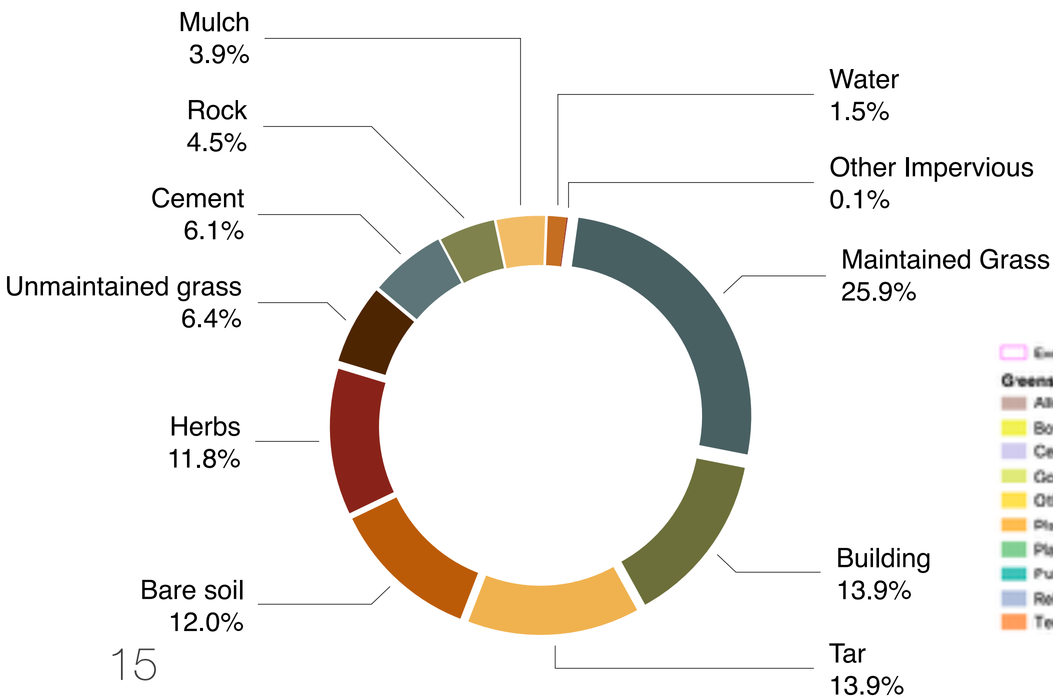


Figure 3: Ground cover types within plots.

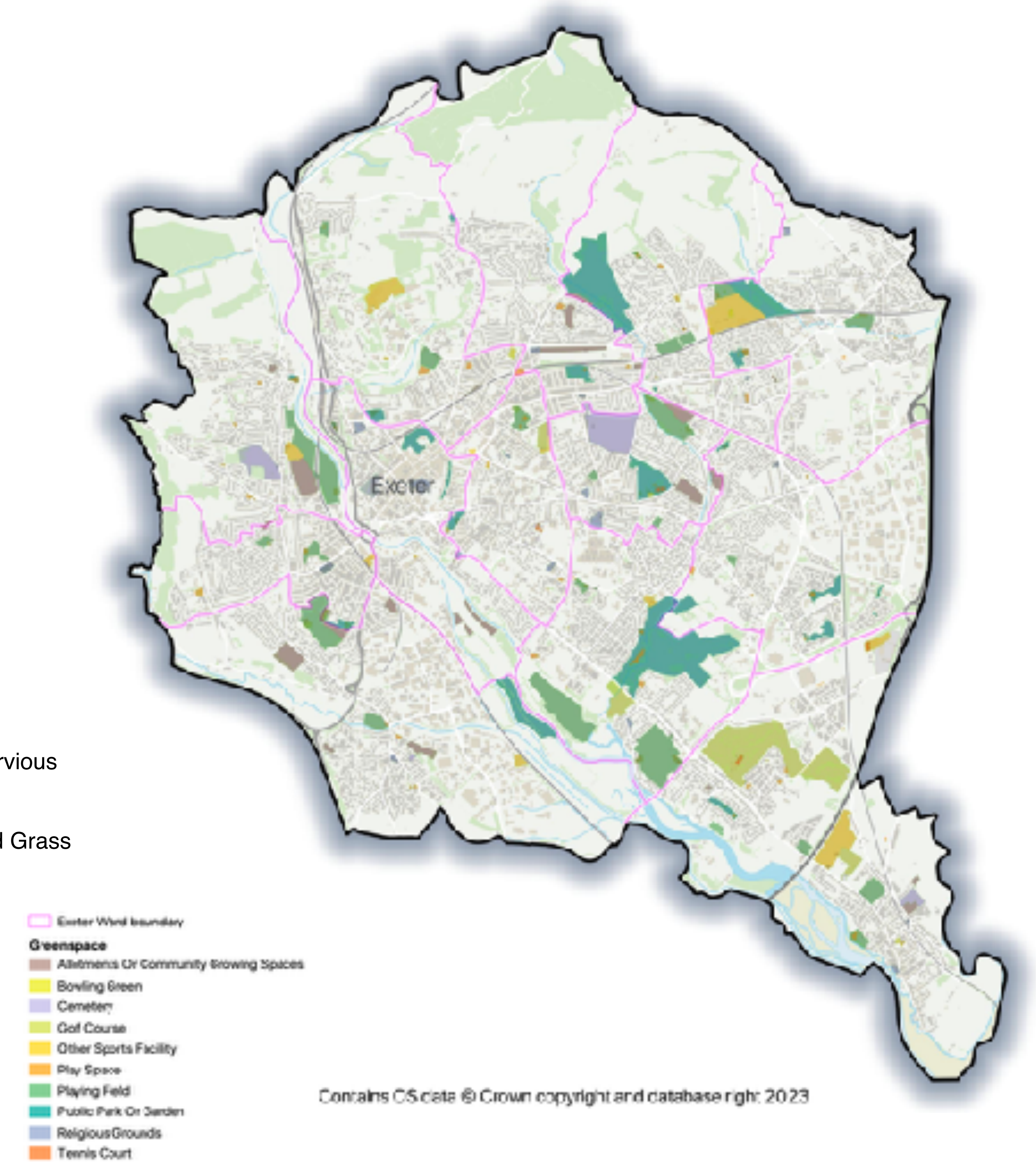


Figure 4: Green space throughout Exeter according to Ordnance Survey official categories

Land Use

Figure 5 shows the average land cover across Exeter. Surveyed plots indicate that on average Exeter's largest land use is residential (31.4%) and agriculture (24.3%). Parks account for 8.9% of land cover across Exeter.

1.5% of land in Exeter is vacant (70.5 ha). This land could potentially be repurposed for tree planting or the creation of new green spaces. Should the 70.5 ha of vacant land be turned over to broadleaved woodland creation, this land could accommodate 112,800 trees (at a spacing of 2.5 x 2.5m/tree). Parkland creation (at a spacing of 25m x 25m/tree) could accommodate 1,128 new trees.

Green spaces make up 38.2% of land cover in Exeter; that is significantly higher than the average for Inner London (21%).

Exeter has been recorded as the 'greenest' city centre in Britain, topping a list of 68 locations of over 100,000 people.*

*(Jones, 2022)

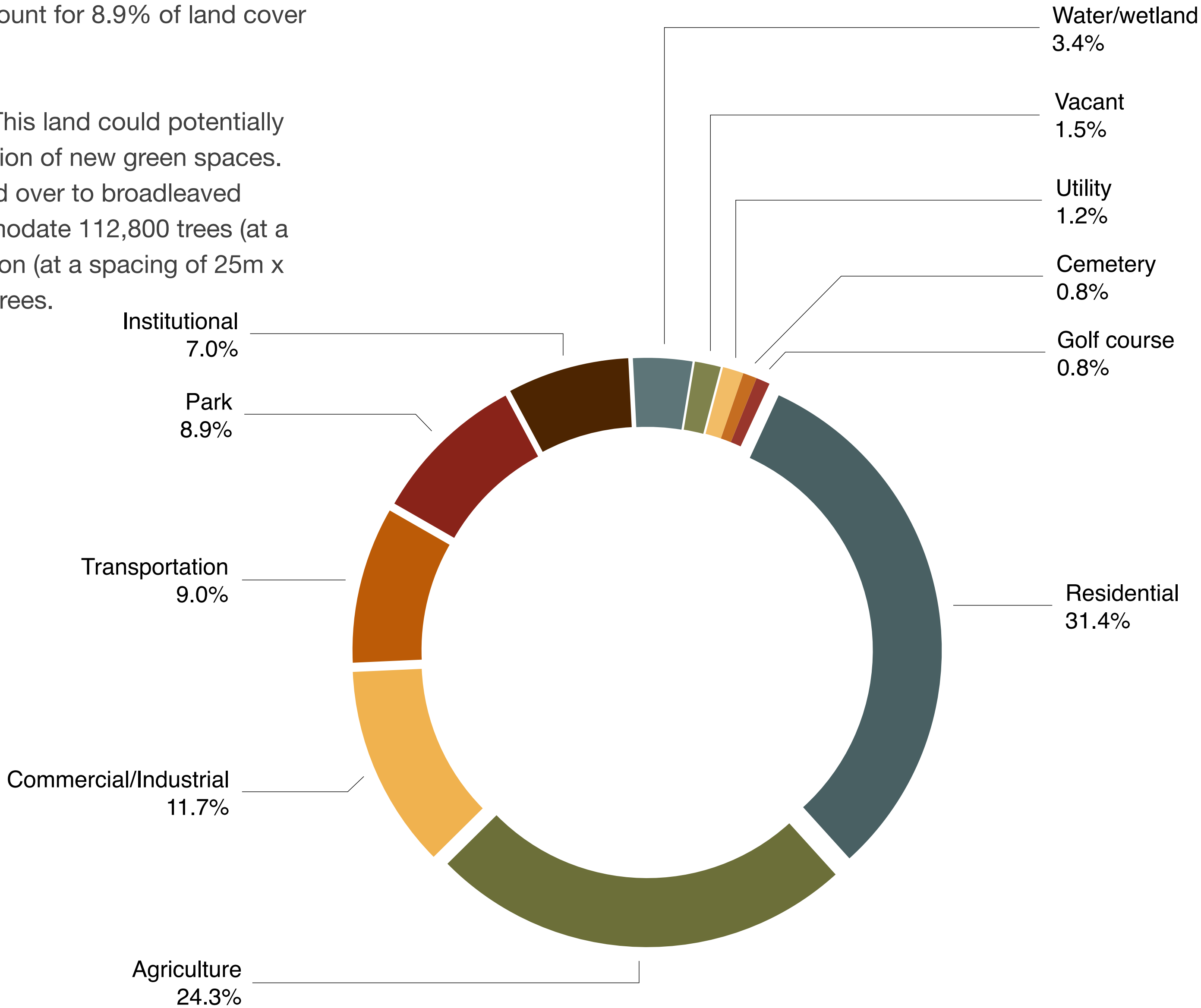


Figure 5: Ground cover types within plots.

Tree Diversity

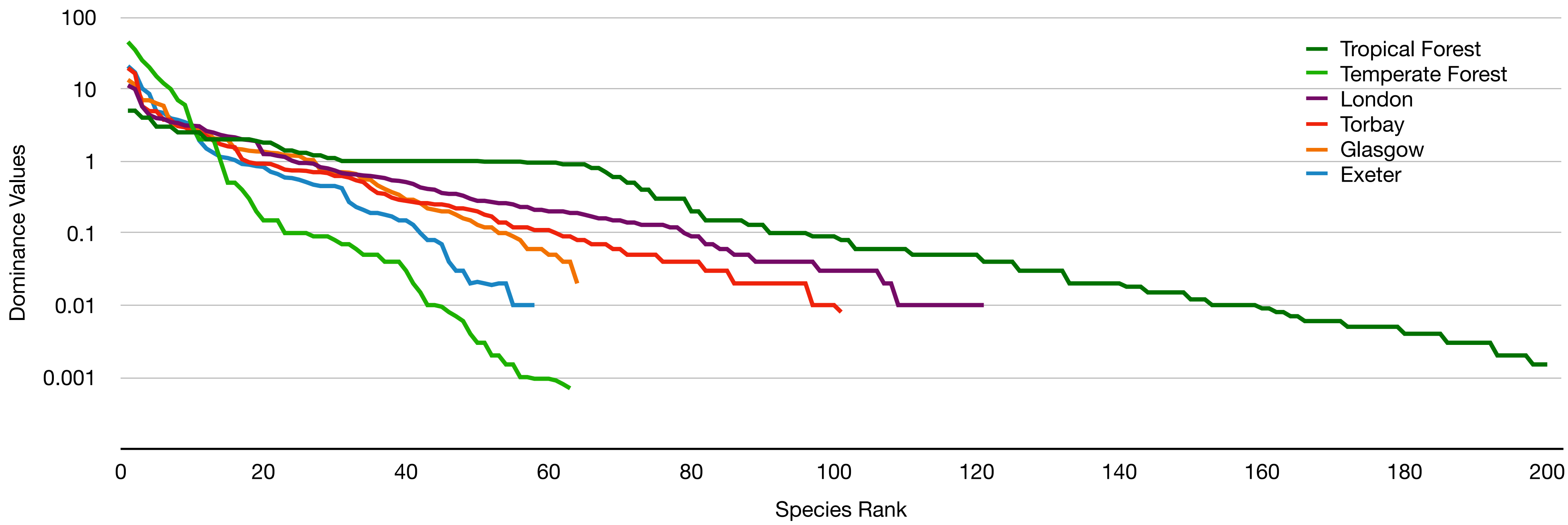


Figure 6: Hubble's Dominance Diversity Curve showing example forest types and selected UK cities.

Many native species are not able to thrive in the artificial environments of our landscaped areas, and the effects of climate change will exacerbate the situation[2]. Maintaining a careful balance of native and non-native species within the population will ensure that habitats are protected whilst providing resilience to our ever-changing climate. Figure 6 shows a dominance diversity curve developed by Hubble.[3]

In this graph, the longer and shallower curves indicate forests with higher diversity and fewer species dominating the population. Challenges exist in valuing biodiversity because it is difficult to identify and measure the passive, non-active use values of biodiversity[4]. However, biodiversity is important because it provides a wide range of indirect benefits to humans.

[2] Gill et al 2007

[3] Hubble, 1970

[4] Nunes et al, 2001

Although i-Tree Eco does not yet calculate a valuation of biodiversity it does provide an indication of tree species diversity using diversity indexes. This is important because the diversity of species within Exeter (both native and non-native) will influence how resilient the tree population will be to future changes, for example by minimising the overall impact of exotic pests, diseases and climate change. These values are provided in Table 3.

Species	Species/ ha	SHANNON	MENHINICK	SIMPSON	EVENNESS
59	5.90	3.40	3.10	18.80	0.80

Table 3: Species richness and diversity indexes for Exeter

- **Species:** is the number of species sampled.
- **Species/ha:** is the average number of species found per hectare of area sampled.
- **SHANNON:** is the Shannon – Wiener diversity index, which assumes that all species within the area have been sampled. It is an indicator of species richness and has a moderate sensitivity to sample size (on this scale, below 1.5 is considered low and over 3.5 is considered high).[5]
- **MENHINICK:** is the Menhinick's index. It is an indicator of species richness and has a low sensitivity to sample size and therefore may be more appropriate for comparison between cities.
- **SIMPSON:** is Simpson's diversity index. It is an indicator of species dominance and has a low sensitivity to sample size and therefore may be more appropriate for comparisons between land use types.
- **EVENNESS**: is the Shannon diversity index, which assumes that all species within the area have been sampled. It is an indicator of species evenness and has a moderate sensitivity to sample size and therefore land use and/or cities may not be comparable.[6]

[5] Gazis, R., Chaverri, P., 2010

[6] i-Tree, 2021

According to most metrics Exeter has a good level of diversity. Whilst Exeter is more diverse than a typical temperate forest, the city still has potential to improve diversity to the level of some other cities in the UK. It is not uncommon for cities to rank highly in diversity often due to non-native tree species.

Exeter has a strong presence of native tree species. These species are important for biodiversity and the ecology of the landscape; however non-native trees will become increasingly important in a changing climate.

Species Richness

The three most common named species are Ash, English Oak, and Sycamore (Figure 7). Some trees were identified at genus level only, however these have not been included in this species level analysis to avoid mixing metrics, and are instead included in 'All Other'.

The ten most common species account for 68.2% of the total population. In total, 59 tree species were recorded in the survey. Increased tree diversity has the potential to minimise the impact upon or destruction of species by specific pathogens and diseases as well as from the effects of climate change; however, there can also be an increased risk to the native tree population and surrounding biodiversity.

Exeter's urban forest has a variety of species present, with only two species exceeding 10% of the total population. With new tree planting, Santamour's 10:20:30 tree population diversity rule[7] would therefore be achievable in the near future, indicating that the urban forest has potential to be more resilient to pests and diseases. The most prominent threats in this regard are Ash Dieback and various threats to the substantial oak population.

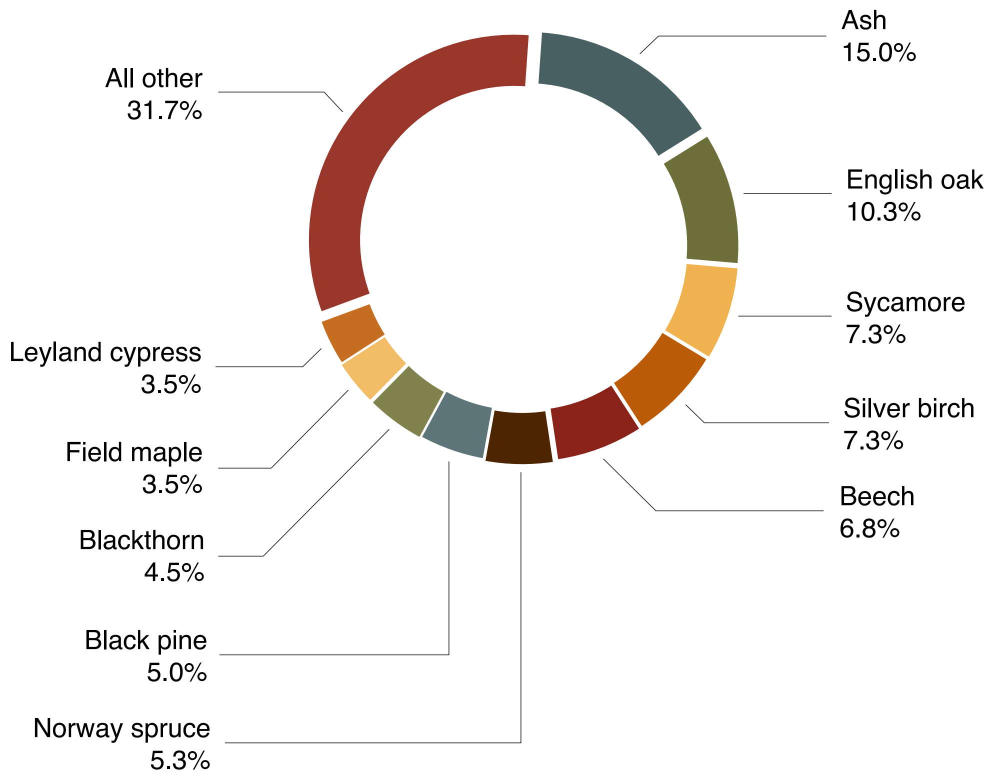


Figure 7: Species composition (most common species).

The range of species diversity in Exeter could be improved. The city may rely too heavily on just a few species. Continuing to even the population with planting selection will help secure the future of this urban forest.

"The conservation of biodiversity is not just about saving a few species, but about preserving the intricate web of life that sustains us all."

Dr. Thomas Lovejoy

[7] Santamour, 1990

Dominance

Numerous benefits derived from trees are directly linked to the amount of healthy leaf surface area that they have.

A high value shows which species are currently delivering the most benefits based on their population and leaf area. These species currently dominate the urban forest structure and are therefore the most important in delivering benefits.

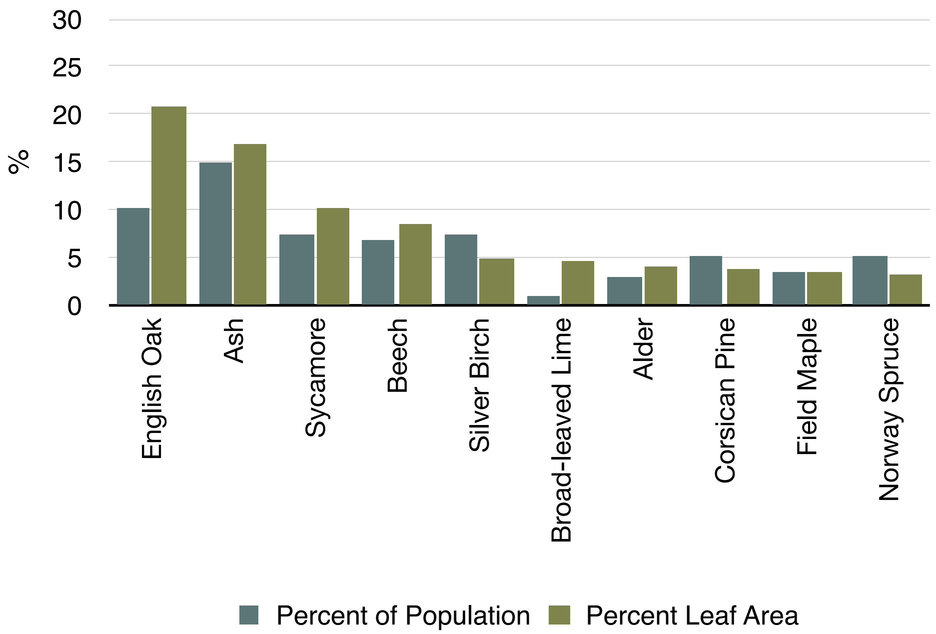


Figure 8: Leaf area and population of Exeter by most dominant tree species.

The Dominance Value is calculated by taking into account the leaf area and relative abundance of the species. In Exeter the most dominant species are Ash, English oak and Sycamore due to having a combination of the largest leaf areas and common species (Figure 8).

Trees such as broad-leaved lime have a high dominance value due to their expansive leaf area even though they represent a relatively low proportion of the population, the same can be said for English oak although they tend to be more widespread. The opposite can be true for species with high population but a smaller leaf area.

Species	Leaf area (ha)	Dominance Value
Ash	488	48.8
English Oak	598	51.8
Sycamore	293	27.6
Beech	246	23.9
Silver Birch	140	17.0
Corsican Pine	107	12.4
Norway Spruce	90	11.5
Field Maple	100	10.5
Alder	112	10.6
Broad-leaved Lime	134	10.0

Table 4: List of the ten most dominant tree species in Exeter.
*See appendix II for the full list of tree dominance value ranking in Exeter

Urban Forest Structure

In this survey trees were sized by their stem diameter at breast height (DBH) at 1.3m. DBH can be considered a proxy for age, bearing in mind species and potential ultimate size and form.

Trees with a DBH of 7-15 cm constitute 25% percent of the tree population of Exeter's urban forest. Larger trees have a greater functional value and provide increased benefits (details of functional value and the resulting benefits are discussed later). It has been estimated in previous studies[8] that a 75cm diameter tree can intercept 10 times more air pollution, can store up to 90 times more carbon and contributes up to 100 times more leaf area to the tree canopy than a 15cm tree[9].

Size class distribution is also an important factor in managing a sustainable tree population. Having a large population of smaller trees is important as this will ensure that there are enough young trees to replace those older specimens that are eventually lost through old age or disease (Figure 9).

Most regions in England only have 10-20% of trees with a DBH that is greater than 30cm*, but in Exeter it is 30.8%

*Trees in Towns II

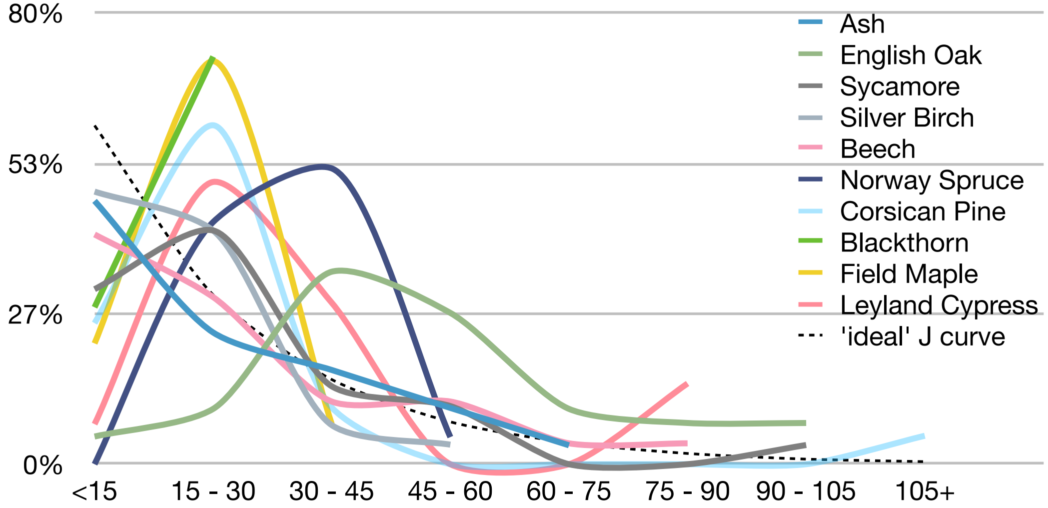


Figure 9: Spread of size classes amongst the top ten species, showing comparison to 'ideal' J-curve
'ideal' J-curve values reduce by half for each increase in DBH class

Where the goal is to continually maintain tree cover within a landscape, a guiding principle is an inverse J-curve of age going from many young to few mature trees[10] (Figure 9). Forests are unique and there is no 'one size fits all' target distribution. However, it is noted that Exeter will benefit from a greater proportion of larger trees as the tree stock matures, if correctly managed.

[8] City of Toronto Parks, Forestry and Recreation, 2013

[9] Hand and Doick, 2019

[10] Kimmins, 2004

Biodiversity of the Urban Forest

Biodiversity is important because it provides a wide range of indirect benefits to humans, however, challenges exist in valuing it because it is difficult to identify and measure the passive, non-use values of biodiversity.[11]

The diversity of species within Exeter (both native and non-native) will influence how resilient the tree population will be to future changes, such as minimising the overall impact of exotic pests, diseases and climate change.

A diverse treescape is better able to serve as a habitat for a wide range of creatures, and native trees are important as they are better suited to support other native species.

Unfortunately, many native species are not able to thrive in the artificial environments of our landscaped areas, and the effects of climate change will exacerbate the situation,[12] therefore non-native species could become increasingly important for the delivery of benefits in Exeter.

Species	Scientific name	Total	Beetles	Flies	True bugs	Wasps & sawflys	Moths & butterflie s	Other
Willow (3 spp)	*Salix (3 spp.)*	450	64	34	77	104	162	9
Oak (2 spp)	*Quercus (2 spp.)*	423	67	7	81	70	189	9
Birch (4 spp)	*Betula (4 spp.)*	334	57	5	42	42	179	9
Hawthorn	*Crataegus monogyna*	209	20	5	40	12	124	8
Poplar (3 spp)	*Populus (3 spp.)*	189	32	14	43	29	68	3
Scots Pine	*Pinus sylvestris*	172	87	2	25	11	41	6
Blackthorn	*Prunus spinosa*	153	13	2	29	7	91	11
Common Alder	*Alnus glutinosa*	141	16	3	32	21	60	9
Elm (2 spp)	*Ulmus (2 spp.)*	124	15	4	33	6	55	11
Hazel	*Corylus avellana*	106	18	7	19	8	48	6
Beech	*Fagus sylvatica*	98	34	6	11	2	41	4
Norway Spruce	*Picea abies*	70	11	3	23	10	22	1
Ash	*Fraxinus excelsior*	68	1	9	17	7	25	9
Rowan	*Sorbus aucuparia*	58	8	3	6	8	33	2
Lime (4 spp)	*Tilia (4 spp.)*	57	3	5	14	2	25	8
Field Maple	*Acer campestre*	51	2	5	12	2	24	6
Hornbeam	*Carpinus betulus*	51	5	3	11	2	28	2
Sycamore	*Acer pseudoplatanus*	43	2	3	11	2	20	5
European Larch	*Larix decidua*	38	6	1	9	5	16	1
Holly	*Ilex aquifolium*	10	4	1	2	0	3	0
Horse Chestnut	*Aesculus hippocastanum*	9	0	0	5	0	2	2
Common Walnut	*Juglans regia*	7	0	0	2	0	2	3
Yew	*Taxus baccata*	6	0	1	1	0	3	1
Holm Oak	*Quercus ilex*	5	0	0	1	0	4	0
False acacia	*Robinia pseudoacacia*	2	0	0	1	1	0	0

Table 5: The number of species of insects associated with British trees: a Re-analysis (Kennedy and Southwood)

[11] Nunes et al, 2001

[12] Gill et al, 2007

Origin of Tree Species

The map below shows the original continent of origin of the tree species found in Exeter. In total, around 88% of the tree population are native to Europe. Of those, it is expected that a smaller percentage are native to the British Isles, however diversity is key to resilience.

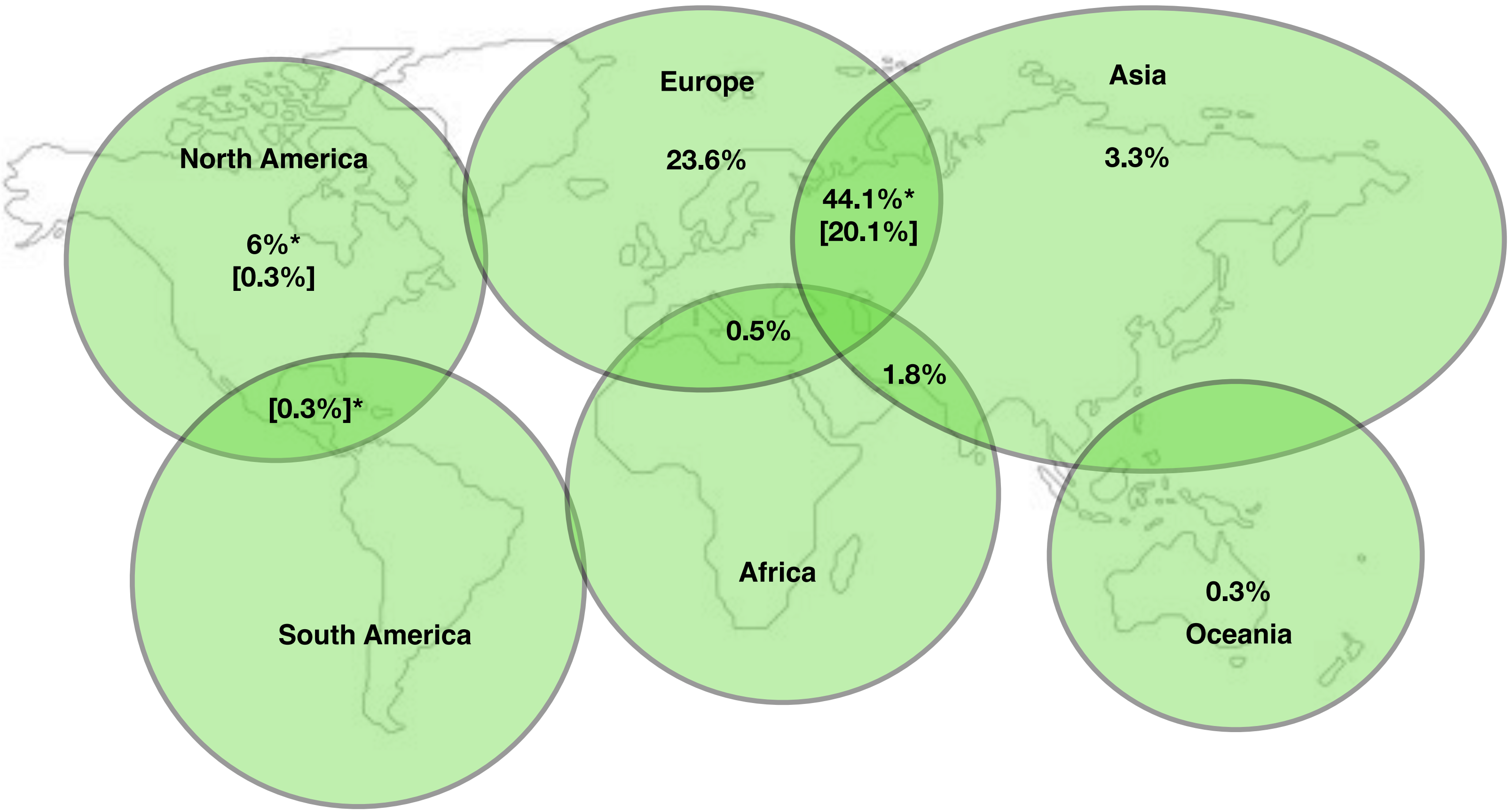


Figure 10: Origin of Tree Species; the share of trees native to different geographical regions. Overlaps indicate origins within both continents

*In these cases, where only genus is available, the proportion in brackets may include additional regions.

**0.2% of trees have unspecified origin as it is unclear which region they originate from, or they are hybrids and therefore from multiple regions.

Valuing the Resource

Air Pollution Removal

Poor air quality is a particular problem in many urban areas and along road networks. Air pollution caused by human activity has become a problem since the beginning of the industrial revolution. With the increase in population and industrialisation, and the use of transport based on fossil fuels, large quantities of pollutants are produced.

The problems caused by poor air quality are well known, ranging from human health impacts to building damage. Trees significantly contribute to improving air quality by reducing air temperature (thereby lowering ozone levels), directly removing pollutants from the air, absorbing them through the leaf surfaces and by intercepting particulate matter (eg: smoke, pollen, aerosols created in the atmosphere, and dusts). They also indirectly reduce energy consumption in buildings, leading to lower air pollutant emissions from power plants.

Particulate matter <2.5 microns ($PM_{2.5}$) can be incredibly damaging to health, as these particulates are small enough to enter the bloodstream. As such, they have superseded PM_{10} in importance, and policies increasingly focus on reducing $PM_{2.5}$.

As well as reducing ozone levels, some tree species also emit the volatile organic compounds (VOCs) that lead to ozone production in the atmosphere. The i-Tree Eco software accounts for both reduction and production of VOCs within its algorithms, and the overall effect of Exeter's trees is to reduce ozone through evaporative cooling[13], however this is not valued in this report as there is no UK Social Damage Cost for this pollutant.

Greater tree cover, air pollution concentrations and leaf area are the main factors influencing pollution filtration and therefore increasing tree planting has been shown to make further improvements in air quality[14]. Furthermore, because filtering capacity is closely linked to leaf area it is generally the trees with larger canopy potential that provide the most benefits.

It is estimated that trees and shrubs combined remove 3.8 metric tonnes of air pollution, including nitrogen dioxide (NO_2), particulate matter less than 2.5 microns ($PM_{2.5}$), and sulphur dioxide (SO_2) per year with an associated value of approximately £279,000 (based on UK social damage costs published by DEFRA)[15]. Total pollution removal per ha in Exeter is equivalent to 0.001 tonnes per ha per yr.

Pollutant	Tonnes removed by trees per year	Value (approx)
Nitrogen dioxide (NO_2)	2.1	£31,000
Particulates (<$PM_{2.5}$)	0.9	£242,000
Sulphur dioxide (SO_2)	0.8	£5,670
Total	3.8	£278,670

Table 6: Quantity and value of the pollutants removed per-annum within Exeter. Valuation methods used are UK social damage cost (UKSDC).

13 Nowak et al, 2000.

14 Escobedo and Nowak (2009)

15 DEFRA (2023)

Avoided Run-Off

Surface run-off can be a cause for concern in many areas as it can contribute to pollution in streams, wetlands, rivers, lakes, and oceans as well as adding to flood risk and thereby exacerbating the impacts of Climate Change.

During precipitation events, a portion of the precipitation will be intercepted by vegetation (trees and shrubs) while a further portion reaches the ground. Precipitation that reaches the ground and does not infiltrate into the soil becomes surface run-off[16].

Within an urban area, the large extent of impervious surfaces increases the amount of run-off. However, trees are effective at reducing this[17]. Trees intercept precipitation, whilst their root systems promote infiltration and storage in the soil. Interception slows down rainwater reaching the ground, and some water will be evaporated off without ever touching the ground.

The trees of Exeter help to reduce run-off by an estimated 82,000 cubic metres a year with an associated value of £257,000.

English Oak trees intercept the most water, removing a total of 17,100 m^3 of water per year, a service worth £53,400 (Figure 11). English Oak trees have an expansive canopy to capture/ intercept rainfall and represent a high proportion of trees within Exeter.

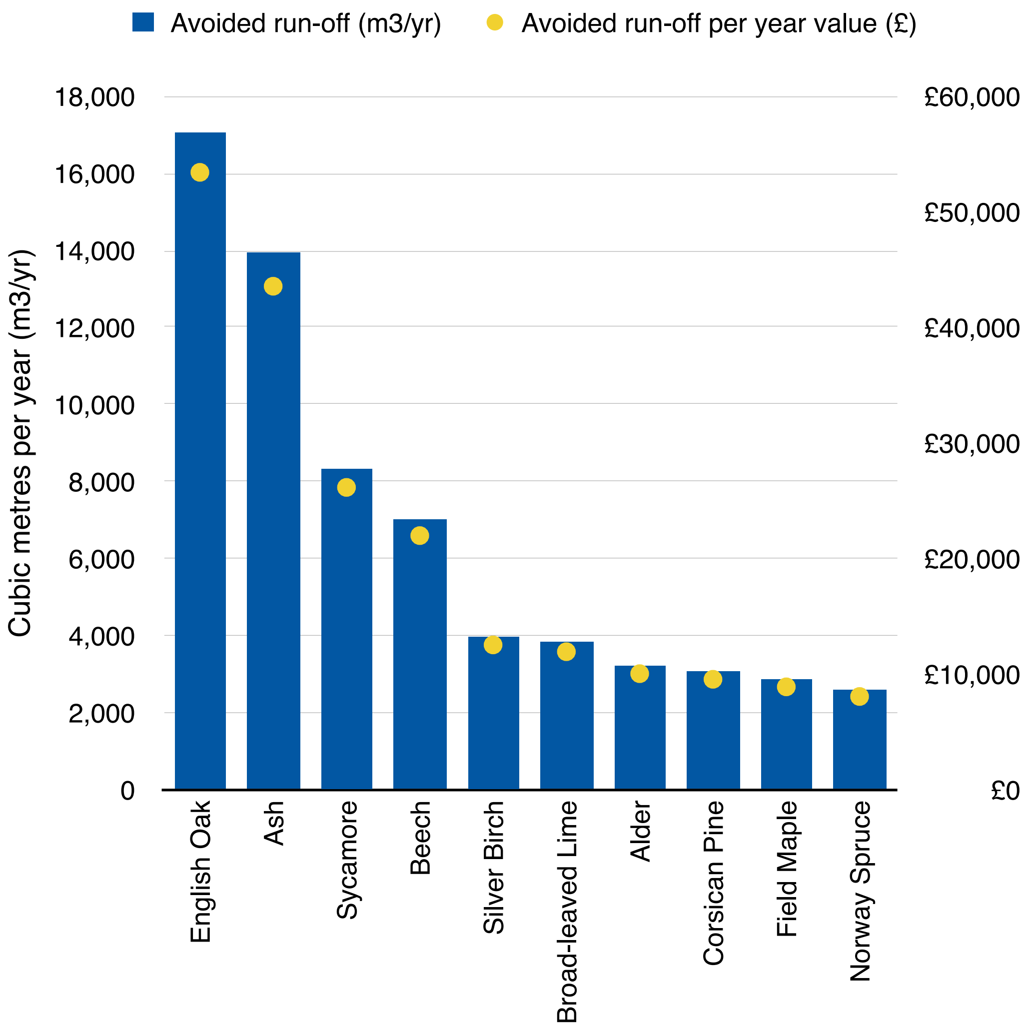


Figure 11: Avoided run-off by the top ten species.

[16] Hirabayashi (2012).

[17] Trees in Hard Landscapes (2014)

Carbon Storage and Sequestration

Trees can help mitigate climate change by sequestering atmospheric carbon. Since about 50% of wood by dry weight is comprised of carbon, tree stems and roots can store up carbon for decades or even centuries[18]. Over the lifetime of a tree, several tonnes of atmospheric carbon dioxide can be absorbed[19].

The gross sequestration of Exeter's trees is about 1,510 tonnes of carbon per year (approximately 0.3t/yr/ha). The value of the carbon sequestered annually is estimated at £1.39 million per year. This value will continue to increase as the trees grow.

Carbon sequestration and storage is a key part of achieving any net-zero target. In 2020, Exeter city produced a total of 476 kt CO_2e emissions*, meaning that sequestration by trees account for 1.16% of the total annual emissions.

*Mitchell et al. 2022

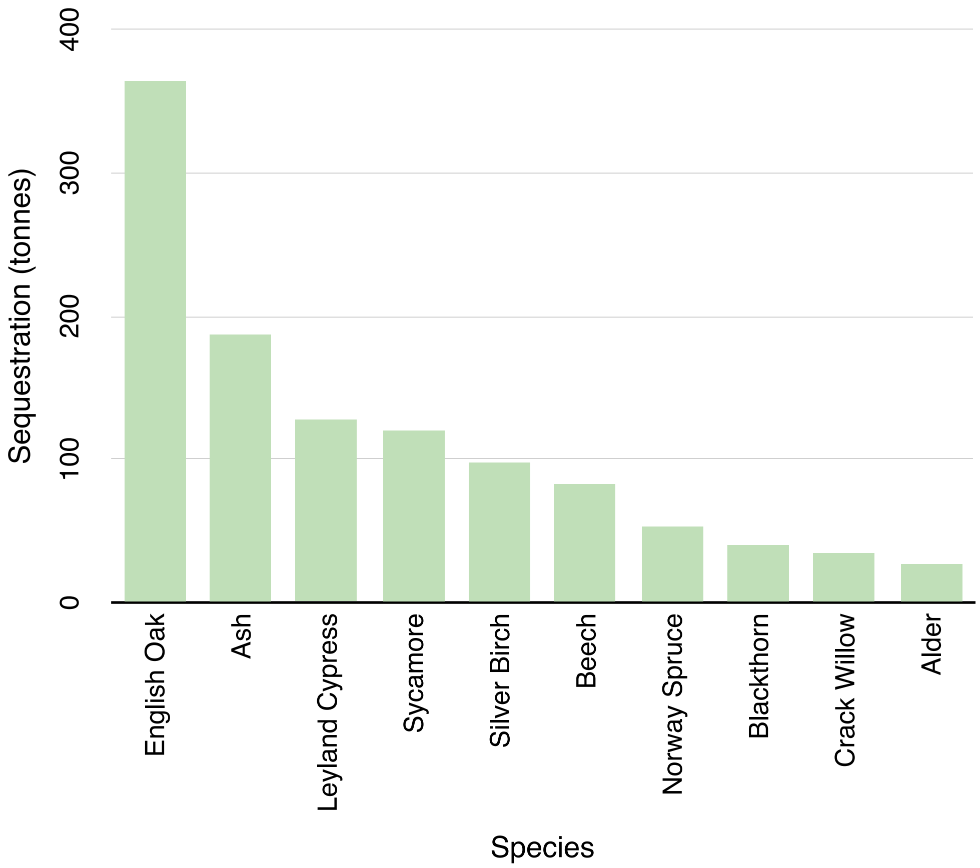


Figure 12: Ten most significant tree species for annual carbon sequestration in Exeter.

18 Kuhns, 2008

19 McPherson, 2007

Carbon storage by trees is a way in which trees can influence global climate change. As trees grow they store more carbon by holding it in their tissue. As trees die and decompose they release much of this carbon back into the atmosphere. Therefore, the carbon storage of trees is an indication of the amount of carbon that could be released if all the trees died.

An estimated 61,200 tonnes (approximately 13/ha) of carbon is stored in Exeter's trees with an estimated value of over £56.6 million (based on current carbon figures from the Department for Energy Security & Net Zero and Department for Business, Energy & Industrial Strategy)[20].

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

Trees also play an important role in protecting soils, which are one of the largest terrestrial carbon sinks. Soils are an extremely important reservoir in the carbon cycle because they contain more carbon than the atmosphere and plants combined[21].

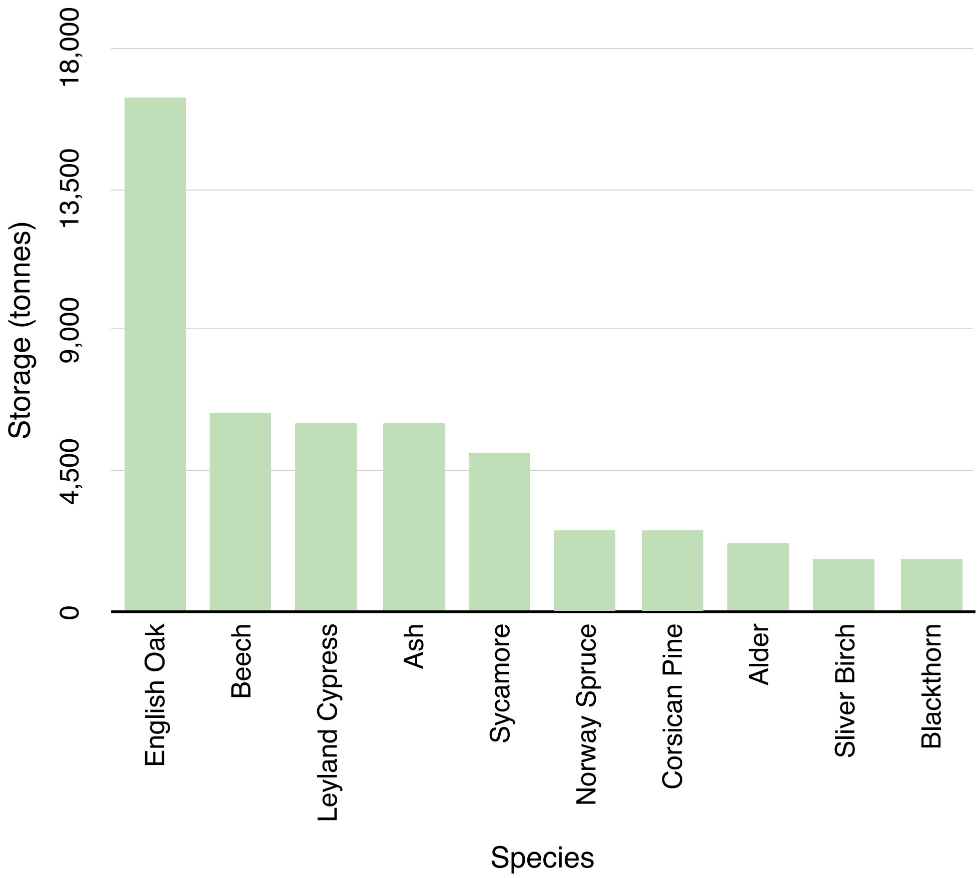


Figure 13: Ten most significant tree species for carbon storage in Exeter.

[20] DBIES (2022)

[21] Ostle *et al.*, (2011)

The Carbon Balance

The Climate Change Survey 2020 found 9 out of 10 councils have declared a climate emergency, with approximately 80% setting official targets to become carbon neutral[22]. Exeter City Council declared a Climate Emergency in 2019, pledging to work towards creating a carbon neutral city by 2030[23].

Exeter City's carbon production has been falling quickly over the past few years, however it still produces around 130,000 tonnes of carbon each year (2.1 x the carbon storage and 86.1 x the annual sequestration rate of the trees in Exeter). The carbon emitted equals approximately 1 tonne per person in Exeter. This comes from a range of sources, the highest of which are Buildings (35%), Power (24%) and Transport (22%)[24].

Carbon offsetting is the process by which an organisation can prove that through action, the carbon which they produce is subsequently captured and stored for a sufficiently long period as to mitigate any environmental damages caused by the initial carbon emission. Invariably urban forestry can only contribute to the carbon balance - to attempt carbon neutrality or 'net-zero' goals through urban forestry alone would be highly unadvisable although it is important to recognise the role it can play in the carbon balance next to other benefits detailed in this report.

Increasing carbon sequestration through urban forestry is a long term solution it is always recommended that carbon emissions should be reduced and other solutions to sequester and store carbon should be sought alongside urban forestry.

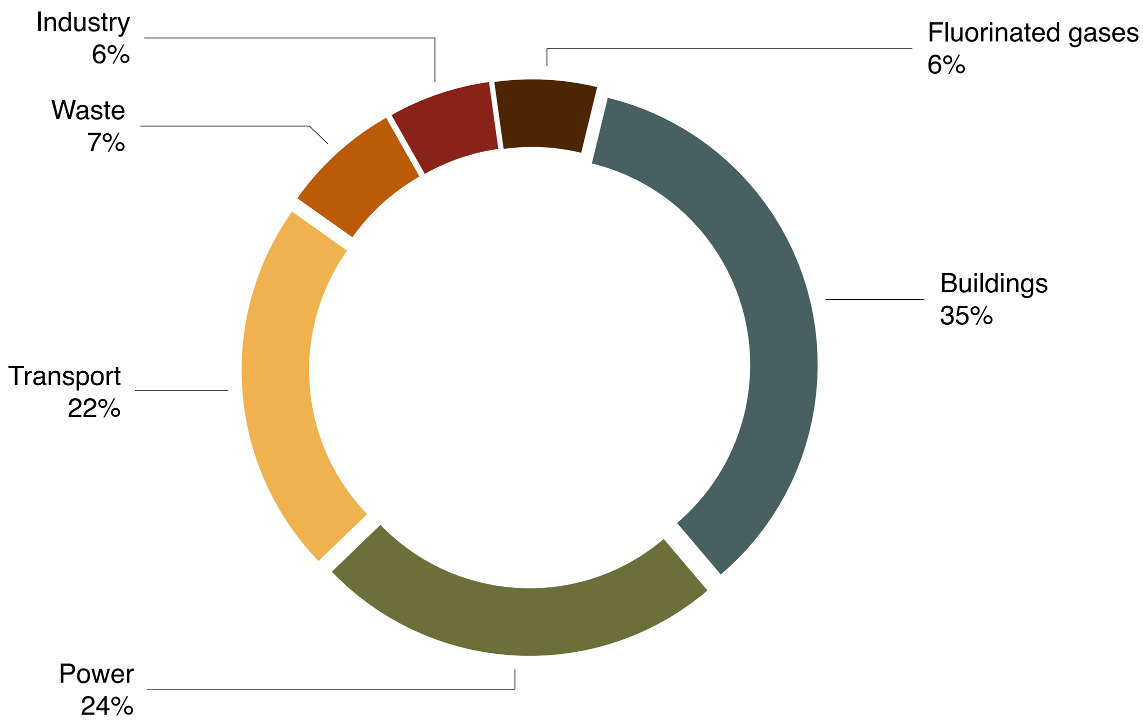


Figure 14: Sources of Exeter's greenhouse gas emission in 2019 (excluding agriculture and land use)

[22] Local Government Association, 2020.

[23] Exeter City Council, 2023

[24] Mitchell *et al.*, 2022

The largest trees sequester the most carbon - gaining in sequestration rate and total carbon stored as they grow to maturity. Depending on the growth rates of species this can take a long time - it is therefore advisable to consider urban forests on timelines that span decades and centuries.

Care and maintenance should be fundamental to any tree planting programme and best practice followed by the present custodians of Exeter's trees, with resources strategically deployed to ensure resources are preserved.

As trees and woodlands age carbon saturation is reached. This is the point when the rate of carbon sequestration becomes balanced with the rate of carbon released through decomposition of organic matter and respiration. As carbon saturation is reached, carbon sequestration will stabilise or decline. The utilisation of felled timber can lock up carbon which would otherwise be returned to the atmosphere, whilst new tree planting can ensure sequestration can continue.

Capital Asset Value for Amenity Trees (CAVAT)

The urban forest of Exeter has an estimated public amenity asset value of £1.32 billion according to CAVAT Adjusted Quick Method valuation, which took into account the size, accessibility, and health of trees as well as any species-specific attributes contributing to public amenity value. English oak had the highest amenity value of any single species in Exeter, contributing 21.8% of the urban forest's amenity value. The next largest contributors were Sycamore, followed by Alder. Combined, these three species represent 42.9% of the total amenity value for Exeter. It is not particularly surprising that the most common and largest stature tree species have higher CAVAT value. A combination of greater size, condition, and longevity in species leads to higher values.

The single most valuable tree encountered in the study was a 21.3m high, 1.02m DBH Sycamore in good condition growing in a park; it was estimated to have an amenity value of £146,000.

The land use type containing the highest amenity value of trees was 'park', with 26% of the total value of the trees, and an estimated value of £337 million when extrapolated for the whole of Exeter. 'Residential' and 'agricultural' were the next most important land-uses, contributing 24% and 17% to the total amenity value, respectively.

CAVAT is a vital metric for valuing trees; it gives an indication of the whole value of the tree, not just the cost of purchase, planting, or management. It is a very different value than replacement cost as it shows how much trees mean to the people and communities who interact with them.

Species	Value of measured trees (£)	Value extrapolated across the area (£)	Proportion of total value (%)
Quercus robur	639,000	£289 million	21.8%
Acer pseudoplatanus	353,000	£160 million	12.0%
Alnus glutinosa	265,000	£120 million	9.1%
Tilia platyphyllos	187,000	£84.5 million	6.4%
Fagus sylvatica	179,000	£80.8 million	6.1%
Pinus nigra	152,000	£68.6 million	5.2%
x Hesperotropsis leylandii	132,000	£59.9 million	4.5%
Picea abies	125,000	£56.7 million	4.3%
Cedrus libani	96,700	£43.8 million	3.3%
Thuja plicata	92,000	£41.6 million	3.1%

Table 7: CAVAT amenity value for the top ten most valuable tree species.

Land use	Value of measured trees per land use (£)	Value per land use extrapolated across the area (£)	Proportion of total value (%)
Park	£747,000	£338 million	12.3%
Residential	£716,000	£324 million	26.8%
Agriculture	£490,000	£222 million	22.6%
Institutional	£376,000	£170 million	5.8%
Commercial/ Industrial	£229,000	£104 million	6.3%
Transportation	£105,000	£47.5 million	5.8%
Cemetery	£90,200	£40.8 million	2.5%
Water/Wetland	£73,300	£33.2 million	2.8%
Vacant	£44,000	£19.9 million	13.3%
Multi-Family Residential	£31,100	£14 million	1.5%
Golf Course	£26,100	£11.8 million	0.5%
Utility	£35	£15,600	0.3%

Table 8: CAVAT amenity value for each land use.

Further details on the CAVAT methodology are included in Appendix IV.

Replacement Cost

Trees and woodlands have a structural value which is based on the depreciated replacement cost of the actual tree.

Large, healthy long-lived trees provide the greatest structural and functional value.

In addition to estimating the environmental benefits provided by trees the i-Tree Eco model also provides a structural valuation which in the UK is termed the 'Replacement Cost'. It must be stressed that the way in which this is calculated means that it does not constitute a benefit provided by the trees, nor is it a true reflection of the value of the trees. The valuation is a depreciated replacement cost, based on the Council of Tree and Landscape Appraisers (CTLA) formulae[25].

The formula allows for tree suitability in the landscape and nursery prices. This explains why the value given for Ash is comparably low even though it is the most common species, on account of the decreased suitability due to Ash Dieback, a pathogen which is discussed later.

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 15.

The total replacement cost of all trees in Exeter currently stands at £111 million, English oak trees are currently the species with the highest replacement value, on account of both their size and population, followed by Beech and Ash. These three species of tree account for £54.2 million (48.7%) of the total replacement cost of the trees in Exeter. A full list of trees with the associated replacement cost is given in appendix III.

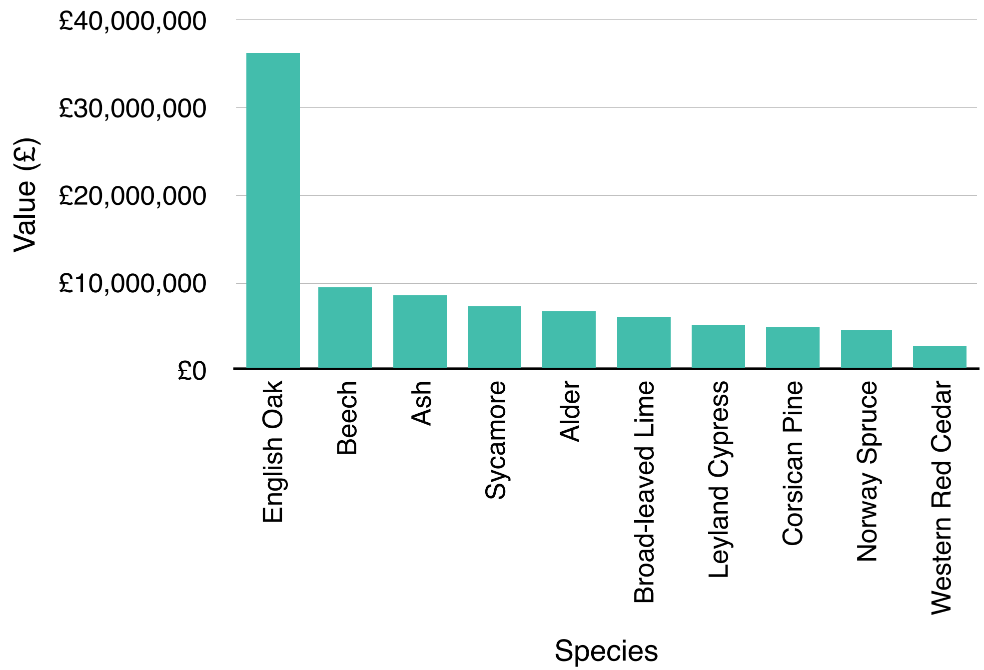


Figure 15: Replacement Cost of the 10 most valuable tree species in Exeter.

25 Hollis (2007)

Potential Pest and Disease Impact

Animal pests and microbial pathogens are a serious threat to urban forests and society, causing direct economic costs from damage, and impacting on ecosystem service provision[26]. It is likely that climate change will result in the introduction of pests and diseases not yet present in the UK[27]. The changing climate of the UK is predicted to increase growth or spore release of root pathogens, and to make trees more susceptible to infection[28]. Further temperature changes are likely to affect the geographical range, development rate and seasonal timing of life-cycle events of insects, and will have an impact on their host plants and predators.

The potential damage from pests and diseases varies according to a wide variety of factors such as tree health, local tree management, and the weather. In addition, a tree community that is dominated by a few species is more vulnerable to a significant impact from a particular disease than a population which has a wider variety of tree species present.

Risk matrices were devised for determining the potential impact of a pest or pathogen, should it become established within the South West, based on whether it affected a single tree genus shown in Table 9, or multiple genera in Table 10.

Prevalence	% of Community at Risk		
	0-25	26-50	>50
Not in UK			
Present in UK			
Present in South West			

Table 9: Risk matrix used for the probability of a pest or disease, which affects a single tree genus, becoming prevalent in the South West.

Prevalence	% of Community at Risk		
	0-5	6-10	>10
Not in UK			
Present in UK			
Present in South West			

Table 10: Risk matrix used for the probability of a pest or disease, which affects multiple tree genera, becoming prevalent in the South West.

[26] Kew Royal Botanical Garden (2017)

[27] Wainhouse and Inward (2016)

[28] Federickson-Matika and Riddell (2021)

This informed Table 11, which gives an overview of the existing and emerging risks to Exeter's urban forest, including the predicted proportion of the tree community that would be affected, and the associated amenity value of those trees across the study area.
The UK plant risk register contains 1,240 entries, and is multifaceted, considering the current extent of a disease, the likelihood of its spread, the severity of its damage, and the ability to mitigate it[29]. Here, emphasis has been given to a subset of pests and pathogens which severely impact trees, or pose human health risks. The matrix emphasises causative agents which are damaging, and would affect >0.01% of the area's trees.

The pest which could potentially have the greatest estimated impact across Exeter's urban forest is the citrus longhorn beetle (though this is not currently present in the UK), which could affect 42% of its trees, worth £34.5 million. The greatest risk which is already present in the UK are threats to the oak population from acute oak decline which threatens 11% of the total tree population valued at £38.3 million. Dothistroma Needle Blight only threatens 6% of the species in Exeter however it is widespread and is therefore one of the greater threats. Dothistroma Needle Blight is known to be a problem in the nearby forest park of Haldon Hill[30] and as it greatly affects the growth rate of pine species could be a cause for the low condition ratings of Corsican Pine (see page 38). The population at risk from Dothistroma Needle Blight is valued at £5.6 million.

[29] DEFRA 2022; Forest Research, 2022

[30] Forest Research, 2018

Figure 16: Symptoms of Acute Oak Decline (Source: Forest Research)

Pest/Pathogen	Major tree hosts affected	Prevalence in UK	Replacement cost of trees	Tree Population at risk (%)
Acute oak decline	Oak species	Central and SE England, Welsh borders and SE Wales	£38,300,000	11%
Asian longhorn beetle	Many broadleaf species	None (previous outbreaks contained)	£34,500,000	62%
Beech leaf Disease	Mainly American beech species but also others	None	£9,430,000	7%
Bronze Birch Borer	All birch species	None	£2,750,000	9%
Chalara dieback of ash	Many ash species	Occurs in most parts of the UK	£8,390,000	15%
Citrus longhorn beetle	Many broadleaf species	None	£34,500,000	47%
Dothistroma Needle Blight	Many pine species	Widespread	£5,600,000	6%
Elm zigzag saw fly	Some elm species	Present in SE England and East Midlands	£844,000	2%
Emerald ash borer	Common ash and narrow-leaved ash	None	£8,390,000	15%
Great Spruce Bark Beetle	Spruce species	Present	£4,380,000	5%
Horse chestnut leaf miner	Horse Chestnut	Present in all parts of GB	£0	0%
Mountain ash ringspot	Rowan	Widespread through Scotland and the North. Likely present across the whole UK.	£896	0%
Oak Lace bug	Oak species	None	£38,300,000	11%
Oak processionary moth	Oak species	Established in Greater London and some surrounding counties	£38,300,000	11%
Oriental Chestnut gall wasp	Sweet Chestnut	Around London and the South East	£448	0%
Phytopthora austrocedri	*Juniperus spp, Chamaecyparis lawsonia, Chamaecyparis nootkkatensis*	Scotland and England only	£58,000	0%

Pest/Pathogen	Major tree hosts affected	Prevalence in UK	Replacement cost of trees	Tree Population at risk (%)
Phytophthora lateralis	*Chamaecyparis formosensis, Chamaecyparis lawsoniana, Chamaecyparis obtuse, Chamaecyparis pisifera, Rhododendron spp., Thuja plicata, Thuja occidentalis, Pseudotsuga menziesii, Taxus brevifolia*	Occurs across the whole of the UK	£2,810,000	1%
Pine processionary moth	*Pinus nigra, Pinus sylvestris, Pinus pinea, Pinus halepensis, Pinus pinaster, Pinus contorta, Pinus radiata, Pinus canariensis, Cedrus atlantica, Larix decidua, Pseudotsuga menziesii*	None	£5,670,000	6%
Plane Lace bug	Plane species	None	£0	0%
Plane wilt	Plane species	None	£0	0%
Rednecked Long-horn Beetle	Cherry species	None	£541,000	6%
Sirococcus tsugae	Cedar and Hemlock species	Yes	£1,630,000	2%
Sweet chestnut blight	Chestnut species	Yes but uncommon	£142,000	0%

Table 11. The significance of a range of existing and emerging pests and diseases to Exeter's urban forest.

Ash Dieback

Ash Dieback is a vascular wilt fungus which causes the dieback and death of Ash trees. It has had a major impact upon the Ash population across Europe. Since Ash Dieback was first recorded in the UK in 2012, the rate of infection has increased at a steady rate and is now considered endemic, causing significant damage across the country.

Whilst initially occurring predominantly in Ash populations that had been recently planted, by the summer of 2014 infected trees were being found within established trees in the wider environment.

The impact of Ash Dieback in Devon has been particularly severe and the implications of losing Ash trees cannot be understated; Ash is the most populous tree species in Exeter and provides 16.9% of the total leaf area. The effects of Ash Dieback in Devon have already been significant, with many woodlands, hedgerows and landscapes losing a significant proportion of their Ash trees, which compromises social wellbeing and environmental health.

To address the impact of Ash Dieback in Devon, the Devon Ash Dieback Action Plan was developed in 2016. The plan aims to mitigate the effects of the disease on both the natural environment and the local economy. It is a collaborative effort between a range of organisations, including the Tree Council, the Forestry Commission, Natural England, the Woodland Trust, and local authorities.

Figure 17: Example of effect from Ash Dieback (Source: Forest Research)

Figure 18: Ash Dieback causing the wilting of leaves
(Source: Joe Bates, Woodland Trust)

The Devon Ash Dieback plan has several key objectives:

- To educate the local population in how to identify Ash Dieback affected trees in the hopes to reduce its spread. However, this is no longer a priority as Ash Dieback is now considered endemic.
- It aims to ensure the resilience of the local ecosystem by promoting the planting of diverse tree species and by supporting the regeneration of woodlands and hedgerows.
- It aims to support the local economy by promoting the use of sustainable wood products and by encouraging the development of alternative land uses, such as agroforestry.

However, substantial shortfalls still remain, as identified in the Devon Ash Dieback Action Plan Refresh 2021. It highlights 20 priorities, where there is need for increased action in order to meet current or anticipated circumstances. These include increasing resources for tree inspection, felling and replanting, in addition to firmly embedding the 3:2:1 principle (replacing every large, medium or small tree with at least 3, 2, or 1 trees respectively).

It is important to continually monitor and evaluate the progress of the plan, identify areas for improvement, and adjust strategies as needed. This ongoing process of monitoring, evaluation, and adaptation can help to ensure that the plan remains relevant and effective in addressing the impact of Ash Dieback in Devon.

Tree condition

One of the most important factors when dealing with any potential pest or disease impact is to consider the health of the tree. Tree condition was measured as part of the survey and Figure 19 shows the health of the 10 most common trees in Exeter. Overall, tree health in Exeter requires improvement, with 23.8% rated as excellent condition and a further 35.6% rated good or fair. 40.6% of trees rated as poor or worse. Approximately 10% are dying or already dead.

Over 75% of Ash trees in Exeter are in a 'poor' condition or worse. 25% are categorised as 'Dying'. This indicates the severity of the Ash Dieback disease in Exeter, and as Ash is the most common tree species, this is a serious concern.

Improving the diversity of species, and particularly the evenness of species across the population will increase the resilience of the urban forest as a whole.

It will be important to tackle Ash Dieback and prepare to replace the trees which will inevitably be lost. Selecting species which are suitable replacements for Ash is key to replacing the lost canopy cover and replacement species should have roughly the same potential for ecosystem service provision as those which are lost.

Blackthorn and Corsican Pine also have serious concerns regarding the proportion their population which can be considered critical or worse.

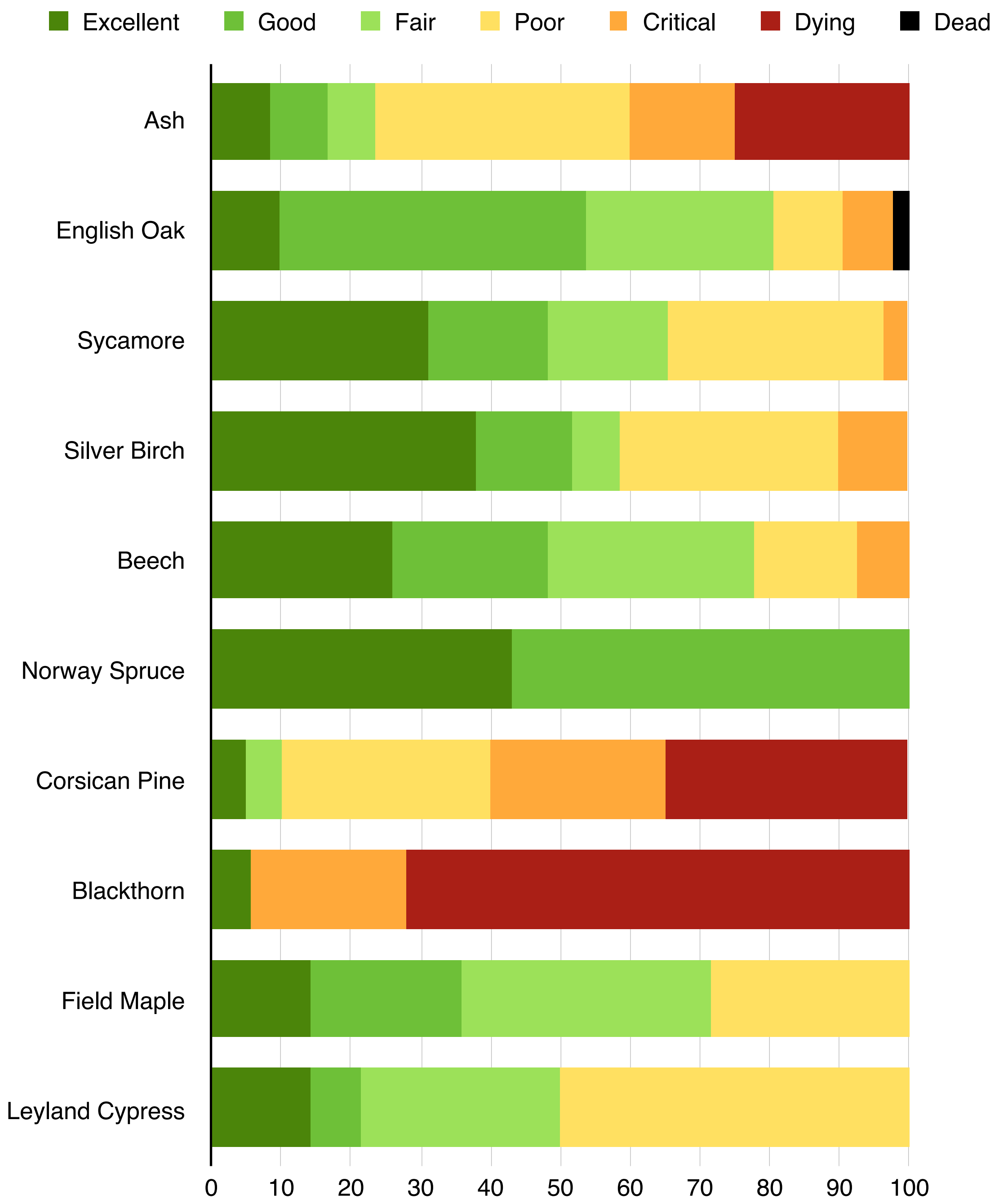


Figure 19: Condition of the 10 most common tree species in Exeter

Conclusions and Recommendations

Trees confer many benefits such as habitat provision, soil conservation and noise reduction which currently cannot be valued, but should be considered in conjunction with this document to shape policy or strategy documents.

The results and data from previous i-Tree Eco studies have been used in a variety of ways to better manage trees and inform decision making such as:

- Carry out a cost benefit analysis using this data and influence management strategies and operational documents and synchronise reviews of urban forest management documents with further i-Tree Eco studies to ensure continuous monitoring.
- Combine this data with other potential data sources to help target new tree planting and to inform species choice, eg:
    - To address localised flooding and drainage issues to identify and assess potential opportunities to enhance the water management benefits.
    - To address local air pollution and assess potential opportunities to enhance air pollution mitigation benefits.
- Use data to support bids for funding and to develop and drive both small and large scale community projects, educational resources and public information.

With better information we can make better decisions regarding trees and this is one of the key benefits of undertaking a project such as this.

This is a preliminary report, designed to provide the relevant data to facilitate future reports, strategies, and policies.

In relation to the benefits assessed by i-Tree, the trees that offer the greatest benefits are those that are larger and therefore have a greater canopy cover. Trees are more likely to achieve larger canopies through appropriate management, species selection, and planting location. This can also allow biodiversity value to increase, maintenance costs to be reduced, and a less stressed tree stock of generally better quality, which in turn reduces the susceptibility of trees to pests and diseases. Woodland compartments that are not managed are much less likely to achieve these objectives.

The production of a Tree Strategy and a Tree Planting Opportunity Mapping exercise would be a means to prioritise these and the following ideas and actions and to set key performance indicators with measurable outcomes.

In particular, the authors would like to draw attention to the following recommendations:

- Continue to plant a wide diversity of species (with due consideration to local site factors) to replace the future loss of ash, and reduce the likelihood of severe impact from any given pest or disease outbreak.
- Produce a Tree Planting Strategy; see the TDAG species selection guide for further information (Tree Species Selection for Green Infrastructure: A Guide for Specifiers).
- Continue new planting to maintain a healthy size diversity within Exeter to avoid significant losses in ecosystem service provisions in the future and to address lack of canopy and unequal distribution of the urban forest.

- Aim to retain large, mature trees wherever possible, as large trees provide the most benefits - make them part of developments rather than lose them. Use CAVAT to highlight amenity values of threatened trees to developers and communities, and to leverage compensation or sufficient replacement planting for amenity trees that are removed by developers. TDAG's guide to delivering trees in planning and development contains recommendations for ensuring that the value of trees is recognised and reflected in new developments (Trees in Hard Landscapes: A Guide for Delivery).
- Carry out a Tree Planting Opportunity Mapping study to target prioritised areas and optimise resources. This can facilitate additional planting alongside main roads, and joining up/filling in gaps within the existing urban forest to enhance wildlife corridors and the connectivity of pathways and cycle lanes through green infrastructure. Tree equity analysis at neighbourhood level can be incorporated to target areas that lack canopy cover, particularly areas with high deprivation and which experience high pollution, surface flooding, limited green space, or lack of shade.
- Set up community tree care schemes to encourage engagement by local people and help to ensure the good health of young trees, particularly new plantings as they are at the most risk from external factors such as drought, disease and even vandalism.
- Promote Exeter's urban forest to all, and emphasise the benefits it provides though educational resources and public information.
- Establish values that can be used in cost-benefit analysis to better inform asset and risk management.
- Consider developing an Urban Forest Master Plan to follow on from this study providing a vision of what the city would like to achieve with its urban forest and step to realise those goals.

Appendix I. Relative Tree Effects

The urban forest in Exeter provides 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 passenger automobile emissions.

Carbon storage is equivalent to:

- Annual carbon (C) emissions from 191,000 family cars
- Annual C emissions from 78,400 single-family houses

Nitrogen dioxide removal is equivalent to:

- Annual nitrogen dioxide emissions from 11,300 family cars
- Annual nitrogen dioxide emissions from 135 single-family houses

Sulphur dioxide removal is equivalent to:

- Annual sulphur dioxide emissions from 17,700 family cars
- Annual sulphur dioxide emissions from 47 single-family houses

Annual carbon sequestration is equivalent to:

- Amount of carbon emitted in Exeter in 0.9 days
- Annual C emissions from 4,730 family cars
- Annual C emissions from 1,930 single-family houses

Average family car emissions per mile were based on dividing total 2021 pollutant emissions from light-duty gas vehicles (National Emission Trends http://www.epa.gov/ttn/chief/trends/index.html) divided by total miles driven in 2021 by passenger cars (National Travel Survey https://www.gov.uk/government/statistical-data-sets/nts09-vehicle-mileage-and-occupancy). The CO and Nitrogen dioxide figures were converted from mg of pollution per km into kg of pollution that an average car in a year will produce using UK averages updated in 2022 (https://carfueldata.vehicle-certification-agency.gov.uk).

Average CO2 emissions per car mile in the UK were based on Department for Transport for the UK in 2020 (https:// www.nimblefins.co.uk/average-co2-emissions-car-uk) and were converted into equivalent Carbon emissions per average car per year.

Appendix II. Species Dominance Ranking List

Scientific Name	Common Name	% Population	% Leaf Area	Dominance value
Quercus robur	English oak	20.8%	31.0%	51.8
Fraxinus excelsior	Ash	16.9%	31.9%	48.8
Acer pseudoplatanus	Sycamore	10.2%	17.4%	27.6
Fagus sylvatica	Beech	8.6%	15.3%	23.9
Betula pendula	Silver birch	4.9%	12.1%	17.0
Pinus nigra	Corsican pine	3.7%	8.7%	12.4
Picea abies	Norway spruce	3.1%	8.4%	11.5
Alnus glutinosa	Alder	3.9%	6.7%	10.6
Acer campestre	Field maple	3.5%	7.0%	10.5
Tilia platyphyllos	Broad-leaved lime	4.6%	5.4%	10.0
x Hesperotropsis leylandii	Leyland cypress	1.3%	4.8%	6.1
Prunus spinosa	Blackthorn	0.7%	5.2%	5.9
Salix fragilis	Crack willow	1.9%	3.7%	5.6
Ulmus glabra	Wych elm	1.5%	3.2%	4.7
Cedrus libani	Cedar of Lebanon	1.1%	2.9%	4.0
Betula pubescens	Downy birch	1.1%	2.6%	3.7
Corylus avellana	Hazel	0.8%	1.8%	2.6
Quercus rotundifolia	Holm oak	1.0%	1.5%	2.5
Acer platanoides	Norway maple	0.7%	1.7%	2.4
Pyrus calleryana	Callery pear	0.6%	1.6%	2.2
Crataegus monogyna	Hawthorn	0.4%	1.7%	2.1
Prunus avium	Wild cherry	0.4%	1.7%	2.1
Thuja plicata	Western red cedar	0.9%	1.1%	2.0
Acer saccharinum	Silver maple	0.8%	1.1%	1.9
Ilex aquifolium	Holly	0.1%	1.6%	1.7
Pinus sylvestris	Scots pine	0.5%	1.2%	1.7
Carpinus betulus	Hornbeam	0.6%	1.1%	1.7
Malus sylvestris	Wild crab	0.4%	0.9%	1.3
Pinus radiata	Monterey pine	0.4%	0.9%	1.3
Alnus cordata	Italian alder	0.5%	0.8%	1.3
Castanea sativa	Sweet chestnut	0.5%	0.8%	1.3
Salix caprea	Goat willow	0.2%	1.0%	1.2
Populus nigra	Black poplar	0.2%	0.9%	1.1
Tilia x europaea	European lime	0.3%	0.8%	1.1
Trachycarpus fortunei	Chusan palm	0.0%	1.0%	1.0
Sequoiadendron giganteum	Giant sequoia	0.9%	<0.1%	0.9
Malus domestica	Orchard apple	0.2%	0.7%	0.9
Sambucus nigra	Elder	0.0%	0.8%	0.8
Laurus nobilis	Bay	0.1%	0.6%	0.7
Sorbus aucuparia	Rowan	0.1%	0.6%	0.7

Scientific Name	Common Name	% Population	% Leaf Area	Dominance value
Cornus mas	Cornelian cherry	0.2%	0.5%	0.7
Quercus cerris	Turkey oak	0.2%	0.4%	0.6
Salix	Willow	0.2%	0.4%	0.6
Chamaecyparis lawsoniana	Lawson cypress	0.0%	0.5%	0.5
Ulmus procera	English elm	0.0%	0.5%	0.5
Alnus incana	Grey alder	0.1%	0.4%	0.5
Larix decidua x kaempferi	Hybrid European and Japanese larch	0.1%	0.4%	0.5
Acer negundo	Box elder	<0.1%	0.3%	0.3
Betula utilis ssp. jacquemontii	Himalayan birch	<0.1%	0.3%	0.3
Magnolia x loebneri	Loebner's Magnolia	<0.1%	0.3%	0.3
Photinia x fraseri	Photinia x fraseri	<0.1%	0.3%	0.3
Pittosporum arborescens	Pittosporum arborescens	0.1%	0.3%	0.3
Prunus	Cherry	<0.1%	0.3%	0.3
Prunus padus	Bird cherry	<0.1%	0.3%	0.3
Prunus serrulata	Flowering cherry	<0.1%	0.3%	0.3
Pseudophoenix sargentii	Florida cherry palm	<0.1%	0.3%	0.3
Salix alba	Whit willow	<0.1%	0.3%	0.3
Thuja occidentalis	Eastern white cedar	<0.1%	0.3%	0.3
Ulmus minor ssp. angustifolia	Field elm	0.1%	0.3%	0.3

Appendix III. Tree values by species

Species	Common Name	Estimated No. of Trees	Carbon Stored (tonnes)	Net Seq (tonnes/yr)	Avoided Runoff (m^3/yr)	Replacement Cost (£)
Fraxinus excelsior	Ash	26,884	6,005	187	13,905	£8,394,597
Quercus robur	English oak	18,371	16,366	363	17,051	£36,352,617
Acer pseudoplatanus	Sycamore	12,994	5,054	119	8,349	£7,139,556
Betula pendula	Silver birch	12,994	1,708	97	3,998	£2,363,600
Fagus sylvatica	Beech	12,098	6,362	83	7,017	£9,430,108
Picea abies	Norway spruce	9,409	2,656	53	2,573	£4,377,345
Pinus nigra	Corsican pine	8,961	2,587	20	3,048	£4,758,639
Prunus spinosa	Blackthorn	8,065	986	13	578	£199,358
Acer campestre	Field maple	6,273	1,020	23	2,840	£1,418,644
x Hesperotropsis leylandii	Leyland cypress	6,273	6,022	127	1,069	£5,065,157
Alnus glutinosa	Alder	4,929	2,178	27	3,204	£6,628,621
Cedrus libani	Cedar of Lebanon	3,136	1,043	15	904	£1,628,354
Salix fragilis	Crack willow	3,136	884	35	1,579	£1,207,605
Ulmus glabra	Wych elm	3,136	574	26	1,223	£816,847
Betula pubescens	Downy birch	2,688	599	12	936	£376,954
Ilex aquifolium	Holly	2,688	113	10	108	£338,346
Crataegus monogyna	Hawthorn	2,240	232	13	367	£308,365
Prunus avium	Wild cherry	2,240	273	18	368	£305,475
Acer platanoides	Norway maple	1,792	219	19	540	£610,017
Corylus avellana	Common hazel	1,792	188	9	677	£728,240
Pyrus calleryana	Callery pear	1,792	371	27	485	£997,258
Trachycarpus fortunei	Chusan palm	1,792	67	3	33	£487,544
Pinus sylvestris	Scots pine	1,344	47	5	382	£77,030
Populus nigra	Black poplar	1,344	41	4	159	£6,595
Salix caprea	Goat willow	1,344	73	5	192	£270,641
Sambucus nigra	Elder	1,344	67	4	17	£267,804
Tilia platyphyllos	Broad-leaved lime	1,344	1,700	40	3,811	£6,120,878
Carpinus betulus	Hornbeam	896	130	7	474	£156,021
Chamaecyparis lawsoniana	Lawson cypress	896	44	4	15	£58,013
Laurus nobilis	Bay	896	407	17	123	£380,510
Malus domestica	Orchard apple	896	59	7	147	£116,372
Malus sylvestris	Wild crab	896	150	9	342	£290,979

Species	Common Name	Estimated No. of Trees	Carbon Stored (tonnes)	Net Seq (tonnes/yr)	Avoided Runoff (m^3/yr)	Replacement Cost (£)
Pinus radiata	Monterey pine	896	199	10	368	£762,417
Quercus rotundifolia	Holm oak	896	605	16	842	£1,894,075
Sorbus aucuparia	Rowan	896	68	4	65	£29,394
Tilia x europaea	European Lime	896	21	2	219	£71,766
Ulmus procera	English elm	896	10	1	16	£13,634
Acer negundo	Box elder	448	24	4	4	£38,282
Acer saccharinum	Silver maple	448	193	12	696	£653,465
Alnus cordata	Italian alder	448	90	7	447	£569,732
Alnus incana	Grey alder	448	36	2	119	£23,961
Betula utilis ssp. jacquemontii	Himalayan birch	448	7	1	25	£12,069
Castanea sativa	Sweet chestnut	448	43	3	421	£141,888
Cornus mas	Cornelian cherry	448	159	4	174	£440,245
Larix decidua x kaempferi	Hybrid European and Japanese larch	448	68	1	83	£68,782
Magnolia x loebneri	Loebner's Magnolia	448	1	1	15	£16,464
Photinia x fraseri	Photinia x fraseri	448	5	1	16	£15,917
Pittosporum arborescens	Pittosporum arborescens	448	28	2	54	£23,715
Prunus	Cherry	448	5	2	20	£13,988
Prunus padus	Bird cherry	448	12	1	3	£2,460
Prunus serrulata	Flowering cherry	448	26	3	6	£19,971
Pseudophoenix sargentii	Florida cherry palm	448	7	0	10	£151,728
Quercus cerris	Turkey oak	448	10	2	137	£20,028
Salix	Willow	448	12	1	154	£18,046
Salix alba	Whit willow	448	2	1	10	£20,809
Sequoiadendron giganteum	Giant sequoia	448	1,041	23	747	£1,588,502
Thuja occidentalis	Eastern white cedar	448	23	2	25	£26,809
Thuja plicata	Western red cedar	448	295	1	732	£2,729,440
Ulmus minor ssp. angustifolia	Field elm	448	7	1	62	£12,061

Appendix IV. Notes on Methodology

i-Tree Eco is designed to use standardised field data from randomly located plots 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 Ash Dieback, Asian longhorned beetle and a variety of threats to oak populations.

The 0.04 hectare plots were randomly distributed. All field data was collected during the leaf-on season to properly assess tree canopies. Within each plot, data collection includes land use, ground cover, stem diameter, height, crown width, percent of crown missing, percent dieback and condition

Once the data has been uploaded to i-Tree, the software is able to determine current carbon storage, biomass for each tree which 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[31]. 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 were 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 O_2 release (kg/yr) = net C sequestration (kg/yr) × 32/12. To estimate the net carbon sequestration 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[32].
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.

31 Nowak 1994

21 Nowak et al (2007)

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[33]. 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[34] [35] that were adjusted depending on leaf phenology and leaf area. Particulate removal incorporated a 50 percent resuspension rate of particles back to the atmosphere[36].

Annual avoided surface run-off is calculated based on rainfall interception by vegetation, specifically the difference between annual run-off with and without vegetation. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface run-off, only the precipitation intercepted by leaves is accounted for in this analysis. The value of avoided run-off is based on estimated or user-defined local values. As the local values include the cost of treating the water as part of a combined sewage system the lower, national average externality value is reported.

Replacement Costs were based on valuation procedures of the Council of Tree and Landscape Appraisers which uses tree species, diameter, condition and location information[37] [38].

An amended CAVAT quick 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 used:

- the current Unit Value, representing the fiscal value of the tree, by cross-sectional area,
- Diameter at Breast Height (DBH),
- Community Tree Index (CTI) 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 Life Expectancy.

33 Baldocchi (1987), (1988)

34 Bidwell and Fraser (1972)

35 Lovett (1994)

36 Zinke (1967)

37 Hollis (2007)

38 Rogers et al (2012)

The Unit Value is determined by the CAVAT steering group and published online. The Unit Value for 2023 is £18.44.

DBH is taken directly from the field measurements.

The CTI rating is determined from the LTOA approved list and is calculated on a borough by borough basis.

Functionality was calculated directly from the amount of canopy remaining from field observations.

For the purposes of this report trees with data entered only at genus level were not represented in the figures so as to more accurately represent species level results.

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