Forest Research

Treeconomics

Valuing urban trees in Glasgow

Assessing the Ecosystem Services of Glasgow's Urban Forest: A Technical Report

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The Research Agency of the
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Forest Research is the Research Agency of the Forestry Commission and is the leading UK organisation engaged in forestry and tree related research. The Agency aims to support and enhance forestry and its role in sustainable development by providing innovative, high quality scientific research, technical support and consultancy services.

Treeconomics is a social enterprise, whose mission is to highlight the benefits of trees. Treeconomics works with businesses, communities, research organisations and public bodies to achieve this.

i-Tree is a state-of-the-art, peer-reviewed software suite from the USDA Forest Service that provides urban and community forestry analysis and benefits assessment tools. The Forest Service, Davey Tree Expert Company, National Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, and Casey Trees have entered into a cooperative partnership to further develop, disseminate and provide technical support for the suite.

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Summary

Urban trees provide a range of services, often termed ecosystem services, that help alleviate problems associated with the high population densities found in urban areas. Urban trees improve local air quality, capture carbon, reduce flooding and cool urban environments. They provide food and habitat for animals, such as birds and bees, and can improve social cohesion in communities. Urban forests are, therefore, a valuable source of ecosystem services in towns and cities.

Planning developments often overlook the value of urban trees, quantifiable or otherwise. Valuing the quantifiable services provided by trees in Glasgow could improve this and allow Glasgow City Council and Forestry Commission Scotland to increase the profile of the urban forest and ensure its value is maintained and improved upon. Valuing ecosystem services also aids town planners, landscape architects and tree officers to plan where trees can be planted for maximum benefit.

An i-Tree Eco survey was undertaken in summer 2013 to value a number of ecosystem services provided by Glasgow City Council's trees. i-Tree Eco is a model developed by the US Forest Service to measure a range of ecosystem services provided by urban trees, from carbon sequestration to pollutant removal. The study was funded by Glasgow City Council and Forestry Commission Scotland and was carried out by Forest Research.

Residents in Glasgow benefit significantly from the urban trees present, with quality of life improved by trees helping alleviate flash flooding and sewer blockages, providing cleaner air and supporting wildlife. Glasgow's urban forest also contributes significantly to the local economy, saving an estimated £4.5 million in services per year. This would be enough money to plant 2 900 medium sized oak trees in Glasgow and is comparable to the £4 million spent on the Glasgow 2014 Cultural Programme Open Fund, which provided cultural experiences during the Glasgow 2014 XX Commonwealth Games. However, this value only includes those ecosystem services currently assessed within i-Tree and omits a large range of other ecosystem services such as cooling the urban heat island and reducing noise pollution. This value is, therefore, likely to underestimate the true value of ecosystem service provision by Glasgow's trees.

Glasgow has a high density of trees compared to other cities in England and Scotland. Canopy cover in Glasgow is also high compared to the average in England, but lower than in neighbouring Edinburgh. Glasgow had a higher proportion of large trees (60cm+) than all previous i-Tree studies conducted by Forest Research. However, a lack of medium sized trees puts this at risk in the future.

Vacant land supports a significant number of trees in Glasgow, second only to parks. This could be a major consideration in development plans, particularly as vacant land is

most likely to be developed. Development of this land would remove a significant portion of ecosystem services provision by trees and the mitigation of this should be considered.

There may be up to 32% of Glasgow's urban space available to plant trees or shrubs. Planting a diverse range of tree species will improve the resilience of Glasgow's urban forest to pests and diseases and further improve the quality of life for Glasgow's residents by providing more ecosystem services.

A summary of key results is presented below.

Key Results

The **ecosystem services** provided by Glasgow's trees in 2013 have an estimated value of **£4.5 million** per year

- Glasgow has an **above average** urban tree density of **112 trees per hectare**, totalling **2 million trees**
- Glasgow has **15% urban tree cover**
- The three most commonly encountered species in Glasgow were **ash, hawthorn** and **alder**
- Glasgow's urban forest would benefit from more medium and large sized trees
- The **asset value** (not including ecosystem services) of Glasgow's trees is **between £4 billion and £4.6 billion**
- The **most valuable** trees in Glasgow are located in **parks**
- Glasgow's urban forest intercepts an estimated **812 000 m^3 of water** every year, equivalent to an estimated **£1.1 million** in sewerage charges
- **283 tonnes of air pollution** are estimated to be removed by Glasgow's trees per year, worth more than **£1.4 million** in damage costs
- **183 000 tonnes of carbon** are currently estimated to be stored in Glasgow's trees
  - This amount of carbon is estimated to be **worth £40 million**
  - **By 2050** this value will be **£120 million** according to current forecasts
- Each year Glasgow's trees **remove an estimated 9 000 tonnes of carbon** from the atmosphere
  - This amount of carbon is estimated to be **worth £2.04 million**

Introduction

Urban trees provide a range of services that benefit humans, "ecosystem services". A range of the ecosystem services provided by urban trees are quantifiable using models such as i-Tree Eco, developed by the US Forest Service to aid in planning tree planting. i-Tree Eco is currently the most complete method available to value a whole suite of urban forest ecosystem services (Sarajevs 2011), including pollutant interception and carbon uptake. i-Tree Eco has been used successfully in over 60 cities globally, including cities in the UK. In this report we present the findings of an i-Tree survey undertaken in Glasgow, Scotland in 2013.

Trees improve health by improving local air and water quality by absorbing and filtering pollutants (Bolund & Hunhammar 1999). Trees also reduce the urban heat island effect (Akbari, Pomerantz & Taha 2001), decreasing illnesses associated with heat. There is also evidence that urban greenery can help reduce stress levels and improve recovery time from illness (Ulrich 1979).

Urban trees also provide economic benefits. They store carbon, absorbing it into their tissues, helping to offset carbon emissions produced by other urban activities (Nowak, Crane, Stevens, *et al.* 2008). Urban trees also alleviate flash flooding, a problem that costs cities millions of pounds each year (Bolund & Hunhammar 1999). Commercial and private property value is also increased with the addition of trees (Forestry Commission 2010).

Trees provide valuable habitat for much of the UK's urban wildlife, including bats (Entwistle, Harris, Hutson, *et al.* 2001) and bees (RHS 2012). They provide local residents with a focal point to improve social cohesion and aid education with regards to environmental issues (Trees for Cities 2011).

Assessing the value of these services to Glasgow City Council as an asset to the community will help protect its urban forest, raising the profile of urban trees. It will also support work currently being carried out in Glasgow, such as the improvements being undertaken in Castlemilk and Linn Park, by enabling coherent cases to be put forward to funders. In addition, assessing the value of urban trees can encourage the good planning and execution of new urban tree plantings, maximising the use of space and budgets.

Methodology

i-Tree Eco uses a plot based method of sampling, with data recorded from a number of plots across the city that are extrapolated to represent the city as a whole. This allows data to be collected not only on woodland and tree area, as in previous studies based on aerial photography (John Clegg Consulting Ltd, The Campbell Palmer Partnership Ltd & Cawdor Forestry Ltd 2007), but results in high resolution data that includes information about individual trees. 200 plots were selected from a randomised grid covering Glasgow (Fig. 1). The randomised grid method was chosen to overcome problems associated with patchy land use, for example aggregations of industrial units in one area or residential properties in another. Grid squares present on the edges of the sample area were only included if they contained at least 50% of the grid square area. The total sample area was 17 643 Ha, resulting in a sample every 88 Ha, similar to the sample density used in the Chicago, USA i-Tree Eco study (every 80 Ha).

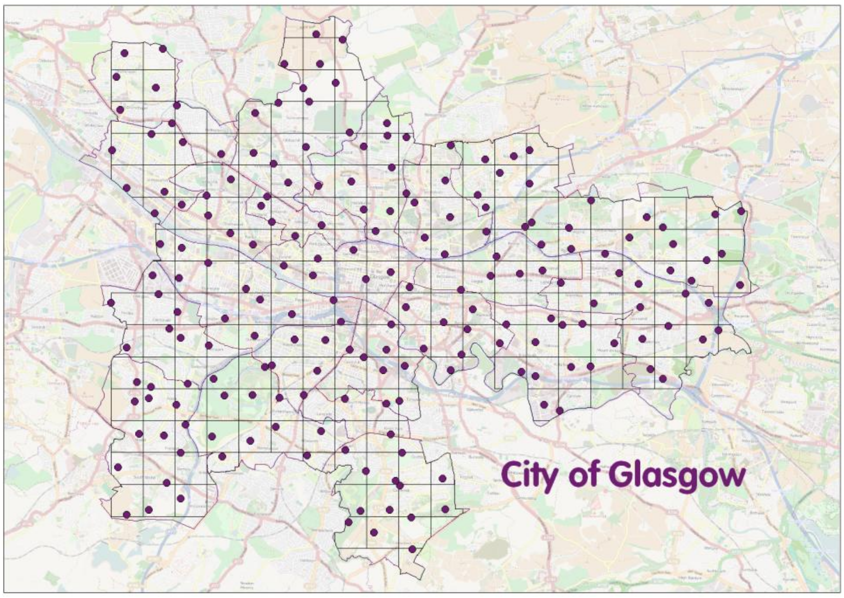

Fig. 1. The sample area for the study included plots within Glasgow's urban boundary. In total 200 plots were sampled (basemap: ©OpenStreetMap contributors)

i-Tree Eco uses a standardised field collection method outlined in the i-Tree Eco Manual (v 5.0 for this study) (i-Tree 2013), and this was applied to each plot.

Each plot covered 0.04 Ha and from each was recorded:

- The type of land use it was, e.g. park, residential

- The percentage distribution of cover present in the plot e.g. grass, tarmac
- The percentage of the plot that could have trees planted in it[1]
- Information about trees[2] (over 7 cm trunk girth)
    - The number of trees and their species
    - The size of the trees including height, canopy spread and girth of trunk
    - The health of the trees including the fullness of the canopy
    - The amount of light exposure the canopy receives
- Information about shrubs[3] (less than 7 cm in trunk girth, but over 1 m in height)
    - The number of shrubs and their species
    - The size and dimensions of the shrubs

Data collected in the field was submitted to the US Forest Service for use in the i-Tree Eco model and a number of outputs calculated (Table 1). i-Tree Eco calculates the species and age class structure, biomass and leaf area index (LAI) of the urban forest. This data is then combined with local climate, phenology and air pollution data to produce estimates of a number of ecosystem services (Table 1) and adjusted for UK Benefit Prices to assess their current and future value.

Standard i-Tree outputs are currently designed for a US audience. Thus, raw valuations are reported in terms of how ecosystem services are valued in the US and, in addition, values are reported in US dollars. Ecosystem services valuations were, therefore, "anglicised", using ecosystem services valuation methods outlined by the UK Treasury, and details of how this was carried out are within the results of each section.

Weather data was for the year 2012, recorded at Glasgow Bishopton weather station, approximately 7km West of the sample area (NOAA 2012). NO_2 (2012), CO (2006) and PM's 10 (2010) and 2.5 (2012) were recorded at the Glasgow Kerbside station in the centre of Glasgow. O_3 (ozone) (2011) and SO_2 (2011) was recorded at the Glasgow Centre station. All pollution data was obtained from www.scottishairquality.co.uk.

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[1] "Plantable space" was defined as an area that could be planted with little structural modification (i.e. permeable surfaces such as grass and soil) and that was not in close proximity to trees or buildings (i.e. would not be hampered in their growth).
[2] In this study, a "tree" is defined as a woody plant with a trunk girth of over 7 cm
[3] For the purposes of this study, a "shrub" is defined as a plant, woody or otherwise, with a total height over 1 m but a trunk girth of less than 7 cm

Table 1. Outputs calculated based on field collected data. Italic entries denote non-standard i-Tree outputs conducted by the authors

Urban forest structure and composition	Species diversity, canopy cover, age class and leaf area Urban ground cover types % leaf area by species
Ecosystem services	Air pollution removal by urban trees for CO, NO_2, SO_2, O_3, PM_{10} and $PM_{2.5}$ % of total air pollution removed by trees Current carbon storage by the urban forest Carbon sequestered
Replacement costs and functional values	Replacement cost based upon structural value in £ (CTLA) *Replacement cost based upon amenity value in £ (a CAVAT assessment)* Carbon storage and sequestration value in £ Pollution removal value in £
Habitat provision	*Pollinating insects* *Insect herbivores*
Potential insect and disease impacts	*Acute oak decline, asian longhorn beetle, chalara dieback of ash, emerald ash borer, gypsy moth, oak processionary moth, Phytophthora ramorum, Phytophthora kernoviae, Phytophthora lateralis, Dothistoma (red band needle blight), sweet chestnut blight*

i-Tree Eco provides replacement costs for trees based on The CTLA (Council of Tree and Landscape Appraisers 1992) valuation method. However, the Capital Asset for Amenity Trees (CAVAT) (Nielan 2010) method was also used in the current study. CAVAT has been developed in the UK and has been used by councils to aid decision making (for example, Bristol Council; Nielan n.d.). CAVAT provides a value for trees in towns, based on an extrapolated and adjusted replacement cost. This value relates to the public amenity that trees provide, rather than their worth as property (as per the CTLA method). Particular differences to the CTLA trunk formula method include the addition of the Community Tree Index (CTI) factor, which adjusts the CAVAT value to take account of the greater amenity benefits of trees in areas of higher population density, using official population figures. An amended CAVAT full method was chosen to assess the trees in this study, developed in conjunction with the creator of the system.

In addition to the i-Tree Eco outputs, pest susceptibility was assessed using information regarding the number of trees within pathogen/pest target groups. The habitat provided by different species was also assessed. A detailed methods section for both i-Tree Eco calculations and additional calculations, including CAVAT, is provided in Appendix I.

Comparisons between cities are drawn from previous i-Tree reports:

- Torbay (Rogers, Jarratt & Hansford 2011)
- Edinburgh (Hutchings, Lawrence & Brunt 2012)
- Wrexham (Rumble, Rogers, Doick *et al.,* 2014)

Results and Discussion

Sample Area

Based on the sample plots in Glasgow, 32(±3)% of the ground cover in Glasgow is suitable for planting with trees. Tree canopy cover is 15(±2)%, which is lower than that found in Edinburgh (17%) but much higher than the average in English towns (8%, Britt & Johnston, 2008). The total size of Glasgow's forest is, therefore, 2 647 hectares. This is over twice the size of Great Cumbrae in the Firth of Clyde (Haswell-Smith 2004) (Fig. 2) and is over 25% larger than Seven Lochs Wetland Park, Scotland's largest urban nature park (www.sevenlochs.org). Shrub cover, including shrubs below the tree canopy, are 5(±1)%, lower than that found in Edinburgh (15%) and Wrexham (11%).

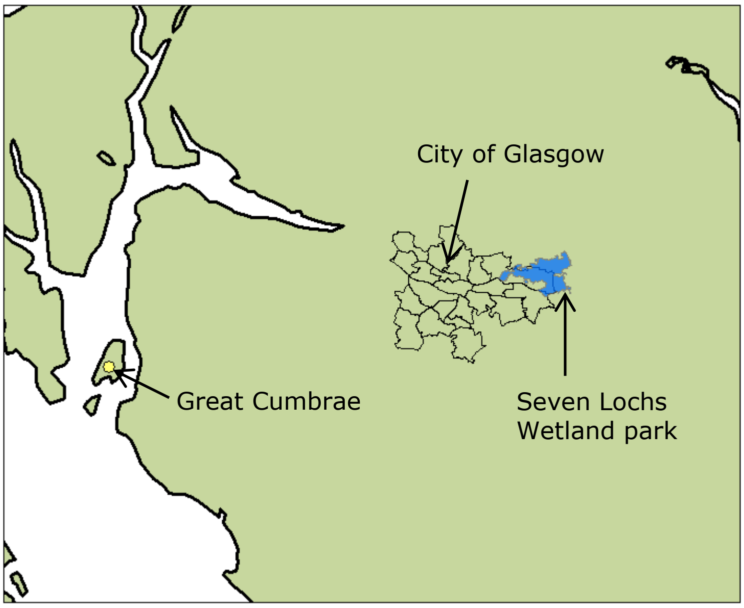


Fig 2. Glasgow's urban forest covers a size of 2 647 hectares, twice that of nearby island Great Cumbrae (1 168 hectares, Haswell-Smith 2004) and 25% larger than Seven Lochs Wetland Park.

52% of the ground cover in Glasgow consisted of permeable materials such as grass and soil (Fig. 3). The remainder of the ground cover consisted of non-permeable surfaces such as tar and cement (Fig. 3). Permeable surfaces can reduce problems associated with flash flooding and reduce loads on sewer systems, potentially preventing travel disruption caused by flooding, as occurred in Glasgow in 2012 (BBC News Scotland 2012). Glasgow has a lower percentage of permeable ground cover than Torbay (approx. 66%) but the same as Wrexham.

Table 2: Outputs from Glasgow i-Tree Eco survey compared to 3 other UK surveys

	Glasgow	Edinburgh	Torbay	Wrexham
Study area size (Ha)	17 643	11 468	6 375	3 833
Sample density (plot per Ha)	88	57	26	19
Forest Cover (Ha)	2 647	1 950	752	652
% Forest cover	15	17	12	17
Average number of trees per Ha	112	56	105[1]	95

[1] Torbay report records 128 trees per hectare, however the survey included trees with <7 cm dbh which have been removed and the value recalculated for consistence in this table

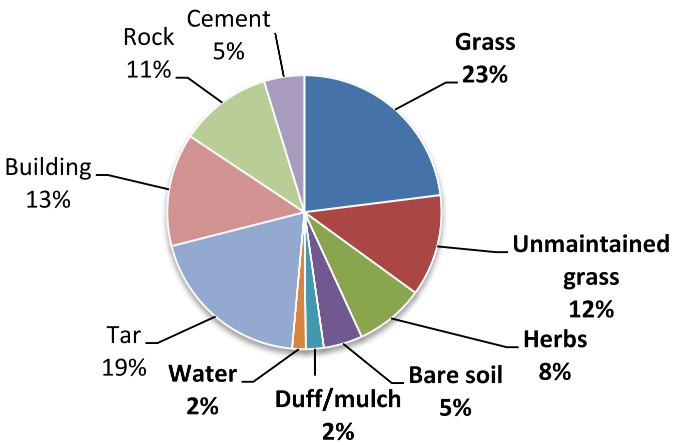


Fig. 3. Types of ground cover encountered in Glasgow. Bold labels denote permeable surfaces, the remainder are non-permeable.

Urban Forest Structure

Glasgow's urban forest has an estimated tree population of 2 million. This is a density of 112 trees per hectare. This is higher than both Wrexham (95), Edinburgh (56) and higher than the English average (58) (Britt & Johnston 2008).

The three most common species are ash, hawthorn and alder (Fig. 4). The ten most common tree species account for 63% of the population (Fig. 4).

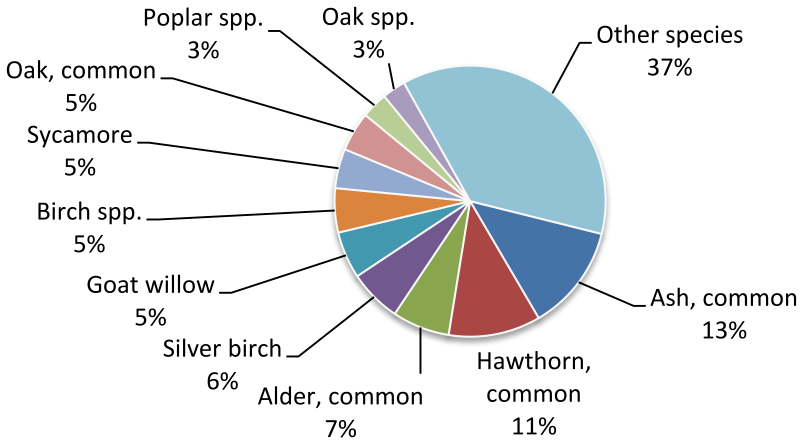


Fig. 4. Breakdown of tree species in Glasgow

Where trees were present, they most commonly occurred in parks (55%) and on vacant land (17%) (Fig. 5).

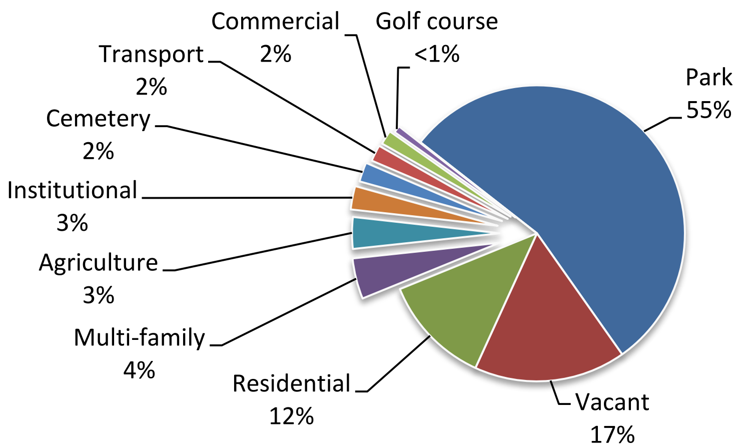


Fig. 5. Land use types on which trees were present. Land use types where no trees were found are omitted

The diversity of tree species, i.e. the number of different species present in a population and their numbers, is important because diverse populations are more resistant to pests and diseases (Johnston, Nail & Murray 2011). The diversity of populations can be calculated using the Shannon-Wiener index. This is a measure of the number of different species, taking into account whether the population is dominated by certain species. The diversity of Glasgow's urban forest is 3.3 according to this index. This is marginally higher than Edinburgh (3.2) and Wrexham (3.1). The highest diversity of trees was found in residential areas (3.0) and parks (2.9) (Fig. 6).

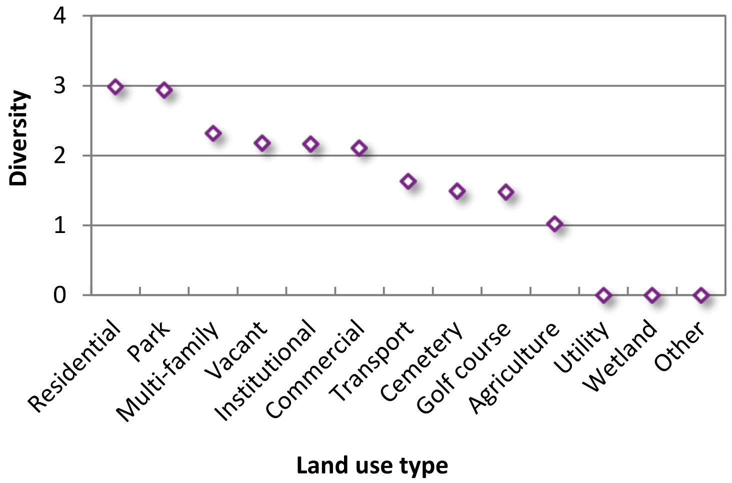


Fig. 6. Shannon wiener diversity index values for trees on different land use types in Glasgow

Santamour (1990) recommends that for urban forests to be resilient to pests and diseases, no species should exceed 10% of the population, no genus 20% and no family 30%. Two species exceeded the 10% guideline (ash and hawthorn). No genus exceeded 20% frequency and no family exceeded 30%. Table 3 outlines the top three species, genus and family frequencies in Glasgow.

Table 3. Top three frequency tree species, genus and family.

Species	**Ash,**	**12.5%**	**Hawthorn,**	**11.2%**	Alder,	6.7%
Genus	Fraxinus,	12.5%	Betula,	12.2%	Crataegus,	11.2%
Family	Betulacaea,	22.9%	Rosaceae,	21.4%	Salicaceae,	14.2%

Bold entries denote groups exceeding the guidelines outlined by Santamour (1990) of no species exceeding 10%, no genus 20% and no family 30%

The origin of tree species also impacts their ability to resist pests and diseases. New pests and diseases, such as Chalara ash dieback, are emerging (Forestry Commission, 2014). Additionally, stresses such as prolonged exposure to drought, could also increase due to climate change (UKCP09 2009). These factors are leading some council's to consider the use of exotic species. Exotic species tend to have fewer pests associated with them due to being removed from the home range of their specialist herbivores and diseases (Connor, Faeth, Simberloff, *et al.* 1980). Trees from warmer climates may also be able to withstand the effects of climate change better (RHS 2014). However, there is an ongoing debate about whether these benefits outweigh the costs of planting exotics (Johnston, Nail & Murray 2011). Exotic species can disrupt native ecosystems by changing the available niches for wildlife to fill (Townsend, Begon & Harper 2008). They also support fewer native animals (Kennedy & Southwood 1984) and can become invasive due to their lower association with pests (Mitchell & Power 2003). Thus, a balance of native and non-native species may provide the most resilient solution.

Of those trees identified to species level, 65% are native to Scotland, 9% are naturalised in Scotland and 8% are non-native[4].

The size distribution of trees is also important for a resilient population. Large, mature trees offer unique ecological roles not offered by small, younger trees (Lindenmayer, Laurance & Franklin 2012). To maintain a level of mature trees, young trees are also needed to restock trees as they age and need to be planted in a surplus to include planning for mortality.

It is estimated that trees with diameters (diameter at breast height; DBH) less than 20 cm constitute 83% of the total tree population in Glasgow (Fig. 7). The number of trees in each DBH class then declines successively, where trees with DBH's higher than 60 cm make up less than 1%. However, with small stature trees removed, 60cm+ diameter trees make up nearly 9% of the tree population, close to the 10% ideal value suggested for street trees in America to ensure healthy urban tree stocks (Richards 1983). However, the proportion of trees with diameters between 40 and 60cm is low, suggesting a shortage of large sized trees in the near future.

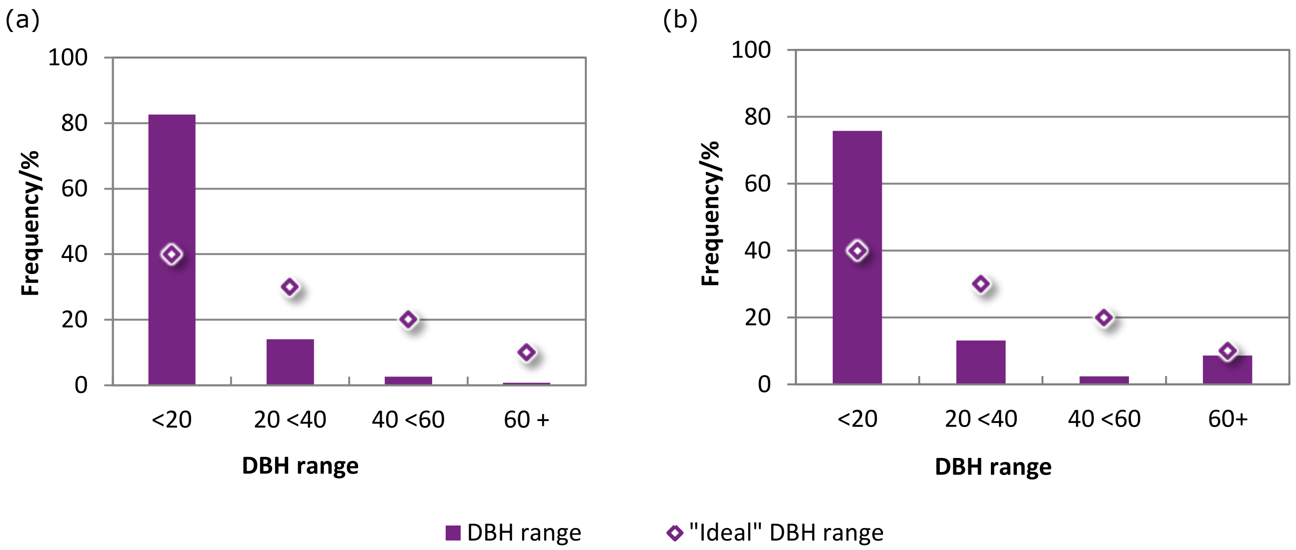


Fig. 7. DBH ranges of trees (a) encountered in Glasgow and (b) encountered in Glasgow, with small stature trees removed from the analysis. Diamonds represent recommended frequencies for that DBH class as outlined by Richards (1983)

[4] 18% were identified to genus level only so could not be assigned a native, naturalised or non-native status

Small stature trees (trees that will never attain a maximum height of 10 m) make up 29% of Glasgow's tree population. These trees will never attain large stature and contribute to the high numbers of trees in the lowest DBH class. Removing these from DBH calculations reduces the proportion of trees below 20 cm in diameter to 76%.

There is evidence to suggest that large trees provide more ecosystem services than small stature ones and provide more benefits compared to their costs (USDA 2003; Sunderland, Rogers & Coish 2012), little work has been conducted to compare large trees with dense stands of small stature trees, such as those that hawthorn produce, so a value comparison is difficult. It is recommended that small stature trees are supplemented with young, large stature trees to future proof the large tree component of the urban forest, but retain the potential benefits small stature thickets may provide.

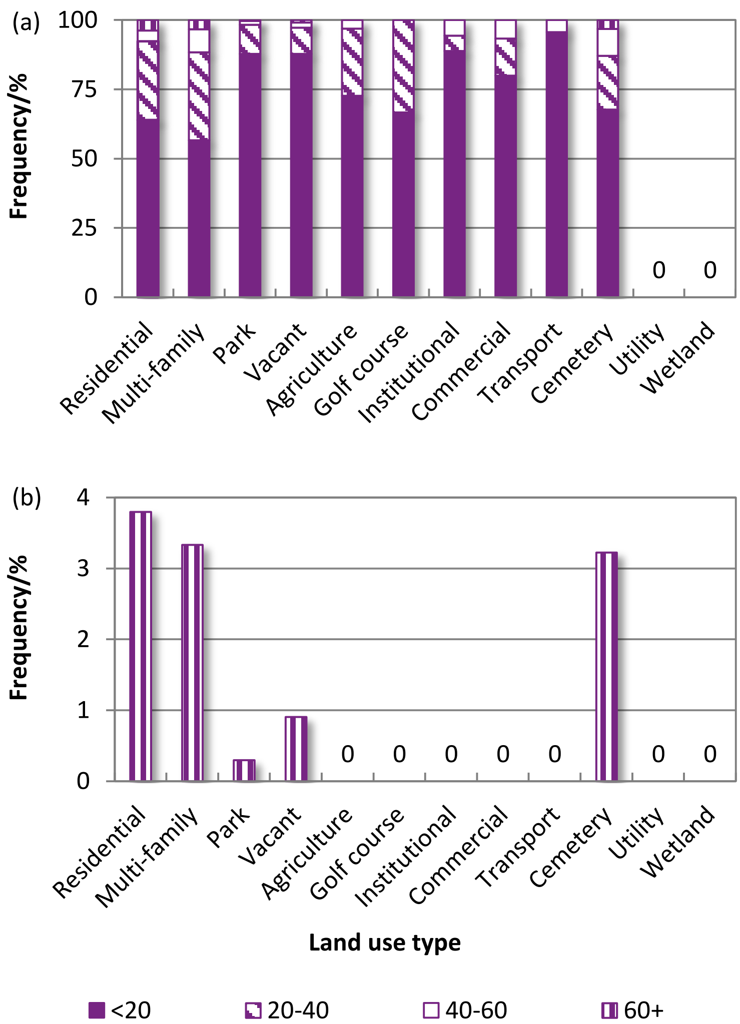


Fig. 8. Proportion of diameter size classes per land use type for (a) all DBH size classes and (b) 60cm+ stems only. The number 0 denotes land use types where no trees were found.

Small trees (<20 cm DBH) were highest in proportion in parks, on vacant and institutional land and in transport areas (Fig. 7). Large trees (60 cm+ DBH) were highest in proportion on residential land, including multi-family residential land, and in cemeteries (Fig. 8).

The condition of Glasgow's trees was good, with 90% of trees in Excellent condition (no dieback). Only 5% of trees had more than 25% dieback (poor to dead rating) (Fig. 9).

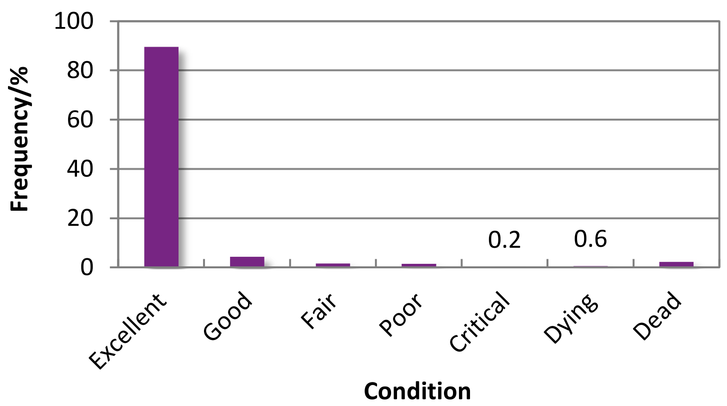


Fig. 9. Condition of trees encountered in Glasgow

Leaf Area

The healthy leaf surface area of trees is an indicator of many of the benefits trees can provide. The removal of pollutants from the atmosphere, for example, relies on leaf surface area (Nowak, Crane & Stevens 2006), as are other factors such as shading ability.

The total leaf area provided by Glasgow's trees is 112km^2, nearly the same surface area as Glasgow itself occupies (176 km^2). Ash, sycamore and goat willow provided the most leaf surface area (13%, 12% and 7% respectively) (Fig. 10).

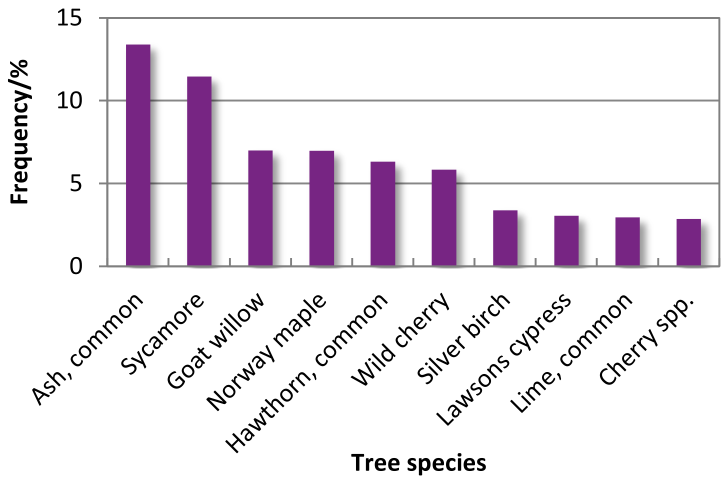


Fig. 10. Top ten tree species in order of leaf area/% in Glasgow

Taking leaf area and prevalence into account, it is possible to rank tree species by calculating an 'importance value' (IV).

In the case of the Glasgow study, the three most important species were a mix of trees with dense, small leaves, such as ash and hawthorn, and trees with large leaves, such as sycamore. Thus, the most prevalent species were not always the most important (Fig. 12).

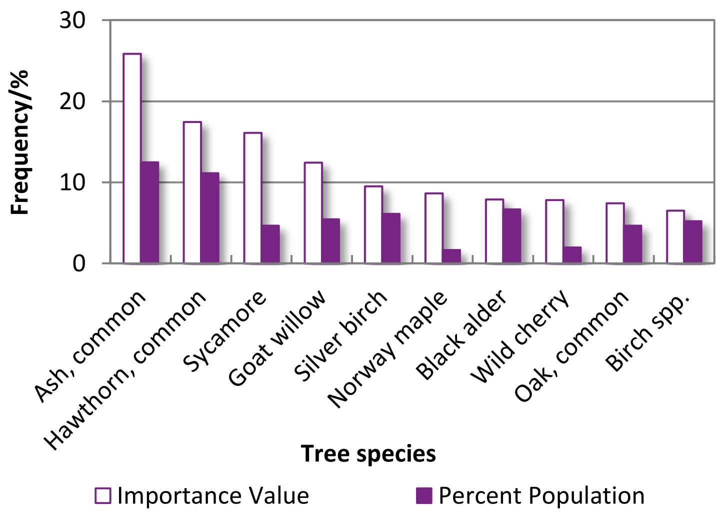


Fig. 12. Importance value (IV) for the top ten most important trees and their frequency/%.

Phenology

Mean average leaf-on/leaf-off dates were calculated using datasets from the UK phenology records (Woodland Trust 2014). The data from 10 species were selected to calculate a UK average (field maple, sycamore, horse chestnut, common alder, silver birch, common beech, common ash, common oak, sessile oak and rowan) over a five year period (2009-2013) to provide a leaf-on date. However, because leaf-off is not in itself an event in the UK phenology database, a further average was taken from the first leaf fall and bare tree events for the 10 species across the five years (2008-2012) to provide an average date for the leaf off event. The average date calculated for leaf on was April the 14th. The average date calculated for leaf off was November the 2nd.

Replacement Cost

CTLA valuation

According to CTLA valuation, which does not take into account the health or amenity value of trees, Glasgow's urban forest is worth approximately £4.6 billion. This is the cost of replacing Glasgow's urban forest should it be lost.

CAVAT valuation

Glasgow's urban forest is estimated to be worth £4 billion according to CAVAT valuation, taking into account the health of trees and their amenity value. The ash in Glasgow have the highest overall replacement cost (Fig. 13, Table 4), representing 12% of the replacement value of all the trees. The single most valuable tree encountered in the study was a birch, estimated have an asset value of £42 988.

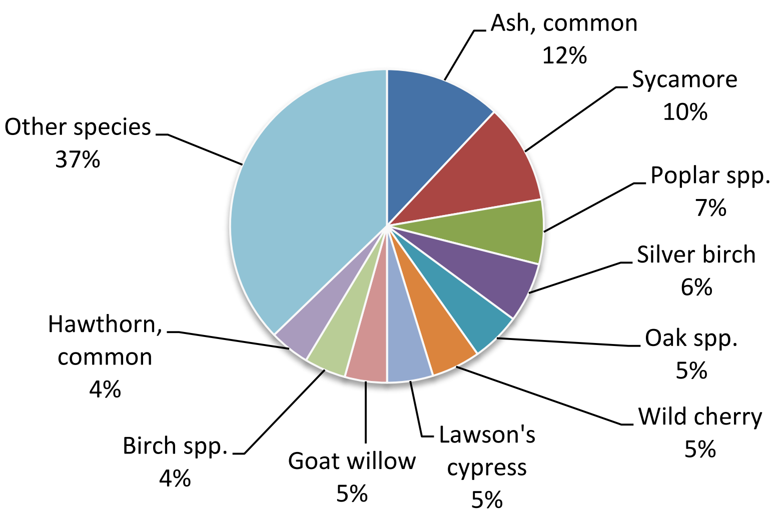


Fig. 13. Percentage value held by tree species in Glasgow according to CAVAT analysis.

Table 4 CAVAT values for the top ten trees by genus		
Genus	Value (£)measured	Value across Glasgow
Ash spp.	£219,390	£481,287,045
Poplar spp.	£209,913	£460,497,614
Birch spp.	£200,828	£440,566,571
Sycamore	£187,601	£411,551,507
Cherry spp.	£150,812	£330,844,525
Oak spp.	£143,168	£314,075,257
Willow spp.	£99,891	£219,115,197
Lawson's cypress	£86,607	£189,995,259
Hawthorn spp.	£83,171	£182,457,472
Rowan/Service tree spp.	£80,004	£175,509,182

The land use type containing the highest CAVAT value of trees is parks, with the total value of trees within this land use type estimated at approximately £893,234 in the plots sampled. This equates to around £1.9 billion when extrapolated for the whole of Glasgow. Street trees (occurring across all land use types) account for around 5% of the total value (Fig. 14). Transportation land use accounted for the lowest value of trees at 0.35% of total value.

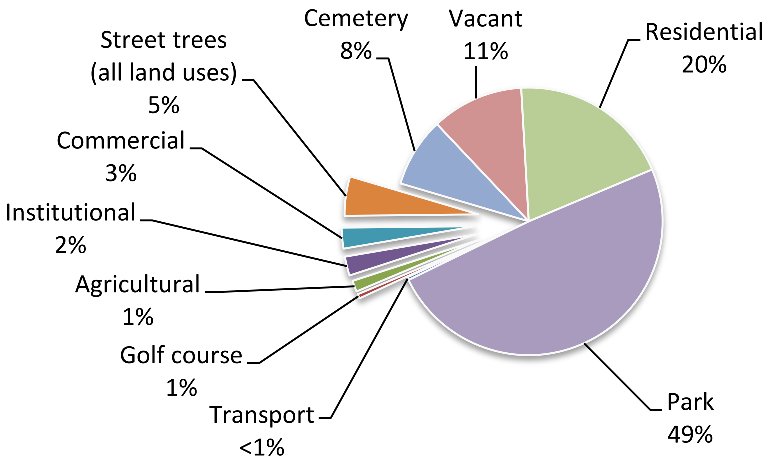


Fig. 14. Percentage amenity value held by tree species in Glasgow according to land use type

Avoided surface water runoff

The infrastructure required to remove surface water from towns and cities is costly and in the UK in particular can be outdated. This means that in large storm events or failed water pipes, surface water may not be removed quickly and damage to property can incur.

Trees can ameliorate this problem by intercepting rainwater, retaining it on their leaves and absorbing some into their tissues for use in respiration. The trees in Glasgow intercept an estimated 812 000 m^3 of water per year. This is more water than is held in Castle Semple Loch (623 000 m^3, Murray & Pullar 1908) and is the equivalent of the new Glasgow training pool at Tollcross International Swimming Centre being filled 406 times[5].

Plate 1. Castle Semple Loch (Roger Griffith, 2008) situated approx. 16 km (10 miles) to the South West of the sample area holds 623 000 m^3 of water (Murray & Pullar 1908), 77% of the water intercepted by Glasgow's urban forest. Barr Loch is depicted in the background and is not included in this calculation.

Based on the standard local rate charged for sewerage[6], this would save £1.1 million in sewerage charges in Glasgow. Ash intercepts the most water, removing 109 000 m^3 of water per year, worth £147 000 in sewerage charges (Fig. 15).

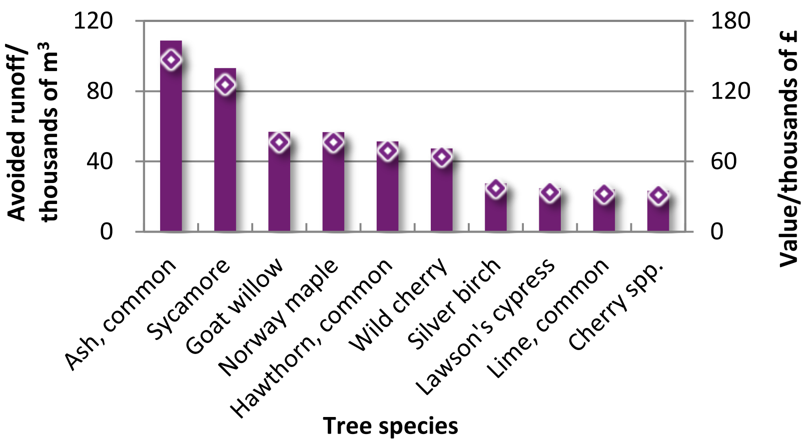


Fig. 15. Avoided surface water runoff provided by urban trees in Glasgow (columns) and their associated value in avoided sewer costs (diamonds)

[5] Based on the Tollcross International Swimming Centre training pool holding 2000 m^3 of water (Thomson 2012)
[6] This value is based on the 2013/14 household standard volumetric rate per cubic metre charged by Scottish Water and does not include standing charges or special discounts. This rate is stated as £1.3464 per m^3 (Scottish Water 2013)

Air Pollution Removal

Air pollution leads to a decline in human health, a reduction in the quality of ecosystems and it can damage buildings through the formation of acid rain (Table 5).

Table 5. Urban pollutants, their health effects and causes (air-quality.org.uk)

Pollutant	Health effects	Source
NO_2	Shortness of breath Chest pains	Fossil fuel combustion, predominantly power stations (21%) and cars (44%)
O_3	Irritation to respiratory tract, particularly for asthma sufferers	From NO_2 reacting with sunlight
SO_2	Impairs lung function Forms acid rain that acidifies freshwater and damages vegetation	Fossil fuel combustion, predominantly burning coal (50%)
CO	Long term exposure is life threatening due to its affinity with haemoglobin	Carbon combustion under low oxygen conditions i.e. in petrol cars
PM_{10} and $PM_{2.5}$	Carcinogenic Responsible for 10 000 premature deaths per year	Varied causes, cars (20%) and residential properties (20%) major contributors

Trees and shrubs can mitigate the impacts of air pollution by directly reducing airborne pollutants as well as reducing local temperatures. Trees can absorb pollutants through their stomata, or simply intercept pollutants that are retained on the plant surface (Nowak, Crane & Stevens 2006). This leads to year-long benefits, with bark continuing to intercept pollutants throughout winter (Nowak, Crane & Stevens 2006). Plants also reduce local temperatures by providing shade and by transpiring (Bolund and Hunhammar, 1999), reducing the rate at which air pollutants are formed, particularly ozone (O_3; Jacob & Winner 2009). However, trees can also contribute to ozone production by emitting volatile organic compounds (VOC's) that react with pollutants (Lee, Lewis, Monks, *et al.* 2006). Research indicates that, of the trees present in Glasgow, oaks, poplars and willows have the potential to worsen air quality through release of VOC's (Stewart, Owen, Donovan, *et al.* 2002). i-Tree Eco takes the release of VOC's by trees into account to calculate the net difference in ozone production and removal.

It is estimated that 283 tonnes of airborne pollutants per year are removed by Glasgow's urban forest, including NO_2, ozone, SO_2, CO and PM_{10} and $PM_{2.5}$. Ozone and NO_2 were the pollutants removed in the highest volume by trees. This demonstrates that although trees can increase ozone levels by producing VOC's, they remove far more that they produce. In addition, as ozone production increases with temperature, the cooling benefits of trees reduce ozone production overall (Nowak, Civerolo, Trivikrama Rao, *et al.* 2000).

The pollution removed from the atmosphere can be valued to aid interpretation of this data. In both the USA and the UK, pollutants are valued in terms of the damage they cause to society. However, these are valued by slightly different methods in each country, using United States Externality Costs in the US (USEC) and United Kingdom Social Damage Costs (UKSDC) in the UK. The UK method does not cover all airborne pollutants (Table 5) because of the uncertainty associated with the value of removing some airborne pollutants. In addition, the value of PM_{10}'s can vary depending on their emission source. In most urban environments, a value between domestic emissions and transport emissions are commonly used.

Using the US valuation system, £2.75 million worth of pollutants are removed by urban trees in Glasgow (Fig. 16). Using the UK system, which only includes three pollutants, £1.4 million[7] worth of pollutants are removed from the atmosphere (Table 6).

Table 6. Amount of each pollutant removed by the urban forest and its associated value. Dashes denote unavailable values. USEC denotes United States Externality Cost, UKSDC denotes United Kingdom Social Damage Cost

Pollutant	Mean amount removed/tonnes per annum	US value per tonne/£	USEC value/£	UK value per tonne/£	UKSDC value/£
CO	3.96	1592	6304	-	-
NO_2	105.63	11207	1 183 795	955 (NO_x)	100 877
O_3	77.27	11207	865 965	-	-
PM_{10}	46.69	7482	349 335	28 140 (PM_{10}, domestic)	1 313 716
				55 310 (PM_{10}, transport urban medium)	2 582 424
$PM_{2.5}$	44.38	7842	348 028	-	-
SO_2	4.70	2744	12 897	1633 (SO_x)	7 675

[7] Using the lower "domestic" emission source for PM_{10}'s

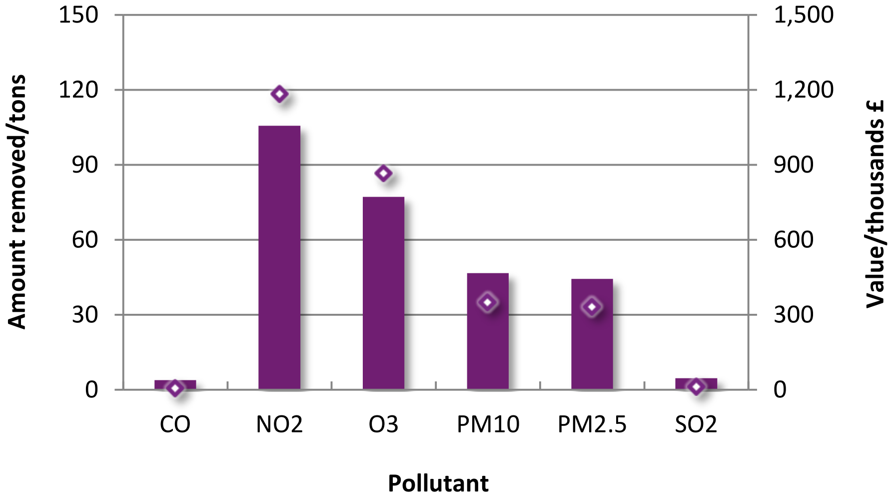
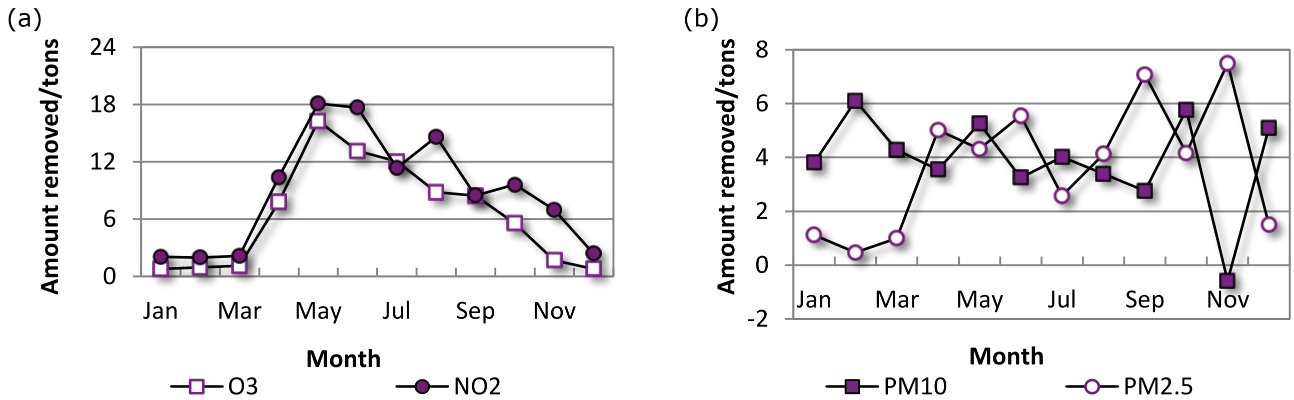


Fig. 16. Mean pollutants removed by urban trees in Glasgow (columns) and their associated value (diamonds) as valued using the USA externality system. PM_{10} excludes particles smaller than 2.5 microns.

The volume of airborne pollutants varied over the year, with a seasonal pattern evident in the removal of ozone, which was removed in higher volumes during the summer (Fig. 17). This is because ozone is a product of the combination of NO_x, which was also removed in greater volumes in summer, and VOC's. The production of ozone is also more prevalent in warm temperatures (Sillman & Samson 1995). In addition, this creates a diurnal pattern, with ozone levels higher during the day than at night (Nowak, 2000).



(c)

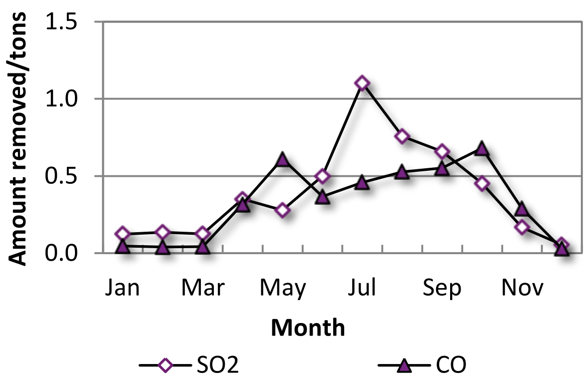


Fig. 17. Monthly pollutants removed by Glasgow's urban trees. (a) O_3 and NO_2, (b) PM_{10}'s and $PM_{2.5}$'s and (c) SO_2 and CO

Carbon Storage and Sequestration

It is estimated that Glasgow's trees store a total of 183 000 tonnes of carbon in their wood, with ash storing the greatest amount (Fig. 18). This is equivalent to the annual carbon emissions of 134 000 homes[8] and equates to 47% of the carbon emissions produced by Glasgow households[9]. Alternatively, this is the equivalent of the annual CO_2 emissions of 324 000 cars[10], almost twice (177%) the total estimated annual CO_2 emissions produced by all the cars owned in Glasgow[11].

Similarly to leaf area, carbon storage depends not only on the number of trees present, but also their characteristics. In this case, the mass of a tree is important, as larger trees store more carbon in their tissues. Sycamore, for example, makes up 4.7% of Glasgow's tree population, but is responsible for storing 8.5% of the total carbon stored in trees, the biggest difference between frequency and carbon stored displayed by any of Glasgow's tree species.

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[8] Based on an average UK household emission of 5 tonnes of CO_2 per year in 2009 (Palmer & Cooper 2011)
[9] Estimate based on the number of households estimated by the Glasgow Registry Office, 2012 (General Regsiter Office for Scotland 2012)
[10] Based on average emissions of 157g/CO_2 per km (cars registered after 2001, Department for Transport 2014), with the average UK car travelling 13 197 km per year (Department for Transport 2013)
[11] Based on the 2011 Glasgow car ownership figure of 182 948 cars (National Records of Scotland 2011).

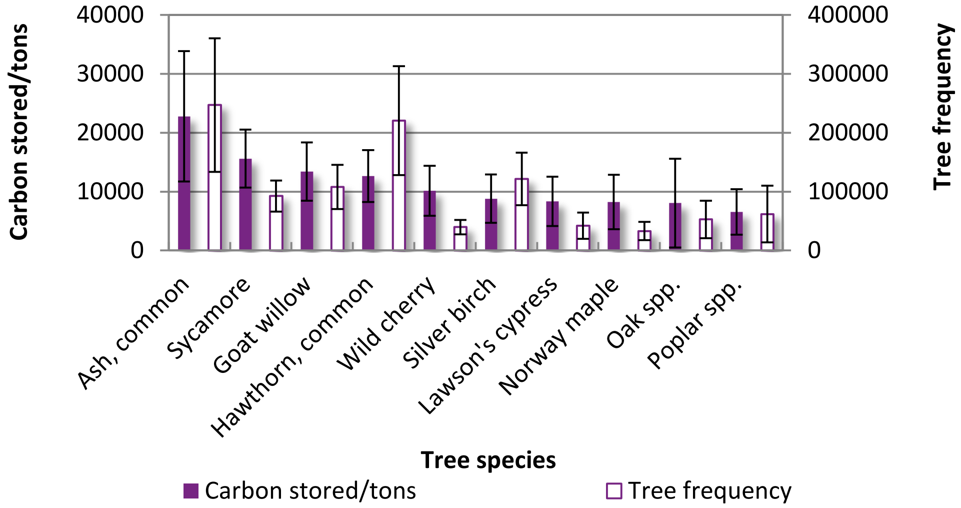

Fig. 18. Amount of carbon stored in Glasgow's urban forest and the frequency of each species in Glasgow. Only the ten trees with the highest storage rates are displayed.

The gross amount of carbon sequestered by the urban forest in Glasgow each year is estimated at 9 000 tonnes. Taking into account the number of dead trees (net storage), which release carbon into the atmosphere, Glasgow's urban forest sequesters 8 000 tonnes of carbon per year (0.5 t/Ha). This is the equivalent to the annual emissions from 16 500 automobiles (9% of the number of cars in Glasgow), or 6 000 family homes (2% of Glasgow's total estimated households).

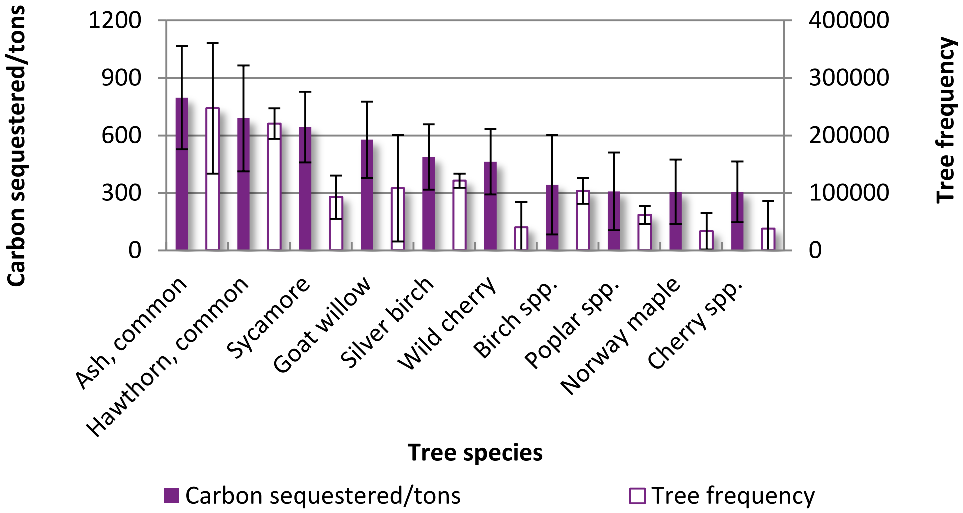

Fig. 19. Carbon sequestered per year by the ten trees with highest rates, along with their frequency. Error bars denote standard error of the mean (SEM).

Elm and yew were the only species encountered where individuals were losing significant amounts of carbon on an annual basis (Fig. 20), totalling an annual loss of 330 tonnes. However, there is some uncertainty around this figure, hence the large standard error (Fig. 20). Four common yew individuals encountered were all in the same plot and had suffered storm damage. Three Wych elm individuals were encountered, one of which had died, one had significant dieback (68%) and one healthy individual. Two further species were found to be losing carbon on an annual basis, but this value is based on only one individual each and so have large uncertainty associated with them. Aside from these species, dead trees produce around 12 tonnes of carbon per year in Glasgow. However, it must be noted that both deadwood and old trees that are losing carbon provide valuable habitat for a variety of species (see: Humphrey *et al.* 2002), some with economic importance (Hagan & Grove 1999; Kennedy and Southwood 1984). It is, therefore, important to retain this component of the urban forest.

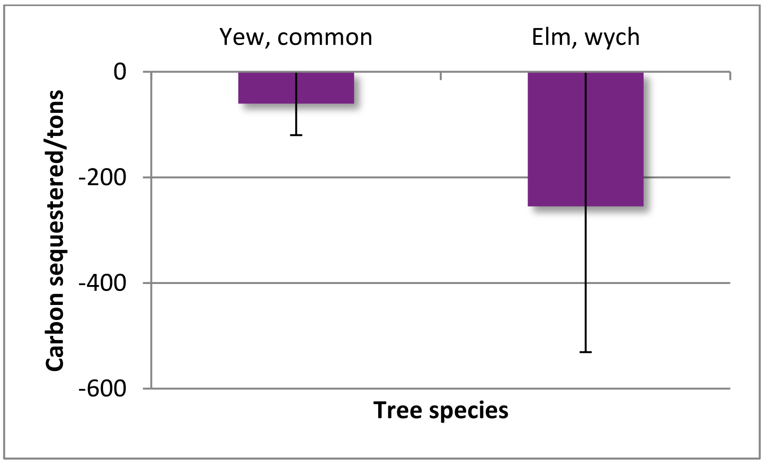

Fig. 20. Carbon sequestered per year by tree species for which net sequestered carbon was negative, i.e. carbon is annually lost from tissue. Error bars denote standard error of the mean (SEM).

The carbon stored and sequestered by trees can be valued within the framework of the UK government's carbon valuation method (DECC 2014). This is based on the cost of the fines that would be imposed if the UK does not meet carbon reduction targets. These values are split into two types, traded and non-traded. Traded values are only appropriate for industries covered by the European Union Emissions Trading Scheme. Tree stocks do not fall within this category so non-traded values are used instead. Within non-traded values, there are three pricing scenarios: low, central and high. These reflect the fact that carbon value could change due to outer circumstances, such as fuel price.

Based on the central scenario for non-traded carbon, it is estimated that the current tree stock will be storing £119.5 million worth of carbon by 2050, assuming that the structure of the forest in terms of species assemblage, tree size and population size remains unchanged (Fig. 21). Table 7 outlines stored carbon value from now until 2050 for all three pricing scenarios, again assuming no changes to Glasgow's urban forest occur in this time.

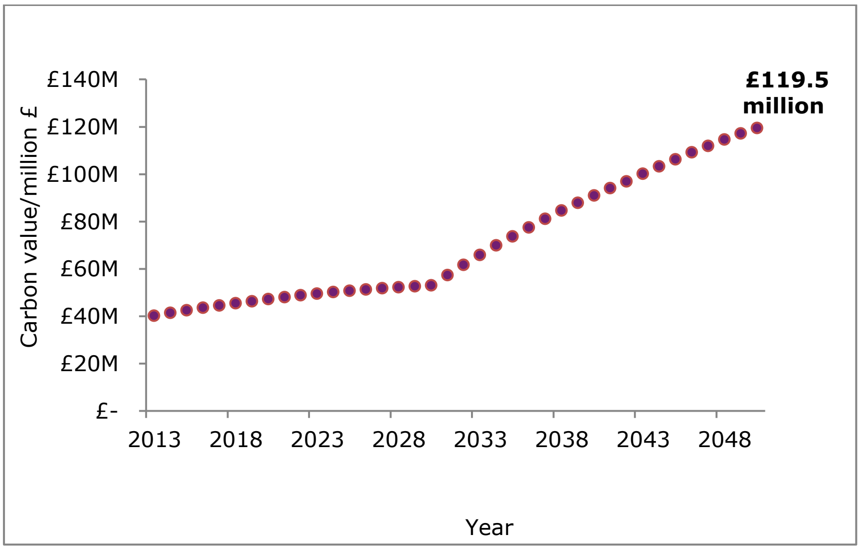

Fig. 21. Value of stored carbon within Glasgow's urban forest during the period 2013-2050. These values are based on the UK governments non-traded carbon valuation method and assume the structure of the urban forest remains the same over time.

Table 7. Non-traded values for the carbon stored in Glasgow's trees in all three valuation scenarios. These values are based on the UK governments non-traded carbon valuation method and assume the structure of the urban forest remains the same over time

						Non-traded unit value (£/tCO2e)					Value of discounted stored tCO2e		
	Year	Stored C (t)	Net sequestered C (t)	Stored C (tCO2e)	Net sequestered C (tCO2e)	Low	Central	High	Discount rate	Discount factor	Low	Central	High
1	2013	182801	9295	670270	34082	30	60	90	3.5	1.00	£ 20,101,498	£ 40,202,997	£ 60,304,495
2	2014	192096	9295	704352	34082	30	61	91	3.5	0.97	£ 20,690,070	£ 41,380,139	£ 62,070,209
3	2015	201391	9295	738435	34082	31	62	93	3.5	0.93	£ 21,246,012	£ 42,492,024	£ 63,738,036
4	2016	210686	9295	772517	34082	31	63	94	3.5	0.90	£ 21,770,417	£ 43,540,833	£ 65,311,250
5	2017	219982	9295	806599	34082	32	64	95	3.5	0.87	£ 22,264,344	£ 44,528,688	£ 66,793,032
6	2018	229277	9295	840682	34082	32	65	97	3.5	0.84	£ 22,728,824	£ 45,457,649	£ 68,186,473
7	2019	238572	9295	874764	34082	33	66	98	3.5	0.81	£ 23,164,859	£ 46,329,717	£ 69,494,576
8	2020	247867	9295	908846	34082	33	67	100	3.5	0.78	£ 23,573,418	£ 47,146,836	£ 70,720,255
9	2021	257162	9295	942929	34082	34	68	102	3.5	0.75	£ 23,994,783	£ 47,989,567	£ 71,984,350
10	2022	266458	9295	977011	34082	34	69	103	3.5	0.73	£ 24,385,216	£ 48,770,433	£ 73,155,649
11	2023	275753	9295	1011093	34082	35	70	105	3.5	0.70	£ 24,745,406	£ 49,490,811	£ 74,236,217
12	2024	285048	9295	1045176	34082	36	71	107	3.5	0.68	£ 25,076,063	£ 50,152,126	£ 75,228,190
13	2025	294343	9295	1079258	34082	36	72	108	3.5	0.65	£ 25,377,921	£ 50,755,841	£ 76,133,762
14	2026	303638	9295	1113340	34082	37	73	110	3.5	0.63	£ 25,651,726	£ 51,303,452	£ 76,955,178
15	2027	312933	9295	1147423	34082	37	74	112	3.5	0.61	£ 25,898,240	£ 51,796,480	£ 77,694,720
16	2028	322229	9295	1181505	34082	38	75	113	3.5	0.59	£ 26,118,234	£ 52,236,468	£ 78,354,703
17	2029	331524	9295	1215587	34082	38	77	115	3.5	0.57	£ 26,312,487	£ 52,624,975	£ 78,937,462
18	2030	340819	9295	1249670	34082	39	78	116	3.5	0.55	£ 26,481,783	£ 52,963,566	£ 79,445,350
19	2031	350114	9295	1283752	34082	42	85	127	3.5	0.53	£ 28,689,557	£ 57,379,113	£ 86,068,670
20	2032	359409	9295	1317834	34082	46	92	138	3.5	0.51	£ 30,835,251	£ 61,670,502	£ 92,505,754
21	2033	368705	9295	1351917	34082	50	99	149	3.5	0.49	£ 32,916,136	£ 65,832,272	£ 98,748,408
22	2034	378000	9295	1385999	34082	53	107	160	3.5	0.47	£ 34,929,901	£ 69,859,802	£ 104,789,703
23	2035	387295	9295	1420081	34082	57	114	171	3.5	0.46	£ 36,874,624	£ 73,749,248	£ 110,623,872
24	2036	396590	9295	1454164	34082	60	121	181	3.5	0.44	£ 38,748,743	£ 77,497,485	£ 116,246,228
25	2037	405885	9295	1488246	34082	64	128	192	3.5	0.43	£ 40,551,026	£ 81,102,052	£ 121,653,078
26	2038	415180	9295	1522328	34082	68	135	203	3.5	0.41	£ 42,280,548	£ 84,561,097	£ 126,841,645
27	2039	424476	9295	1556411	34082	71	143	214	3.5	0.40	£ 43,936,665	£ 87,873,330	£ 131,809,995
28	2040	433771	9295	1590493	34082	75	150	225	3.5	0.38	£ 45,518,989	£ 91,037,978	£ 136,556,967
29	2041	443066	9295	1624575	34082	78	157	235	3.5	0.37	£ 47,027,369	£ 94,054,738	£ 141,082,107
30	2042	452361	9295	1658658	34082	82	164	246	3.5	0.36	£ 48,461,871	£ 96,923,742	£ 145,385,613
31	2043	461656	9295	1692740	34082	86	171	257	3	0.35	£ 50,080,906	£ 100,161,811	£ 150,242,717
32	2044	470952	9295	1726822	34082	89	179	268	3	0.33	£ 51,641,482	£ 103,282,965	£ 154,924,447
33	2045	480247	9295	1760905	34082	93	186	279	3	0.32	£ 53,143,182	£ 106,286,364	£ 159,429,546
34	2046	489542	9295	1794987	34082	97	193	290	3	0.32	£ 54,585,738	£ 109,171,477	£ 163,757,215
35	2047	498837	9295	1829069	34082	100	200	300	3	0.31	£ 55,969,025	£ 111,938,050	£ 167,907,075
36	2048	508132	9295	1863152	34082	104	207	311	3	0.30	£ 57,293,046	£ 114,586,093	£ 171,879,139
37	2049	517427	9295	1897234	34082	107	215	322	3	0.29	£ 58,557,928	£ 117,115,856	£ 175,673,784
38	2050	526723	9295	1931316	34082	111	222	333	3	0.28	£ 59,763,906	£ 119,527,812	£ 179,291,719

Habitat Provision

Trees and shrubs provide valuable habitat and food for many animal and plant species, from non-vascular plants, such as moss, to insects, birds and mammals. Two examples are included in this section to highlight some of the organisms trees can support. For a broader review see Alexander, Butler and Green (2006).

Pollinating insects provide ecosystem services by pollinating food crops, but they are under threat from pressures including land-use intensification and climate change (Vanbergen & The Insect Pollinators Initiative 2013). Providing food sources could help. Glasgow's trees and shrubs are contributing to this food source, with thirty of the genus' found in Glasgow supporting pollinating insects (RHS, 2012) (Table 8).

Many insect herbivores are supported by trees and shrubs. Some specialise on just a few tree species, whilst others are generalists that benefit from multiple tree and shrub species. Of the species found in Glasgow, native willows and oaks support the most varied insect herbivore species (Fig 22). Beetles, however, are best supported by a single species, Scots pine (Table 9), highlighting that though some species have fewer insects associated with them, they are extremely important for certain groups.

Non-native trees associate with fewer species than native trees as they have had less time to form associations with native organisms (Kennedy and Southwood, 1984). In addition, some native species form few insect herbivore associations due to their high level of defence mechanisms, yew being a good example (Daniewski, Gumulka, Anczewski, *et al.* 1998). These species may support wildlife in other ways, for example by supplying structural habitat dead wood (buglife.org.uk 2013).

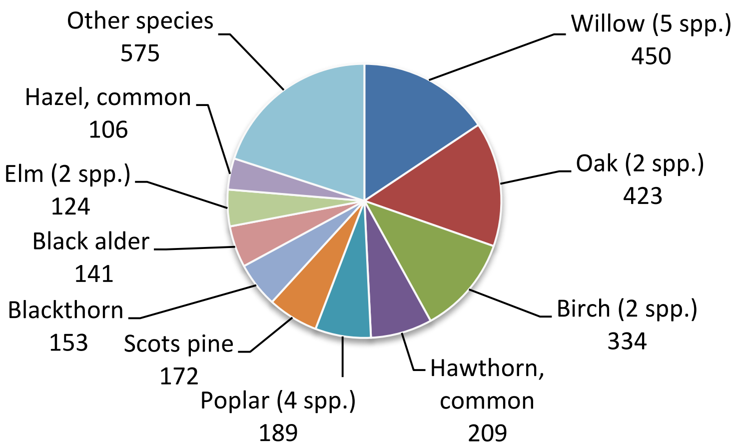

Fig. 22. The number of insect species that associated with trees found in the Glasgow survey[12]. Where multiple species are denoted in brackets, insect species associate with more than one host (e.g. Common oak and sessile oak support the same insect species or the literature does not separate these two species). Data from Southwood (1961) and Kennedy and Southwood (1984).

[12] NB: Insect data is not available for all species encountered in Glasgow; only species studied in Southwood (1961) and Kennedy and Southwood (1984) are included. Even closely related species such as apples and pears are not included as data was not available for the domesticated species.

Table 8. Species/genus encountered in Glasgow that are beneficial to pollinators (RHS, 2012)

Species	Sp/Gen	Season	Species	Sp/Gen	Season
Acer spp.	Genus	Spring	*Mahonia spp.*	Genus	Winter, spring
Acer campestre	Species	Spring	*Malus spp.*	Genus	Spring
Acer platanoides	Species	Spring	*Photinia spp.*	Genus	Summer
Acer pseudoplatanus	Species	Spring	*Pieris japonica*	Species	Spring
Acer saccharinum	Species	Spring	*Pieris spp.*	Genus	Spring
Aesculus spp.	Genus	Spring, summer	*Potentilla fruiticosa*	Species	Summer
Aesculus hippocastanum	Species	Spring	*Prunus spp.*	Genus	Spring
Aesculus indica	Species	Summer	*Prunus avium*	Species	Spring
Berberis darwinii	Species	Spring	*Prunus laurocerasus*	Species	Spring
Berberis spp.	Genus	Spring	*Prunus padus*	Species	Spring
Berberis thunbergii	Species	Spring	*Prunus spinosa*	Species	Spring
Buddleja spp.	Genus	Summer	*Pyracantha spp.*	Genus	Summer
Buddleja davidii	Species	Summer	*Ribes sanguineum*	Species	Spring
Buxus sempervirens	Species	Spring	*Ribes spp.*	Genus	Spring
Cornus spp.	Genus	Spring, summer	*Rosa spp.*	Genus	Summer
Cotoneaster spp.	Genus	Spring, summer	*Rosa canina*	Species	Summer
Cornus mas	Species	Spring	*Rubus spp.*	Genus	Summer
Crataegus monogyna	Species	Spring, summer	*Salix spp.*	Genus	Spring
Fuchsia spp.	Genus	Summer	*Salix caprea*	Species	Spring
Hebe spp.	Genus	Spring, summer	*Sorbus aria*	Species	Summer
Hebe speciosa	Species	Spring, summer	*Sorbus aucuparia*	Species	Summer
Hydrangea spp.	Genus	Summer	*Spiraea spp.*	Genus	Summer
Ilex aquifolium	Species	Spring, summer	*Symphoricarpos spp.*	Genus	Summer
Ilex spp.	Genus	Spring, summer	*Symphoricarpos albus*	Species	Summer
Jasminum spp.	Genus	Summer	*Tilia spp.*	Genus	Summer
Lavandula angustifolia	Species	Summer	*Tilia cordata*	Species	Summer
Ligustrum ovalifolium	Species	Summer	*Tilia x europaea*	Species	Summer
Ligustrum ovalifolium aurea	Species	Summer	*Viburnum opulus*	Species	Summer
Ligustrum spp.	Genus	Summer	*Viburnum spp.*	Genus	Winter
Lonicera spp.	Genus	Winter	*Weigela spp.*	Genus	Summer

Table 9. Species of insect supported by trees encountered in Glasgow. Bold species names denote non-native species. Brightest green boxes denote the highest number of species supported in that insect group, red the lowest and middle values are represented by a gradient between the two ("Total" column shows gradient in order). Data from Southwood (1961) and Kennedy and Southwood (1984)

	Ref	Total	Beetles	Flies	True bugs	Wasps and sawflys	Moths and butterflies	Other
Salix (5 spp.)	1984	450	64	34	56	104	162	9
Quercus petrea and *robur*	1984	423	67	7	43	70	189	9
Betula (2 spp.)	1984	334	57	5	30	42	179	9
Crataegus monogyna	1984	209	20	5	23	12	124	8
Populus (4 spp.)	1984	189	32	14	34	29	69	3
Pinus sylvestris	1984	172	87	2	10	11	41	6
Prunus spinosa	1984	153	13	2	25	7	91	11
Alnus glutinosa	1984	141	16	3	18	21	60	9
Ulmus (2 spp.)	1984	124	15	4	22	6	55	11
Corylus avellana	1984	106	18	7	3	8	48	6
Fagus sylvatica	1984	98	34	6	7	2	41	4
Picea abies	1984	70	11	3	14	10	22	1
Fraxinus excelsior	1984	68	1	9	7	7	25	9
Sorbus aucuparia	1984	58	8	3	6	6	33	2
Tilia (2 spp.)	1984	57	3	5	7	2	25	8
Acer campestre	1984	51	2	5	10	2	24	6
Carpinus betulus	1984	51	5	3	10	2	28	2
Acer pseudoplatanus	1984	43	2	3	10	2	20	5
Larix decidua	1984	38	6	1	6	5	16	1
Abies spp	1961	16	8	N/A	5	N/A	3	N/A
Ilex aquifolium	1984	10	4	1	2	0	3	0
Aesculus hippocastanum	1984	9	0	0	5	0	2	2
Taxus baccata	1984	6	0	1	1	0	3	1

Risks of Pests and Disease

Pests and diseases are a serious threat to urban forests. Severe outbreaks have occurred within living memory, with Dutch Elm Disease killing approximately 30 million trees in the UK (Webber 2010). Climate change may exacerbate this problem, ameliorating the climate for some pests and diseases, making outbreaks more likely (Forestry Commission 2014b). Assessing the risk pests and diseases pose to urban forests is, therefore, of paramount importance.

Acute Oak Decline

Acute oak decline (AOD) affects mature trees (>50 years old) of both native oak species (common oak and sessile oak). Over the past four years, the reported incidents of stem bleeding, a potential symptom of AOD, have been increasing. The incidence of AOD in Britain is unquantified at this stage but estimates put the figure at a few thousand affected trees. The condition seems to be most prevalent in the Midlands and the South East of England. Acute Oak Decline poses a threat to 4.7% of Glasgow's urban forest.

Asian Longhorn Beetle

Asian Longhorn Beetle (ALB) is a major pest in China, Japan and Korea, where it kills many broadleaved species. In America, ALB has established populations in Chicago and New York. Where the damage to street trees is high felling, sanitation and quarantine are the only viable management options.

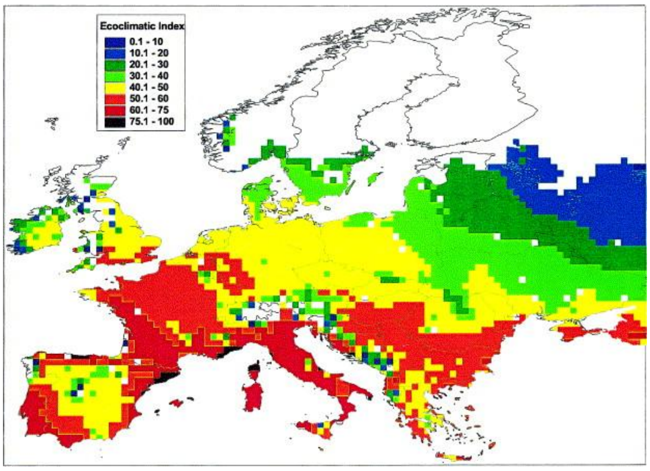

Fig. 23. MacLeod *et al.,* (2002). Ecoclimatic Indices for countries across Europe. An index of >32 is suggested to be suitable for ALB.

In March 2012 an ALB outbreak was found in Maidstone, Kent. The Forestry Commission and Fera removed more than 2 000 trees from the area to contain the outbreak. No further outbreaks have been reported in the UK. MacLeod, Evans & Baker (2002) modelled climatic suitability for outbreaks based on outbreak data from China and the USA and suggested that CLIMEX (the model used) Ecoclimatic Indices of >32 could be suitable habitats for ALB. Fig. 23 suggests that Glasgow may not be amenable to ALB under this model.

However, if an ALB outbreak did occur in Glasgow it would pose a significant threat to 68.7% of Glasgow's trees, not including attacks on shrub species.

The known host tree and shrub species include:

Acer spp. (maples and sycamores)

Aesculus spp. (horse chestnut)

Albizia spp. (Mimosa, silk tree)

Alnus spp. (alder)

Betula spp. (birch)

Carpinus spp. (hornbeam)

Cercidiphyllum japonicum (Katsura tree)

Corylus spp. (hazel)

Fagus spp. (beech)

Fraxinus spp. (ash)

Koelreuteria paniculata

Platanus spp. (plane)

Populus spp. (poplar)

Prunus spp. (cherry, plum)

Robinia pseudoacacia (false acacia/black locust)

Salix spp. (willow, sallow)

Sophora spp. (Pagoda tree)

Sorbus spp. (mountain ash/rowan, whitebeam etc)

Quercus palustris (American pin oak)

Quercus rubra (North American red oak)

Ulmus spp. (elm)

Bleeding Canker of Horse Chestnut

The pathogen *Pseudomonas syringae* pv *aesculi* causes bleeding canker of horse chestnut (BCHC), causing stem bleeding. The resultant loss of bark can lead to girdling and everntually death, particularly in young trees. In 2007, the Forestry Commission undertook a survey of BCHC in the UK and found that 50% of urban trees in Scotland showed symptoms to some degree, compared to 34% in rural areas. 1.2% of Glasgows urban trees are susceptible to BCHC.

Chalara Dieback of Ash

Ash dieback, caused by the fungus *Chalara fraxinea*, targets common and narrow leaved ash. Young trees are particularly vulnerable and can be killed within one growing season of symptoms becoming visible. Older trees take longer to succumb, but can die from the infection after several seasons. *C. fraxinea* was first recorded in the UK in 2012 in

Buckinghamshire and has now been reported across the UK, including in urban areas. Several confirmed cases have been reported in recently planted sites around Glasgow, as of April 2014. Ash dieback poses a threat to 12.7% of Glasgow's urban forest.

Emerald Ash Borer

There is no evidence to date that emerald ash borer (EAB) is present in the UK, but the increase in global movement of imported wood and wood packaging poses a significant risk of its accidental introduction. EAB is present in Russia and is moving West and South at a rate of 30-40km per year, perhaps aided by vehicles (Straw, Williams, Kulinich, *et al.* 2013). EAB has had a devastating effect in the USA due to its accidental introduction and could add to pressures already imposed on ash trees from diseases such as Chalara dieback of ash. Emerald Ash borer poses a potential future threat to 12.7% of Glasgow's urban forest.

Giant Polypore

Giant polypore (*Meripilus giganteus)* is a fungus that can cause internal decay in trees without any external symptoms (Schmidt 2006), causing trees to potentially topple or collapse (Adlam 2012). It is particularly common in urban areas and can also cause defoliation and crown dieback (Schmidt 2006; Adlam 2012). Giant polypore predominantly affects hardwoods such as horse chestnut, beech, lime and oak. 14% of Glasgow's urban forest could be vulnerable to giant polypore.

Gypsy Moth

Gypsy moth (GM), *Lymantria dispar*, is an important defoliator of a very wide range of trees and shrubs in mainland Europe, where it often reaches outbreak numbers. It can cause tree death if serious defoliation occurs on a single tree. Breeding colonies persist in northeast London and in Aylesbury, Buckinghamshire. Aside from these disparate colonies, GMs range in Europe does not reach as far West as the UK. Some researchers suggest that the climate in the UK is currently suitable for GM should it arrive here and that it would become more so if global temperatures rise (Vanhanen, Veteli, Päivinen, *et al.* 2007). However, the spread of GM in the USA has been slow, invading less than a third of its potential range (Morin, Liebhold, Luzader, *et al.* 2005). If GM spread to Glasgow, it would pose a threat to 21.8% of Glasgow's urban trees.

Oak Processionary Moth

Established breeding populations of oak processionary moth (OPM) have been found in South and South West London and in Berkshire. It is thought that OPM has been spread on nursery trees. The outbreak in London is now beyond eradicating, whereas efforts to stop the spread out of London and to remove those in Berkshire are underway. The caterpillars cause serious defoliation of oak trees, their principal host, but the trees will recover and leaf the following year. On the continent, they have also been associated with hornbeam, hazel, beech, sweet chestnut and birch, but usually only where there is heavy infestation of nearby oak trees. The caterpillars have urticating (irritating) hairs that carry a toxin that can be blown in the wind and cause serious irritation to the skin, eyes and bronchial tubes of humans and animals. They are considered a significant human health problem when populations reach outbreak proportions, such as those in The Netherlands and Belgium have done in recent years. Oak processionary moth poses a threat to 7.6% of Glasgow's urban forest.

Phytophthora ramorum

Phytophthora ramorum (PR) was first found in the UK in 2002 and primarily affects species of oak (Turkey oak, Red oak and Holm oak), beech and sweet chestnut. However, it has also been known to occasionally infect European and hybrid larch and kills Japanese larch. Rhododendron is a major host, which aids the spread of the disease. Many cases have been identified in areas surrounding Glasgow, including in Beith and Darvel. *Phytophthora ramorum* poses a threat to 1.8% of Glasgow's urban forest.

Phytophthora kernoviae

Phytophthora kernoviae (PK) was first discovered in Cornwall in 2003. The disease primarily infects rhododendron and bilberry (*Vaccinium*) and can cause lethal stem cankers on beech. It has been found in Scotland, for example on wild bilberry bushes on the Isle of Arran, but has been contained. *Phytophthora kernoviae* is deemed to pose a risk to 6.7% of Glasgow's urban forest and affects many of Glasgow's shrub species.

Phytophthora lateralis

The main host of *Phytophthora lateralis* (PL) is Lawson cypress. It has resulted in the decline of Lawson cypress hedgerows, with lesions spreading up the lower stem, resulting in crown death. Although there are less than 2 200 hectares of commercially grown Lawson cypress in Britain, there is a huge risk to amenity and garden populations. One case of PL infection has been reported in Glasgow, with others in surrounding areas. *Phytophthora lateralis* is deemed to pose a risk to 2.1% of Glasgow's urban forest.

Dothistroma (Red Band Needle Blight)

Dothistroma (red band) needle blight is the most significant disease of coniferous trees in the North of the UK. The disease causes premature needle defoliation, resulting in loss of yield and, in severe cases, tree death. It is now found in many forests growing susceptible pine species, with Corsican, lodgepole and, more recently, Scots pine all being affected. However, there are no reported cases of red band needle blight on urban trees and only 0.8% of Glasgow's urban forest are at threat from it.

Sweet Chestnut Blight

Sweet chestnut blight (SCB) is a fungal infection affecting sweet chestnut (*Castanea sativa* and *C. dentata*). Common, sessile and holm oak may also be infected, though in these species it is rarely fatal. The European Plant Protection Organisation also lists evergreen beeches (*Castanopsis spp.*), Acers, Stags Horn Sumach and Shagbark Hickory as host species, though how damaging the fungus is to these species is unknown. SCB has not been found to date in Scotland and has no host species in Glasgow, posing no risk to Glasgow's urban forest. However, there are some species in Glasgow for which the risks are not yet quantified (oak, sycamore, etc.). These trees make up 12.1% of Glasgow's urban forest and could potentially be affected.

Pests and Diseases – Conclusions

With increased importation of wood and trees in addition to a climate that is becoming more amenable to many pests and diseases, ensuring urban forests are resilient is of paramount importance. The high prevalence of ash in Glasgow makes the city's urban forest particularly susceptible to threats such as Chalara. Protecting the urban forest as a whole against threats such as this can be helped by increasing the diversity of tree species in Glasgow. Other threats not yet in the UK, such as gypsy moth and Asian longhorn beetle pose a threat to many more species and could potentially devastate a diverse range of urban trees. UK wide initiatives such as plant health restrictions are designed to combat these threats, but many pests are difficult to detect (Forestry Commission, 2014). In order to protect urban forests from all pests and diseases, vigilance is key. Monitoring urban trees for signs of pests and diseases helps fast responses to eradicate pests before they are a problem and informs research targeted at combating diseases in the long term.

Roe deer and squirrel damage is increasing in Glasgow, causing damage to trees by stripping bark. Again, the choice of trees planted and their frequency could be important. Pioneer species, such as alder, birch, sycamore and hawthorn are less vulnerable to deer stripping than other trees, as are trees with spines, thick leaves and low palatability (Best Practice Guidance on the Management of Wild Deer in Scotland n.d.). Physical barriers, such as tree guards, can also reduce bark stripping by deer (Hodge & Pepper 1998). Physical barriers will not, however, prevent damage by squirrels and research is currently underway to determine if there are other methods of tree protection from squirrels (Forest Research 2014). Future research into the impact of these pests on urban trees specifically is needed as, although tree death has been shown in forest stands, it is unknown how species specific this is and whether the level of damage caused would outweigh the cost of control. As urban trees are not generally used for wood production, the costs of damage could be significantly lower than in forest stand trees.

Pests and diseases are not the only threats to our urban trees. Wind damage caused by storms can cause significant tree damage, reducing ecosystem services provision and costing local authorities money. Storm events could increase in intensity as the climate warms, producing stormy winters such as that experienced in 2014 (Met Office 2014). Storm damage is, therefore, an important risk to be able to quantify and future research should be directed at quantifying the damage costs as well as increasing the resilience of trees to wind damage.

Table 10. Risks of emerging pests and diseases

Pest/Pathogen	Species affected	Prevalence in the UK	Prevalence in Scotland	Risk of spreading to Scotland	Population at risk/%	CAVAT value of sampled trees/£	Stored carbon value trees/£
Acute oak decline	*Quercus robur, Q. petraea*	SE England and Midlands	None	Medium – present in England	4.7	48 930	735 845
Asian longhorn beetle	Many broadleaf species, see above	Small outbreak in Kent	None	Low – climate may not be suitable	68.7	1 331 078	27 623 756
Bleeding canker of horse chestnut	*Aesculus spp.*	Common in urban areas	Common in urban areas	High – already present	1.2	22 681	265 432
Chalara dieback of ash	*Fraxinus excelsior, F. angustifolia*	Cases across the UK	Many cases around Glasgow	High - already present	12.7	219 390	4 762 230
Emerald ash borer	*F. excelsior, F. angustifolia*	None	None	Medium risk (imported wood)	12.7	219 390	4 762 230
Giant polypore	Primarily *Quercus spp., Fagus spp., Aesculus spp.* and *Tilia spp.*	Common in urban areas	Common in urban areas	High – already present	14.0	267 561	5 047 810
Gypsy moth	*Quercus sp.*[+]	Two outbreaks in SE England	None	Medium risk – slow spreading	21.8	491 796	8 178 124
Oak processionary moth	*Quercus spp.*	Three sites in S England	None	Medium, small colo-nies are containable	7.6	143 168	2 428 473
Phytophthora ramorum	*Q. cerris, Q. rubra, Q. ilex, F. sylvatica, C. sativa, Larix decidua, L. x eurolepsis*	Many UK sites, particularly in S Wales and SW England	Many cases south and east of Glasgow. Closest outside Beith and Darvel	High – already present	1.8	27 340	1 132 015
Phytophthora kernoviae	*F. sylvatica, Ilex aquifo-lium, Q. robur, Q. ilex*[‡]	Several UK sites	Several Scottish cases	Medium	6.7	76 374	1 873 428
Phytophthera lateralis	*Chamaecyparis lawsonia*	Several UK sites	One case in Glasgow, others surrounding	High – already present	2.1	86 608	1 741 419
Dothistroma (Red band needle blight)	*Populus nigra ssp. laricio, P. contorta var. latifolia, Pinus sylvestris*	Several UK sites	Found in all FC Scotland districts	High – already present	0.8	2 210	107 587
Sweet chestnut blight	*C. sativa, C. dentate*	Nine sites in England	None	Low	0	0	0

[+] secondarily Carpinus betulus, F. sylvatica, Castanea sativa, Betula pendula and Populus sp.; [‡] Shrub species are also affected, some of which were found in Glasgow: Chilean hazelnut, *Gevina avellana;* Tulip tree, *Liriodendron tulipifera;* Winters bark, *Drimys winterii; Magnolia spp.; Pieris spp.; Michelia doltsopa;* Cherry laurel, *Prunus laurocerasus;* Ivy, *Hedera helix;* Rhododendron; Bilberry, *Vaccinium sp*

Conclusions

Glasgow's urban forest provides valuable ecosystem services and improves the quality of life for local residents, making it a significant asset to the area. Glasgow is estimated to contain two million trees, with high tree density per hectare. However, though canopy cover was high compared to the average town in England (Britt & Johnston 2008), it was lower than that of neighbouring Edinburgh. The high density of trees, but lower canopy cover, suggests that Glasgow has more trees with small canopy sizes than Edinburgh. Glasgow had a high number of large diameter trees (after small stature trees had been removed) compared to other surveyed cities, important because they tend to produce more ecosystem services (USDA 2003; Sunderland, Rogers & Coish 2012) and provide more habitat for wildlife (Lindenmayer, Laurance & Franklin 2012). However, very few 40-60cm diameter trees were sampled, suggesting there may be a temporary shortage of large trees in the near future. The provision for large trees in the longer term, however, is good, with a high abundance of small diameter trees and a good overall condition of the urban forest.

The most common species tended to be pioneer species such as ash, hawthorn and sycamore, a pattern also found in i-Tree surveys in other urban areas and reflected by the high proportion of trees found on vacant land. Diversity, important for ensuring the resilience of urban trees against pests and diseases (Johnston, Nail & Murray 2011), was comparable to other i-Tree surveyed cities, but could be improved upon. The ten most abundant tree species in Glasgow made up over half of the population and two species, ash and hawthorn, exceeded 10% abundance. This could lower the resilience of Glasgow's urban forest, particularly in light of the fact that ash could be susceptible to Chalara dieback of ash (Forestry Commission 2014a). Diversity was highest on residential land and in parks, associated with highest abundance of trees. Glasgow could improve the diversity of the urban forest by targeting areas with lower diversity. Some of these, such as institutional properties, transport corridors and multi-family residential areas, may be managed by the council, potentially easing this process.

Glasgow's trees provide valuable habitat for wildlife, with many species present for pollinating insects. Glasgow could improve on this, however, by planting shrubs that encourage pollinators. Only 5% shrub cover was encountered, much lower than in previous i-Tree surveys, highlighting a target area for improvement.

With regards to pests and diseases, Chalara dieback of ash is the only high risk, high impact disease at present in Glasgow. Low risk, high impact pests such as Asian longhorn beetle could affect trees across the UK, but is so far absent from UK tree populations. A number of diseases such as *Phytophthora spp.* are already present in Glasgow, but are only targeting a small proportion of Glasgow's current tree stock. Planning tree stocks that are resilient to these pests and diseases is key and will be aided by maintaining high tree diversity across all of Glasgow, taking into account those trees on private property in addition to council managed trees.

The highest amenity value held by trees in Glasgow was present in parks, emphasising the importance of parks as a benefit to local residents. Research to be released by the Heritage Lottery Fund in mid-2014 suggests that parks may be in danger of becoming neglected and undervalued due to potential spending cuts for discretionary services (Easton 2014). Highlighting the amenity value of trees within these areas could enable Glasgow City Council to demonstrate their value to potential funders.

In addition, a large proportion (17%) of Glasgow's trees were found on vacant land. This highlights the significance vacant land has in providing habitat for trees, particularly in post-industrial cities like Glasgow. However, this land is at risk from development. It is recommended that additional research into the specific value of trees on vacant land is conducted. This would enable local authorities to produce stronger cases for the mitigation of ecosystem services lost during development.

The annual values attributed to the ecosystem services provided by Glasgow's trees in this study are comparable to large spending projects, such as the recent housing development in the Duke Street area (GHA 2014), emphasising their importance as money saving urban infrastructure and enabling cost benefit analyses to be conducted. For example, tree planting or increasing pervious surface area could be a more viable solution to local flooding issues than extending existing sewer networks, with the added benefit of the other ecosystem services provided by trees and green spaces. These values can now be used to highlight the benefits of trees as green infrastructure, protecting existing trees and encouraging the proliferation of the urban forest.

The ecosystem services provided by trees are on-going and, for services such as carbon storage, could become more valuable in the future as external factors change. However, some of these services could be under threat. Ash was the most significant tree in terms of carbon sequestration, due to its prevalence in Glasgow and its large size, but this species could be under threat from Chalara dieback of ash (Forestry Commission 2014a). Planning tree stocks to maintain a high level of ecosystem service delivery is, therefore, of paramount importance.

Some trees were losing carbon on an annual basis, part of the natural cycle of carbon storage by trees. A large proportion of this carbon loss came from elm trees, likely due to the prevalence of Dutch elm disease in the recent past (Webber 2010). Dead wood is an important resource for many animal species (Humphrey, Stevenson, Whitfield, *et al.* 2002) and so should be considered as an important habitat in the urban environment. Taking this carbon loss into account as part of a natural ecosystem is, however, an important aspect when planning ecosystem service provision.

The carbon sequestered annually by Glasgow's trees was significant at 9 000 tonnes per year. This information and other information in this report can be used to shape policy or local targets. The annual carbon sequestration by trees can be compared to other carbon emitting practices, such as car use, and could then be used to inform tree planting to offset a proportion of CO_2 emissions. In this way, tangible and therefore achievable goals can be incorporated into local policy.

This study does have limitations, not all benefits provided by trees could be quantified, including the effect trees have on noise pollution and their ability to cool urban environments. The urban forest in Glasgow is, therefore, far more valuable than stated in this report. Future developments will enable these extra benefits to one day supplement this report, giving a more comprehensive picture.

This study is also limited given it is a snapshot of the forest at one moment in time. Monitoring of the urban forest using the same technique will allow annual variations to be taken into account and could, in the long term, inform us about dynamic processes such as climate change, allowing a more robust long-term picture to be built up. It is, therefore, recommended that an i-Tree survey is conducted every 5-10 years to support the management and planning of Glasgow's urban forest.

Glasgow's urban forest considerably improves the lives of inhabitants and visitors and should be valued as an asset in line with other beneficial infrastructure projects. The urban forest provides a functional service to ensure dense urban spaces are habitable and sustainable for the long-term. Planning practices and policy should reflect this, valuing trees as an integral part of our urban landscape.

References

Adlam, J. (2012) *Pest & Disease Management - Giant polypore*. [Online]. HorticultureWeek. Available at: http://www.hortweek.com/news/1158279/ (Accessed: 10 July 2014).

Akbari, H., Pomerantz, M. and Taha, H. (2001) COOL SURFACES AND SHADE TREES TO REDUCE ENERGY USE AND IMPROVE AIR QUALITY IN URBAN AREAS. *Solar Energy*. 70 (3), 295–310.

Alexander, A., Butler, J. and Green, T. (2006) The value of different trees and shrub species to wildlife. *British Wildlife*. 1818–28.

BBC News Scotland (2012) *Flooding problems in Scotland hit travellers*. [Online]. 2012. Available at: http://www.bbc.co.uk/news/uk-scotland-18716688 (Accessed: 14 May 2014).

Best Practise Guidance on the Management of Wild Deer in Scotland (n.d.) *Best Practise Guides - Tree Protection*. [Online]. Available at: http://www.bestpracticeguides.org.uk/crop/tree-protection.

Bolund, P. and Hunhammar, S. (1999) Ecosystem services in urban areas. *Ecological Economics*. [Online] 29 (2), 293–301. Available at: doi:10.1016/S0921-8009(99)00013-0.

Britt, C. and Johnston, M. (2008) *Trees in Towns II*. pp.1–36.

buglife.org.uk (2013) *Lowland beech and yew woodland*. [Online]. 2013. Available at: http://www.buglife.org.uk/advice-and-publications/advice-on-managing-bap-habitats/lowland-beech-and-yew-woodland (Accessed: 6 June 2014).

Cities, T. for (2011) *Trees for Cities*. [Online]. 2011. Available at: http://www.treesforcities.org/about-us/who-we-are/history-and-mission/ (Accessed: 25 March 2014).

Connor, E.F., Faeth, S.H., Simberloff, D. and Opler, P.A. (1980) Taxonomic isolation and the accumulation of herbivorous insects: a comparison of introduced and native trees. *Ecological Entomology*. [Online] 5 (3), 205–211. Available at: doi:10.1111/j.1365-2311.1980.tb01143.x.

Council of Tree and Landscape Appraisers (1992) *Guide for plant appraisal*. Savoy, Illinois, International Society of Arboriculture.

Daniewski, W.M., Gumulka, M., Anczewski, W., Masnyk, M., et al. (1998) Why the yew tree (Taxus Baccata) is not attacked by insects. *Phytochemistry*. [Online] 49 (5), 1279–1282. Available at: doi:10.1016/S0031-9422(98)00102-2 (Accessed: 28 May 2014).

DECC (2014) DECC/HM Treasury Green Book supplementary appraisal guidance on valuing energy use and greenhouse gas (GHG) emissions. Supporting tables, Table 3

Department for Transport (2013) *National Travel Survey: 2012*. (July 2013) pp.1–25.

Department for Transport (2014) *Vehicle Licensing Statistics: 2013*. (April 2014) pp.1–9.

Easton, M. (2014) *Parks in peril*. [Online]. 2014. BBC News. Available at: http://www.bbc.co.uk/news/uk-27500649 (Accessed: 30 May 2014).

Entwistle, A.C., Harris, S., Hutson, A.M., Racey, P.A., et al. (2001) *Habitat management for bats*. pp.1–52.

Forest Research (2014) *Controlling grey squirrel damage to woodlands*. [Online]. 2014. Available at: http://www.forestry.gov.uk/fr/INFD-6JPLKE.

Forestry Commission (2014a) *Chalara dieback of ash (Chalara fraxinea)*. [Online]. 2014. Available at: http://www.forestry.gov.uk/chalara (Accessed: 30 May 2014).

Forestry Commission (2010) *The case for trees*. pp.1–28.

Forestry Commission (2014b) *Tree threats – an overview*. [Online]. 2014. Available at: http://www.forestry.gov.uk/forestry/infd-9cden2 (Accessed: 25 March 2014).

GHA (2014) *GHA Press*. [Online]. 2014. Available at: http://www.gha.org.uk/content/default.asp?page=s25_1&newsid=4270&back=s25 (Accessed: 29 May 2014).

Glasgow 2014 XX Commonwealth Games (2014) *Glasgow 2014 unveils £4 million fund for cultural sector to celebrate Commonwealth Games*. [Online]. 2014. Available at: http://www.glasgow2014.com/media-centre/press-releases/glasgow-2014-unveils-£4-million-fund-cultural-sector-celebrate.

Hagan, J.M. and Grove, S.L. (1999) Coarse Woody Debris: Humans and Nature Competing for Trees. *Journal of Forestry*. 97 (1), 6–11.

Haswell-Smith, H. (2004) *The Scottish Islands: The Bestselling Guide to Every Scottish Island*. Edinburgh, Canongate.

Hodge, S. and Pepper, H. (1998) The Prevention of Mammal Damage to Trees in Woodland. *Forestry Commission Practice Note*. pp.1–12.

Humphrey, J., Stevenson, A., Whitfield, P. and Swailes, J. (2002) *A guide to managing deadwood in Forestry Commission forests*. p.19.

Hutchings, T., Lawrence, V. and Brunt, A. (2012) Estimating the Value of Estimating the Ecosystem Services Value of Edinburgh ' s Trees Trees: Results of a 2011 Survey. *Forest Research Technical Report*. pp.1–45.

i-Tree (2013) *i-Tree Eco Manual v5*. [Online]. 2013. Available at: http://www.itreetools.org/resources/manuals/Eco_Manual_v5.pdf (Accessed: 5 March 2014).

Jacob, D.J. and Winner, D. a. (2009) Effect of climate change on air quality. *Atmospheric Environment*. [Online] 43 (1), 51–63. Available at: doi:10.1016/j.atmosenv.2008.09.051 (Accessed: 28 May 2014).

John Clegg Consulting Ltd, The Campbell Palmer Partnership Ltd and Cawdor Forestry Ltd (2007) *Assessment of wood energy opportunities within the Glasgow and Clyde valley area*. [Online]. pp.1–77. Available at: http://issuu.com/gcvgreennetworkpartnership/docs/gn_wood_energy_final_report_070408.

Johnston, M., Nail, S. and Murray, B. (2011) " Natives versus aliens ": the relevance of the debate to urban forest management in Britain. In: *Trees, People and the Built Environment*. 2011 pp. 181–191.

Kennedy, C.E.J. and Southwood, T.R.E. (1984) The number of species of insects associated with British trees: A re-analysis. *Journal of Animal Ecology*. 53455–478.

LEE, J., LEWIS, A., MONKS, P., JACOB, M., et al. (2006) Ozone photochemistry and elevated isoprene during the UK heatwave of august 2003. *Atmospheric Environment*. 40 (39), 7598–7613.

Lindenmayer, D.B., Laurance, W.F. and Franklin, J.F. (2012) Ecology. Global decline in large old trees. *Science*. [Online] 338 (6112), 1305–1306. doi:10.1126/science.1231070 (Accessed: 2 May 2014).

MacLeod, A., Evans, H.. and Baker, R.H (2002) An analysis of pest risk from an Asian longhorn beetle (Anoplophora glabripennis) to hardwood trees in the European community. *Crop Protection*. 21 (8), 635-45.

Met Office (2014) *A global perspective on the recent storms and floods in the UK*. [Online]. 2014. Available at: http://www.metoffice.gov.uk/research/news/2014/uk-storms-and-floods.

Mitchell, C.E. and Power, A.G. (2003) Release of invasive plants from fungal and viral pathogens. *Nature*. [Online] 421 (6923), 625–627. Available at: doi:10.1038/nature01317.

Morin, R.S., Liebhold, A.M., Luzader, E.R., Lister, A.J., et al. (2005) *Mapping Host-Species Abundance of Three Major Exotic Forest Pests. Research Paper NE-726.* pp.1–15.

Murray, J. and Pullar, L. (1908) *Bathymetrical Survey of the Fresh-Water Lochs of Scotland, 1897-1909*. London, Royal Geographical Society.

National Records of Scotland (2011) *2011 Scotland Census*.

Nielan, C. (2010) *CAVAT- Full method users guide*. London, London Tree Officers Association.

Nielan, C. (n.d.) *Tree Valuation: CAVAT. The benefits of using a tree valuation method.* [Online]. Available at: http://www.cavattreevalue.com/case-studies.html (Accessed: 25 June 2014).

NOAA (2012) *NCDC*. [Online]. 2012. Available at: http://www.ncdc.noaa.gov/ (Accessed: 14 May 2014).

Nowak, D.J., Civerolo, K.L., Trivikrama Rao, S., Luley, C.J., et al. (2000) A modeling study of the impact of urban trees on ozone. *Atmospheric Environment*. [Online] 34 (10), 1601–1613. Available at: doi:10.1016/S1352-2310(99)00394-5.

Nowak, D.J., Crane, D.E. and Stevens, J.C. (2006) Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*. [Online] 4 (3-4), 115–123. Available at: doi:10.1016/j.ufug.2006.01.007 (Accessed: 28 May 2014).

Nowak, D.J., Crane, D.E., Stevens, J.C., Hoehn, R.E., et al. (2008) A Ground-Based Method of Assessing Urban Forest Structure and Ecosystem Services. *Arboriculture and Urban Forestry*. 34, 347–358.

Palmer, J. and Cooper, I. (2011) *Great Britain's housing energy fact file*. pp.1–118.

RHS (2012) *RHS Perfect for Pollinators plant list*.

RHS (2014) *Trees for climate change*. [Online]. 2014. Available at: http://www.rhs.org.uk/advice/profile?pid=712.

Richards, N.A. (1983) Diversity and stability in a street tree population. *Urban Ecology*. 7159–171.

Rogers, K., Jarratt, T. and Hansford, D. (2011) *Torbay ' s Urban Forest Assessing Urban Forest Effects and Values Torbay ' s Urban Forest*. pp.1–42.

Rumble, H., Rogers, K., Doick, K.J. and Hutchings, T.R. (2014) *Valuing Wrexham's Urban Forest*. Forest Research, Farnham

Santamour, F.S. (1990) TREES FOR URBAN PLANTING: DIVERSITY UNIFORMITY , AND COMMON SENSE. In: *Proceedings of the 7th conference of the metropolitan tree improvement alliance (METRIA)*. 1990 pp. 57–65.

Sarajevs, V. (2011) Street tree valuation systems. *Forestry Commission Research Note*. 008 (2011), 1–6.

Schmidt, O. (2006) *Wood and Tree Fungi; Biology, Damage, Protection and Use*. Berlin, Springer.

Scotland, G.R.O. for (2012) *Glasgow City Council Area - Demographic Factsheet*. [Online]. 2012. Available at: http://www.gro-scotland.gov.uk/files2/stats/council-area-data-sheets/glasgow-city-factsheet.pdf (Accessed: 21 May 2014).

Sillman, S. and Samson, P.J. (1995) Impact of temperature on oxidant phytochemistry in urban, polluted rural and remote environments. *Journal of Geophysical Research*. 100 (11), 11497–11508.

Southwood, T.R.E. (1961) The number of species of insect associated with various trees. *Journal of Animal Ecology*. 30 (1), 1–8.

Stewart, H., Owen, S., Donovan, R., R, M., et al. (2002) *Trees and sustainable urban air quality: Using trees to improve air quality in cities*. pp.1–12.

Straw, N. a., Williams, D.T., Kulinich, O. and Gninenko, Y.I. (2013) Distribution, impact and rate of spread of emerald ash borer Agrilus planipennis (Coleoptera: Buprestidae) in the Moscow region of Russia. *Forestry*. [Online] 86 (5), 515–522. Available at: doi:10.1093/forestry/cpt031 (Accessed: 28 May 2014).

Sunderland, T., Rogers, K. and Coish, N. (2012) What proportion of the costs of urban trees can be justified by the carbon sequestration and air-quality benefits they provide? *Arboricultural Journal*. 34 (2), 62–82.

Thomson, G. (2012) Latest on Tollcross pool upgrade. *Evening Times*. [Online] 30 April. Available at: http://www.eveningtimes.co.uk/news/latest-on-tollcross-pool-upgrade.18076640.

Townsend, C.R., Begon, M. and Harper, J.L. (2008) *Essentials of Ecology*. Chichester, John Wiley and Sons.

Trust, W. (2014) *Nature's Calendar*. [Online]. 2014. Available at: http://www.naturescalendar.org.uk/ (Accessed: 21 May 2014).

UKCP09 (2009) *UK Climate Projections 2009*.

Ulrich, R.S. (1979) Visual landscapes and psychological wellbeing. *Landscape Research*. 4 (1), 17–23.

USDA (2003) *The large tree argument*. pp.1–8.

Vanbergen, A.J. and The Insect Pollinators Initiative (2013) Threats to an ecosystem service: pressures on pollinators. *Frontiers in Ecology and the Environment*. 11251–259.

Vanhanen, H., Veteli, T.O., Päivinen, S., Kellomäki, S., et al. (2007) Climate Change and Range Shifts in Two Insect Defoliators: Gypsy Moth and Nun Moth – a Model Study. *Silva Fennica*. 41 (October), 1–18.

Water, S. (2013) *Metered Charges 2013 - 2014*. [Online]. 2013. Available at: http://www.scottishwater.co.uk/you-and-your-home/your-charges/2013-2014-charges/metered-charges (Accessed: 21 May 2014).

Webber, J. (2010) *Dutch elm disease – Q&A. Forest Research Pathology Advisory Note No. 10.*

Woodland Trust (2014) *Nature's Calendar* Available at: http://www.naturescalendar.org.uk/ (Accessed: 21 May 2014).

Appendix I - Detailed Methodology

i-Tree Eco Models and Field Measurements

i-Tree Eco is designed to use standardised field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects (Nowak and Crane, 2000), including:

- **Urban forest structure** (e.g., species composition, tree health, leaf area, etc.).
- **Amount of water intercepted by vegetation**
- **Amount of pollution removed** hourly by the urban forest and its associated per cent air quality improvement throughout a year. Pollution removal is calculated for ozone, sulphur dioxide, nitrogen dioxide, carbon monoxide and particulate matter (<10 microns; PM_{10} and <2.5 microns; $PM_{2.5}$).
- **Total carbon stored and net carbon annually sequestered** by the urban forest.
- **Replacement cost of the forest**, as well as the value for air pollution removal and carbon storage and sequestration.
- **Potential impact of potential emerging pests and diseases**

All field data were collected during the leaf-on season to properly assess tree canopies. Within each plot, data collected included land use, ground and tree cover, individual tree attributes of species, stem diameter, height, crown width and crown canopy missing and dieback.

To calculate the volume of stormwater intercepted by vegetation an even distribution of rain is assumed. The calculation is split into three stages:

1. The volume of water intercepted by vegetation
2. The volume of water dripping from vegetation once their canopy has reached saturation, minus water evaporation from leaf surfaces during the rainfall event
3. The volume of water that evaporates from leaf surfaces after a rainfall event

The same process is then applied to water reaching impervious ground, with saturation of the holding capacity of the ground causing surface runoff. Pervious cover is treated similarly, but with a higher storage capacity over time. See Hirabayashi (2013) for full methods.

Processes such as the effect tree roots have on drainage through soil are not calculated as part of this model.

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 (Nowak, 1994). 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*.

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 (Baldocchi, 1988; Baldocchi et al., 1987). 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 (Bidwell and Fraser, 1972; Lovett, 1994) that were adjusted depending on leaf phenology and leaf area. Particulate removal incorporated a 50 per cent re-suspension rate of particles back to the atmosphere (Zinke, 1967).

Forest Research are currently developing growth models and leaf-area-index predictive models for urban trees in the UK. This will help improve the estimated value of Glasgow's urban tree stock in the future.

Replacement costs were based on valuation procedures of the US Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition and location information (Nowak et al., 2002), in this case calculated using standard i-Tree inputs such as per cent canopy missing.

US Externality and UK Social Damage Costs

The i-Tree Eco model provides figures using US externality and abatement costs. These figures reflect the cost of what it would take a technology (or machine) to carry out the same function that the trees are performing, such as removing air pollution or sequestering carbon.

In the UK, however, the appropriate way to monetise the carbon sequestration benefit is to multiply the tonnes of carbon stored by the non-traded price of carbon (i.e. this carbon is not part of the EU carbon trading scheme). The non-traded price is not based on the cost to society of emitting the carbon, but is based on the cost of not emitting the tonne of carbon elsewhere in the UK in order to remain compliant with the Climate Change Act. The unit values used were based on those given in DECC (2011). This approach gives higher values of carbon than the approach used in the United States, reflecting the UK Government's response to the latest science, which shows that deep cuts in emissions are required to avoid the worst effects of climate change.

Official pollution values for the UK are based on the estimated social cost of the pollutant in terms of impact upon human health, damage to buildings and crops. This approach is termed 'the costs approach'. Values were taken from Defra (2010a) which are based on the Interdepartmental Group on Costs and Benefits (IGCB).

There are three levels of 'sensitivity' applied to the air pollution damage cost approach: 'High', 'Central' and 'Low'. This report uses the 'Central' scenario based on 2010 prices.

Furthermore, the damage costs presented exclude several key effects, as quantification and valuation is not possible or is highly uncertain. These are listed below (and should be highlighted when presenting valuation results where appropriate).

The key effects that have not been included are:

- Effects on ecosystems (through acidification, eutrophication, etc.)
- Impacts of trans-boundary pollution
- Effects on cultural or historic buildings from air pollution
- Potential additional morbidity from acute exposure to particulate matter
- Potential mortality effects in children from acute exposure to particulate matter
- Potential morbidity effects from chronic (long-term) exposure to particulate matter or other pollutants

CAVAT Analysis

An amended CAVAT full method was chosen to assess the trees in this study, in conjunction with the creator of the system. Although the alternative "quick" method is designed to be used in conjunction with street tree surveys as an aid to asset management of the tree stock as a whole (taking marginally less time to record) it was considered that the greater precision of the full method, in addition to the fact that trees other than street trees were assessed, was more appropriate in the current study.

To reach a CAVAT valuation the following was obtained:

- the current unit value factor rating
- DBH
- the Community Tree Index rating (CTI), 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 (SULE)

The unit value factor, which was also used in CTLA analysis, is the cost of replacing trees, presented in £/cm^2 of trunk diameter.

The CTI rating was constant across Glasgow at 100%. In actuality therefore, the survey concentrated on accessibility, functionality, appropriateness and SULE.

Accessibility was generally judged to be 100% for trees in parks, street trees and trees in other open areas. It was generally reduced to 80% for trees on institutional land, 40-60% on vacant plots and 40% for trees in residential areas and on agricultural land.

Because CAVAT is a method for trained, professional arboriculturists the functionality aspect was calculated directly from the amount of canopy missing, recorded in the field. For highway trees, local factors and choices could not be taken into account, nor could the particular nature of the local street tree make-up. However, the reality that street trees have to be managed for safety, and are frequently crown lifted and reduced (to a greater or lesser extent) and that they will have lost limbs through wind damage was acknowledged. Thus, as highway trees would not be as healthy as their more open grown counterparts, and so tend to have a significantly reduced functionality, their functionality factor was reduced to 50%. This is on the conservative side of the likely range.

For trees found in open spaces, trees were divided into those with 100% exposure to light and those that did not. On the basis that trees in open spaces are less intensively managed, an 80% functionality factor was applied to all individual open grown trees. For trees without 100% exposure to light the following factor was applied: 60% to those growing in small groups and 40% to those growing in large groups. This was assumed more realistic, rather than applying a blanket value to all non-highway trees, regardless of their situation to light and/or other trees.

SULE assessment was intended to be as realistic as possible and was based on existing circumstances. For full details of the method refer to LTOA (2010).

Appendix II - Species Importance List

Fig. A1. Importance values for all species encountered during the Glasgow survey

Rank	Species	Population/%	Leaf Area/%	IV
1	*Fraxinus excelsior*	12.4722	13.3986	25.8708
2	*Crataegus monogyna*	11.1358	6.3159	17.4517
3	*Acer pseudoplatanus*	4.6771	11.4599	16.137
4	*Salix caprea*	5.4566	6.9934	12.4499
5	*Betula pendula*	6.1247	3.3868	9.5115
6	*Acer platanoides*	1.6704	6.9737	8.6441
7	*Alnus glutinosa*	6.6815	1.2094	7.8909
8	*Prunus avium*	2.0045	5.8377	7.8421
9	*Quercus robur*	4.6771	2.7414	7.4185
10	*Betula spp.*	5.2339	1.2809	6.5147
11	*Chamaecyparis lawsoniana*	2.1158	3.0578	5.1736
12	*Prunus spp.*	1.8931	2.863	4.756
13	*Populus spp.*	3.118	1.179	4.297
14	*Cupressocyparis leylandii*	1.559	2.5734	4.1324
15	*Quercus spp.*	2.6726	1.3819	4.0545
16	*Populus tremula*	2.5613	1.1861	3.7474
17	*Sorbus aucuparia*	2.2271	1.482	3.7091
18	*Fagus sylvatica*	1.6704	2.0031	3.6735
19	*Salix alba*	2.1158	1.4498	3.5656
20	*Tilia x europaea*	0.5568	2.9541	3.5109
21	*Prunus padus*	2.0045	1.3515	3.356
22	*Corylus avellana*	1.6704	1.2961	2.9665
23	*Sorbus intermedia*	0.6681	1.9629	2.631
24	*Populus x canescens*	0.3341	2.0728	2.4069
25	*Ligustrum ovalifolium*	1.2249	0.6623	1.8873
26	*Sambucus nigra*	1.1136	0.7472	1.8608
27	*Alnus incana*	1.2249	0.5586	1.7836
28	*Tilia spp.*	0.3341	1.3613	1.6954
29	*Larix spp.*	1.1136	0.3692	1.4828
30	*Prunus cerasifera*	0.7795	0.6999	1.4794
31	*Picea abies*	0.3341	1.0342	1.3682
32	*Alnus spp.*	0.8909	0.3423	1.2332
33	*Betula pubescens*	0.6681	0.5613	1.2295
34	*Pinus sylvestris*	0.7795	0.4103	1.1898
35	*Acer spp.*	0.4454	0.6945	1.1399
36	*Camellia reticulata*	0.1113	1.0261	1.1375
37	*Tilia cordata*	0.3341	0.699	1.0331
38	*Ulmus glabra*	0.3341	0.463	0.7971
39	*Aesculus indica*	0.1113	0.6847	0.796
40	*Taxus baccata*	0.4454	0.286	0.7314
41	*Pinus wallichiana*	0.2227	0.286	0.5088
42	*Chamaecyparis*	0.4454	0.0626	0.508
43	*Cotoneaster frigidus*	0.3341	0.1171	0.4512

Rank	Species	Population/%	Leaf Area/%	IV
44	*Ilex aquifolium*	0.3341	0.0983	0.4324
45	*Salix spp.*	0.2227	0.1966	0.4194
46	*Acer campestre*	0.2227	0.1564	0.3792
47	*Larix decidua*	0.1113	0.2628	0.3741
48	*Acer saccharinum*	0.2227	0.1287	0.3514
49	*Sorbus aria*	0.1113	0.219	0.3303
50	*Aesculus spp.*	0.1113	0.2172	0.3285
51	*Philadelphus*	0.1113	0.1949	0.3062
52	*Laburnum anagyroides*	0.2227	0.0796	0.3023
53	*Cedrus deodara*	0.1113	0.1752	0.2865
54	*Salix nigra*	0.2227	0.0608	0.2835
55	*Acer palmatum*	0.1113	0.1636	0.2749
56	*Prunus laurocerasus*	0.1113	0.1189	0.2302
57	*Malus spp.*	0.1113	0.0983	0.2097
58	*Cupressocyparis*	0.1113	0.0921	0.2034
59	*Corylus colurna*	0.1113	0.0635	0.1748
60	*Quercus x riparia*	0.1113	0.0581	0.1694
61	*Betula pumila*	0.1113	0.0536	0.165
62	*Salix niphoclada*	0.1113	0.0375	0.1489
63	*Ilex spp.*	0.1113	0.0313	0.1426
64	*Carpinus betulus*	0.1113	0.017	0.1283
65	*Eucalyptus spp.*	0.1113	0	0.1113
66	Unidentifiable trees	0.1113	0	0.1113
67	*Prestoea acuminata*	0.1113	0	0.1113

Appendix III - Environmental Services by Species

Table A2. Environmental services provided by all trees encountered in Glasgow

Species	Number of trees	Carbon/ [1]mt	Gross Seq/ [1]mt/yr	Net Seq/ [1]mt/yr	Leaf Area/ km2	Leaf Biomass/ [1]mt	Stored carbon/t	Value/£ (non-traded, central)
Fraxinus excelsior	247002	22785.79	837.85	796.96	14.99	1594.63	83548	4762230
Crataegus monogyna	220537	12645.03	773.23	688.87	7.066	888.86	46365	2642811
Alnus glutinosa	132322	2657.8	276.07	264.94	1.353	98.65	9745	555480.2
Betula pendula	121296	8794.63	519.03	486.83	3.789	225.03	32247	1838078
Salix caprea	108063	13404.07	634.13	576.98	7.824	495.6	49148	2801451
Betula spp.	103653	3587.31	355.38	342.68	1.433	89.59	13153	749747.8
Acer pseudoplatanus	92626	15603.97	681.25	643.62	12.821	896.61	57215	3261230
Quercus robur	92626	3520.79	307.98	299.53	3.067	204.22	12910	735845.1
Populus spp.	61750	6535.7	326.94	307.73	1.319	89.12	23964	1365961
Quercus spp.	52929	8048.28	284.67	250.42	1.546	152.54	29510	1682091
Populus tremula	50724	1725.86	147.97	143.83	1.327	95.78	6328	360704.7
Sorbus aucuparia	44107	3029.78	212.07	158.17	1.658	131.55	11109	633224
Chamaecyparis lawsoniana	41902	8332.15	292.52	188.04	3.421	855.36	30551	1741419
Salix alba	41902	2493.28	193.79	191.68	1.622	102.75	9142	521095.5
Prunus avium	39697	10127.2	501.39	462.43	6.531	505.33	37133	2116585
Prunus padus	39697	909.3	101.65	94.56	1.512	116.95	3334	190043.7
Prunus spp.	37491	5904.68	322.36	305.46	3.203	247.83	21650	1234078
Acer platanoides	33081	8250.98	328.72	305.89	7.802	421.08	30254	1724455
Corylus avellana	33081	591.16	75.49	73.71	1.45	100.68	2168	123552.4
Fagus sylvatica	33081	5318.8	200.49	191.14	2.241	112.15	19502	1111629
Cupressocyparis leylandii	30875	2164.08	141.96	133.36	2.879	450.82	7935	452292.7
Alnus incana	24259	940.15	124.52	120.59	0.625	45.54	3447	196491.4
Ligustrum ovalifolium	24259	599.29	104.01	101.39	0.741	67.33	2197	125251.6
Larix spp.	22054	558.67	45.31	43.98	0.413	22.28	2048	116762
Sambucus nigra	22054	2019.96	134.08	124.51	0.836	62.63	7407	422171.6
Alnus spp.	17643	546.71	49.29	41.61	0.383	21.17	2005	114262.4
Pinus sylvestris	15438	514.77	32.27	20.28	0.459	44.25	1887	107586.9

Species	Number of trees	Carbon/ [1]mt	Gross Seq/ [1]mt/yr	Net Seq/ [1]mt/yr	Leaf Area/ km2	Leaf Biomass/ [1]mt	Stored carbon/t	Value/£ (non-traded, central)
Prunus cerasifera	15438	1148.11	110.43	106.14	0.783	47.6	4210	239955
Betula pubescens	13232	830.76	58.23	56.31	0.628	37.31	3046	173628.8
Sorbus intermedia	13232	5301.53	185.26	173.54	2.196	174.27	19439	1108020
Tilia x europaea	11027	4404.32	126.96	112.76	3.305	153.71	16149	920502.9
Acer spp.	8821	1367.2	68.03	11.28	0.777	43.73	5013	285744.8
Chamaecyparis spp.	8821	168.14	22.22	21.51	0.07	17.46	617	35141.26
Taxus baccata	8821	520.28	5.96	-60.1	0.32	50.1	1908	108738.5
Cotoneaster frigidus	6616	79.47	15.41	15.11	0.131	9.8	291	16609.23
Ilex aquifolium	6616	124.18	20.53	19.99	0.11	14.72	455	25953.62
Picea abies	6616	530.46	38.74	36.62	1.157	192.9	1945	110866.1
Populus x canescens	6616	5119.33	177.29	157.56	2.319	167.31	18771	1069940
Tilia spp.	6616	1007.63	37.96	36.22	1.523	70.84	3695	210594.7
Tilia cordata	6616	531.95	29.7	28.46	0.782	58.56	1950	111177.6
Ulmus glabra	6616	1915.73	21.92	-254.85	0.518	35.25	7024	400387.6
Acer campestre	4411	86.27	11.03	10.81	0.175	9.84	316	18030.43
Acer saccharinum	4411	108.3	16.35	15.89	0.144	7.56	397	22634.7
Laburnum anagyroides	4411	44.22	4.98	4.94	0.089	6.66	162	9241.98
Pinus wallichiana	4411	143.77	9.28	8.71	0.32	30.83	527	30047.93
Salix spp.	4411	1017.87	43.87	41.63	0.22	13.61	3732	212734.8
Salix nigra	4411	201.65	17.38	16.89	0.068	4.32	739	42144.85
Acer palmatum	2205	41.76	9.08	8.89	0.183	10.28	153	8727.84
Aesculus spp.	2205	231.51	21.24	20.29	0.243	17.76	849	48385.59
Aesculus indica	2205	1038.5	45.17	41.13	0.766	56.02	3808	217046.5
Betula pumila	2205	184.15	13.82	13.38	0.06	3.58	675	38487.35
Carpinus betulus	2205	15.97	5.31	5.23	0.019	1.12	59	3337.73
Camellia reticulata	2205	1159.98	25	24.19	1.148	85.95	4253	242435.8
Cedrus deodara	2205	164.43	12.02	11.36	0.196	30.76	603	34365.87
Corylus colurna	2205	58.87	4.41	4.37	0.071	4.91	216	12303.83
Cupressocyparis	2205	79.62	7.49	7.16	0.103	16.12	292	16640.58
Eucalyptus spp.	2205	55.33		-15.22			203	11563.97
Ilex spp.	2205	22.72	2.39	2.37	0.035	4.72	83	4748.48
Larix decidua	2205	97.54	6.23	5.84	0.294	15.85	358	20385.86
Malus spp.	2205	61.74	6.68	6.53	0.11	9.49	226	12903.66

Species	Number of trees	Carbon/ ¹mt	Gross Seq/ ¹mt/yr	Net Seq/ ¹mt/yr	Leaf Area/ km2	Leaf Biomass/ ¹mt	Stored carbon/t	Value/£ (non-traded, central)
Unidentifiable trees	2205	43.92		-12.08			161	9179.28
Philadelphus spp.	2205	2935.17	88.37	77.1	0.218	16.32	10762	613450.5
Prestoea acuminata	2205	1.52		-0.42			6	317.68
Prunus laurocerasus	2205	36.77	3.36	3.33	0.133	10.29	135	7684.93
Quercus x riparia	2205	50.42	6.28	6.16	0.065	6.37	185	10537.78
Salix niphoclada	2205	19.18	2.31	2.3	0.042	2.64	70	4008.62
Sorbus aria	2205	240.45	10.1	9.93	0.245	19.47	882	50254.05

Glossary of Terms

Biomass - the amount of living matter in a given habitat, expressed either as the weight of organisms per unit area or as the volume of organisms per unit volume of habitat

Broadleaf species – For example, alder, ash, beech, birch, cherry, elm, hornbeam, oak, other broadleaves, poplar, Spanish chestnut, and sycamore

Carbon storage - the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation

Carbon sequestration - the removal of carbon dioxide from the air by plants through photosynthesis

Crown – The crown of a plant refers to the totality of the plant's aboveground parts, including stems, leaves, and reproductive structures

Defoliator – (Defoliators) Pests that chew portions of leaves or stems, stripping of chewing the foliage of plants. (Leaf Beetles, Flea Beetles, Caterpillars, Grasshoppers, etc.)

Deposition velocities - In dry deposition: the quotient of the flux of a particular species to the surface (in units of concentration per unit area per unit time) and the concentration of the species at a specified reference height, typically 1m

Diameter at Breast Height (DBH) - Tree DBH is outside bark diameter at breast height. Breast height is defined as 4.5 feet (1.37m) above the forest floor on the uphill side of the tree. For the purposes of determining breast height, the forest floor includes the duff layer that may be present, but does not include unincorporated woody debris that may rise above the ground line

Dieback - In dieback, a plant's stems die, beginning at the tips, for a part of their length. Various causes

Ecosystem services - The benefits people obtain from ecosystems

Height to crown base - In a silvicultural sense, crown base height is simply the height on the main stem or trunk of a tree representing the bottom of the live crown, with the bottom of the live crown defined in various ways

Leaf area index - Leaf Area Index (LAI) is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows

Lesions - A lesion is any abnormal tissue found on or in an organism, usually damaged by disease or trauma

Meteorological - Pertaining to meteorology or to phenomena of the atmosphere or weather

Particulate matter - The term used for a mixture of solid particles and liquid droplets suspended in the air. These particles originate from a variety of sources, such as power plants, industrial processes and diesel trucks. They are formed in the atmosphere by transformation of gaseous emissions

Pathogen - Any organism or substance, especially a microorganism, capable of causing disease, such as bacteria, viruses, protozoa or fungi

Phenology - The scientific study of periodic biological phenomena, such as flowering, breeding, and migration, in relation to climatic conditions

Re-suspension - The remixing of sediment particles and pollutants back into the water by storms, currents, organisms, and human activities, such as dredging

Stem cankers - A disease of plants characterized by cankers on the stems and twigs and caused by any of several fungi

Structural values - value based on the physical resource itself (e.g. the cost of having to replace a tree with a similar tree)

Trans-boundary pollution - Air pollution that travels from one jurisdiction to another, often crossing state or international boundaries

Transpiration - Transpiration is the evaporation of water from aerial parts of plants, especially leaves but also stems, flowers and fruits

Tree-canopy - the aboveground portion of a plant community or crop, formed by plant crowns

Tree dry-weight - The plant, animal, or other material containing the chemical of interest is dried to remove all water from the material. The amount of the chemical found in subsequent analysis is then expressed as weight of chemical divided by weight of the dried material which once contained it

Urticating Hairs - Urticating hairs are possessed by some arachnids (specifically tarantulas) and insects (most notably larvae of some butterflies and moths). The hairs have barbs which cause the hair to work its way into the skin of a vertebrate. They are therefore an effective defence against predation by mammals

Volatile organic compounds - Any one of several organic compounds which are released to the atmosphere by plants or through vaporization of oil products, and which are chemically reactive and are involved in the chemistry of tropospheric ozone production

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