Estimating the Ecosystem Services Value of Edinburgh's Trees

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Summary

Trees and woodlands provide a range of social, environmental and economic benefits. There is strong evidence that trees influence our lives in many ways from improving health and well-being, improved learning, increasing property values, providing a focal point to improve social cohesion, improved air quality, offsetting carbon emissions, promoting biodiversity, limiting the risk of flooding, cooling our towns and cities, promoting inward investment and job creation through to making us drive more safely (Forest Research, 2010[1]). The i-Tree Eco model was developed by the US Forest Service to quantify a selection of these ecosystem services at the town and city scale.

This summary provides an overview of the results from a study which was undertaken using the i-Tree Eco model to estimate some of the major environmental benefits delivered by Edinburgh's trees. The model is still being developed for use in the UK and therefore only a limited number of benefits were able to be quantified from the full range of ecosystem services that trees can provide. The benefits quantified in this study were carbon storage and sequestration and air pollution removal.

The study was funded by Forestry Commission Scotland and City of Edinburgh Council and carried out by Forest Research. A survey of 200 field plots located across Edinburgh was carried out in the summer of 2011. Data from trees and shrubs were recorded from these plots and used to estimate the amount of carbon stored and that sequestered each year by each tree, as well as the amount of gaseous and particulate air pollutants removed by a tree.

Key results

The following list of findings is not exhaustive but provides an overview of the study's main results. For detail on how theses results were derived please read the Results and Discussion section of the main report (page 9).

Edinburgh's trees

- Edinburgh has over 600,000 trees and their canopies are estimated to cover 17.0% of the total land area.
- Over half of Edinburgh's trees are native to Scotland. The ten most common tree species make up over 65% of the total population are: sycamore, holly, silver birch, Leyland cypress, ash, beech, rowan, Scots pine, Wych elm and cherry.
- 71% of Edinburgh's trees were assessed as being in an 'excellent' condition and 15% being in 'critical', 'dying' or 'dead' condition.

[1] Forest Research (2010). *Benefits of green infrastructure*. Report by Forest Research. Forest Research, Farnham.

Removal of Carbon from the atmosphere (carbon storage / carbon sequestration)

Climate change is an issue of global concern. Urban trees can help mitigate climate change by binding up carbon in above-ground and below-ground parts of woody vegetation (carbon storage), and removing carbon dioxide from the air through photosynthesis (carbon sequestration).

- Edinburgh's trees are estimated to store 145,611 metric tonnes of carbon with a non-traded value of **£14.9 million in 2011**.

- They are also estimated to sequester 4,721 metric tonnes of net carbon per year[2] or the equivalent to the annual emissions of 20,801 people or 135 million passenger kilometers by car.

- The total value of carbon stored in Edinburgh's trees would accrue to **£35 million by 2050**[3].

Improving Edinburgh's air quality

Poor air quality is a common problem in many urban areas. It can lead to decreased human health and damage to ecosystem processes. The urban forest helps improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings which consequently reduces air pollutant emissions from power plants.

- Edinburgh's trees remove a total of 100 metric tonnes per year of ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter of less than 10 microns (PM_{10}) and sulphur dioxide (SO_2) - representing an **estimated value more than £2.3 million in 2011.**

Maintaining a healthy tree population

Ensuring Edinburgh's tree population remains healthy is important if the benefits quantified in this study are to continue to be delivered. To assist with this the study examined the potential risk of a range of pests and diseases to the health of the city's trees and impacts on the ecosystems services if specific tree species were removed. For example:

- The study predicated there was a medium risk of Asian Longhorn Beetle affecting the city's trees and if it does then over 300,000 trees may be at risk with a value of £10 million in stored carbon

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[2] A current constraint of the approach is that the software only calculates a single value for annually sequestered carbon. To overcome this, Forest Research are currently developing growth models and leaf-area-index predictive models for urban trees in the UK.

[3] The UK Government concluded a major review of the carbon valuation approach to be used in UK policy appraisal in July 2009. The revised approach moves away from a valuation based on the damages associated with impacts, instead using the cost of mitigation as its basis (DECC, 2011)

Conclusions

Edinburgh's trees improve the quality of life in the city and the survey demonstrates the economic value of the key environmental services that they deliver. The survey and modelling system also has significant potential to inform current and future tree planting and management strategies for improving both the resilience of the tree population, and opportunity to maximise the ecosystem services they provide.

Introduction

This report describes the results of a study of Edinburgh's urban trees, carried out in summer 2011 by Forest Research. The study used the i-Tree Eco model (developed by the US Forest Service) to quantify the structure and estimate some of the major environmental benefits delivered by Edinburgh's trees. i-Tree Eco was identified as the current most complete tool currently available for analysing the urban forest, as it is capable of providing the most detailed results on the structure and functions of trees. It is therefore a very useful tool in order to discover, manage, make decisions on and develop a good strategy concerning the trees present in Edinburgh. The i-Tree Eco model has been used successfully in many towns and cities in over 60 countries throughout the world, but the Edinburgh project is the first known use of the system in Scotland.

A survey was conducted across Edinburgh, recording a wide range of tree and shrub species, their size and condition and the type of land they were found on. Information from the survey was combined with local meteorological and air pollution data to produce an estimate of the monetary value of a range of environmental services from the local trees.

This report outlines the findings of that study. Our main objectives were to:

- Assess the structure, composition and distribution of Edinburgh's urban forest.
- Quantify some of the benefits (ecosystem services) of Edinburgh's trees in order to raise awareness of the value of trees in the urban environment.
- Establish a baseline from which to monitor trends and future progress.

Methodology

To help assess Edinburgh's urban forest, data from 200 field plots located across the city were analysed using the i-Tree Eco model. This, combined with a desktop exercise to collect local hourly pollution and meteorological data, allowed the project to collect information on the elements described in Table 1.

i-Tree Eco (also known as the urban forest effects model or UFORE) calculates the correct number of survey plots needed to give a representative sample of an urban tree population. Survey data from these plots was used to calculate the species and age class structure, biomass and leaf area index (LAI) of the urban forest. This data is then combined with local climate and air pollution data to produce estimates of carbon sequestration and storage, air pollution interception and removal, the monetary value of these ecosystem services and the structural value of the trees. The total study area for Edinburgh was 11,468 ha. This was divided into 200 grid squares and a randomly placed 0.04 hectare (ha) plot was placed within each grid square (Plate 1). This density provided a plot at approximately every 57 ha.

The model also estimates the predicted future benefits of the existing urban forest by applying growth rate calculations to the current stock.

Table 1. Study Outputs

Urban Forest Structure and Composition	Species diversity, tree 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 and PM_{10} % of total air pollution removed by trees Current carbon storage by the urban forest Carbon sequestered
Structural and Functional Values	Structural values in £ Carbon storage and sequestration value in £ Pollution removal value in £
Potential Insect and Disease Impacts	Asian Longhorn Beetle Gypsy Moth and Oak Processionary Moth Emerald Ash Borer Red Band Needle Blight Acute Oak Decline Horse Chestnut Bleeding Canker *Phytophthora ramorum, kernoviae and lateralis*

Data collected included plot information on land-use, percent ground-cover type, percent tree and shrub cover and percent plantable space using the methods set out in the UFORE data collection manual (Nowak et al., 2005). The full list of individual tree information is given in Table 2.

Table 2. Field Survey Data Collected

Plot Information	Tree information
• Land use type • Percent tree cover • Percent shrub cover • Percent plantable space • Percent ground cover type	• Species • Stem diameter • Total height • Height to crown base • Crown width • Percent foliage missing • Percent dieback • Crown light exposure

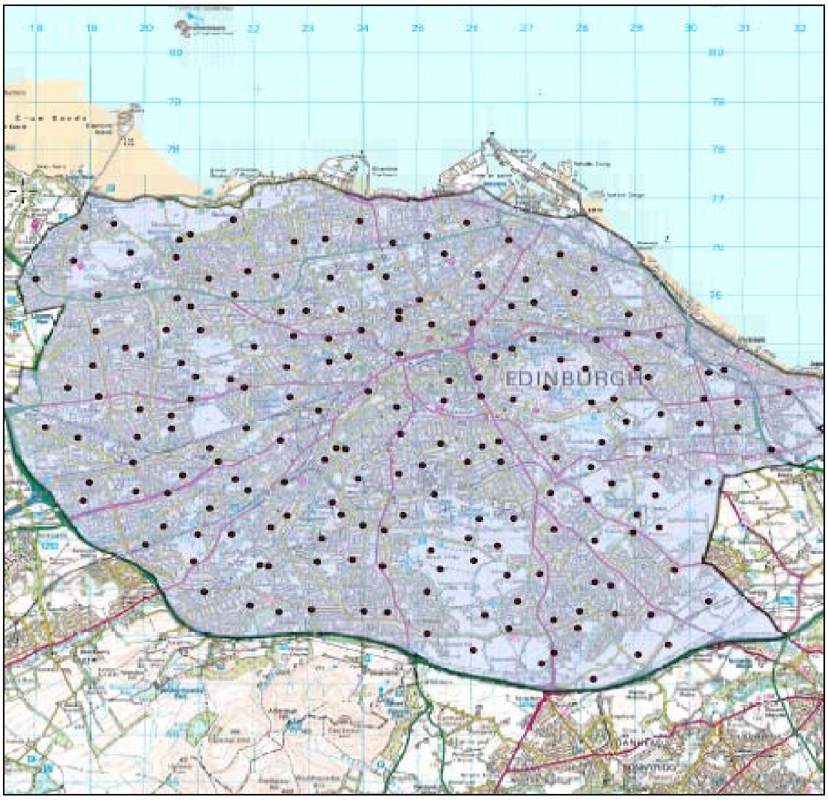

Plate 1. Map of Edinburgh catchment showing position of surveyed plots

UFORE Model and Field Measurements

UFORE 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 pollution removed hourly by the urban forest and its associated percent air quality improvement throughout a year. Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter (<10 microns; PM_{10}).

Total carbon stored and net carbon annually sequestered by the urban forest.

Structural value 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 by Asian longhorned beetle (ALB), emerald ash borer (EAB), gypsy moth (GM), oak processionary moth (OPM), red band needle blight (RBNB), acute oak decline (AOD), bleeding canker of horse chestnuts (BCHC*),* *Phytophthora ramorum* (PR), *Phytophthora kernoviae* (PK) and *Phytophthora lateralis* (PL).

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 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 percent 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 estimated value of Edinburgh's urban tree stock in the future.

Structural values 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).

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.

For 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 to 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 affects 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;

For PM_{10}s, which are the largest element of the air pollution benefit, a range of economic values is available depending on how urban (hence densely populated) the area under consideration is (IGCB). For the purposes of estimating air pollution removal value of Edinburgh's trees, the 'PM Transport Urban Large' figures were used (http://www.defra.gov.uk/environment/quality/air/air-quality/economic/damage/).

Results and Discussion

Urban Forest Structure

The urban forest of Edinburgh has an estimated 638,000 trees with a tree canopy cover of 17.0%. The overall tree density in Edinburgh is 55.6 trees per hectare (see Table 9 and 10 for comparable values from other cities). This is slightly below the UK average of 58.4 trees per hectare (Britt & Johnston, 2008).

Trees that have diameters (diameter at Breast Height; DBH) less than 15.2 cm (6-inches) constitute 45.5% of the total tree population. The three most common species are *Acer pseudoplatanus* (77,402 trees; 12.1%), *Ilex aquifolium* (70,843 trees; 11.1%) and *Betula pendula* (48,540 trees; 7.6%). The ten most common species in Edinburgh account for 65.4% of the total tree population (Figure 1).

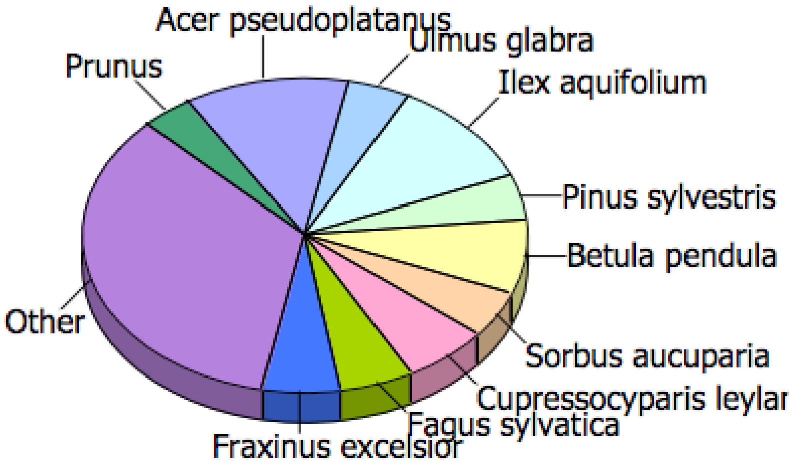

Figure 1. Tree species composition in Edinburgh

Urban forests are composed of a mix of native and exotic tree species. Thus, urban forests often have a tree diversity that is generally much higher than surrounding native landscapes. An increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease. It is estimated that 53% of Edinburgh's trees (n=338,470) are native to Scotland (Figure 4).

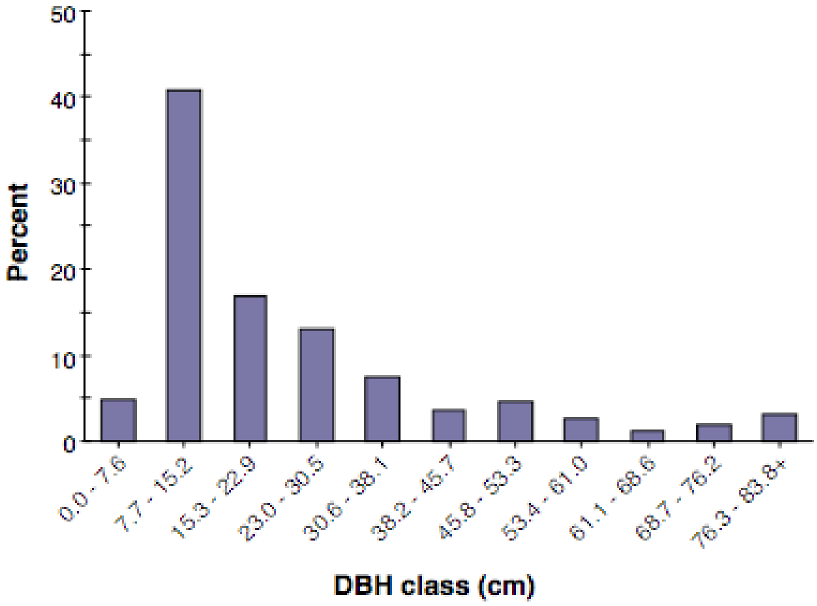

Figure 2. Percent of tree population by diameter class (DBH=stem diameter at 1.37 metres)

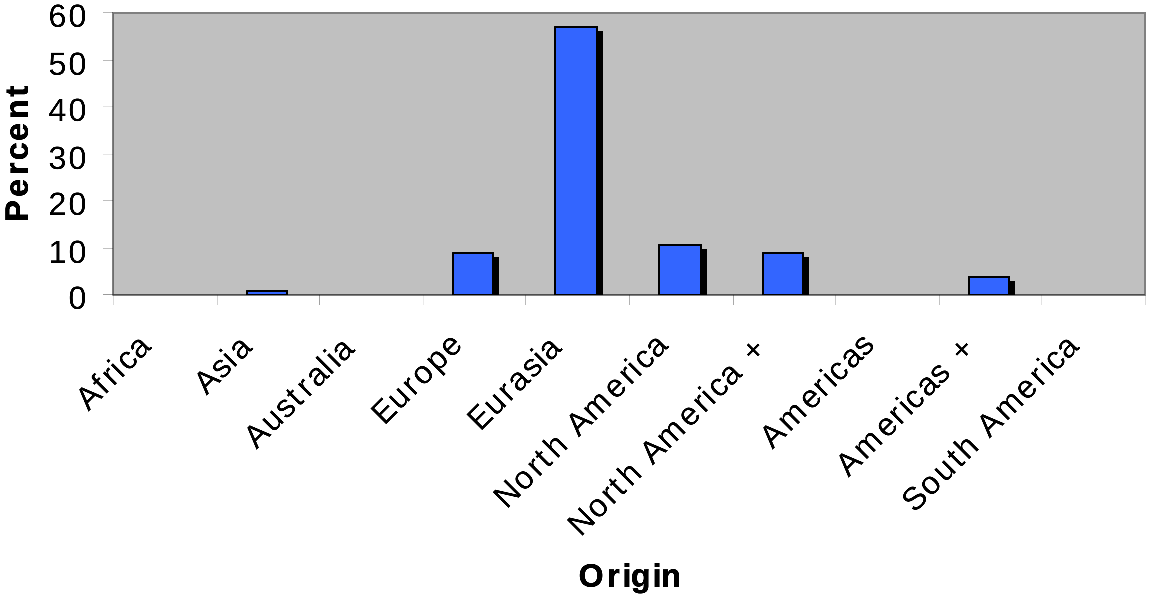

Figure 3. Percent of live trees by species origin

"North America +" = native to North America and at least one other continent except South America
"Americas +" = native to North and South America and at least one other continent

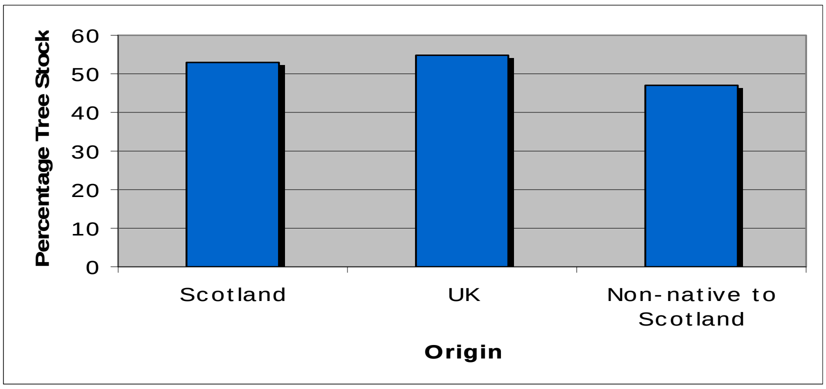

Figure 4. Percentage of tree species native to Scotland and the UK

Urban Tree Cover, Leaf Area and Biomass

Many tree benefits equate directly to the amount of healthy leaf surface area of the plant. In Edinburgh, the three most dominant species in terms of leaf area are *Acer pseudoplatanus*, *Prunus* and *Fagus sylvatica*. Trees cover about 17 percent of Edinburgh and shrubs cover 14.8 percent. Total leaf area of all of the trees in Edinburgh is estimated as 74 km^2 giving an average estimated 6444 m^2 of leaf area per hectare. The 10 most important species are listed in the table below. Importance values (IV) are calculated as the sum of relative leaf area and relative composition (Table

3). It is important to remember that some species may have a relatively low percentage of the population but a much higher importance value. For example, *Prunus* only makes up 3.7% of Edinburgh's tree population making it the tenth most abundant tree species but becomes the third most important tree species in Edinburgh. This is due to *Prunus* having a high leaf area index and thus providing more benefits.

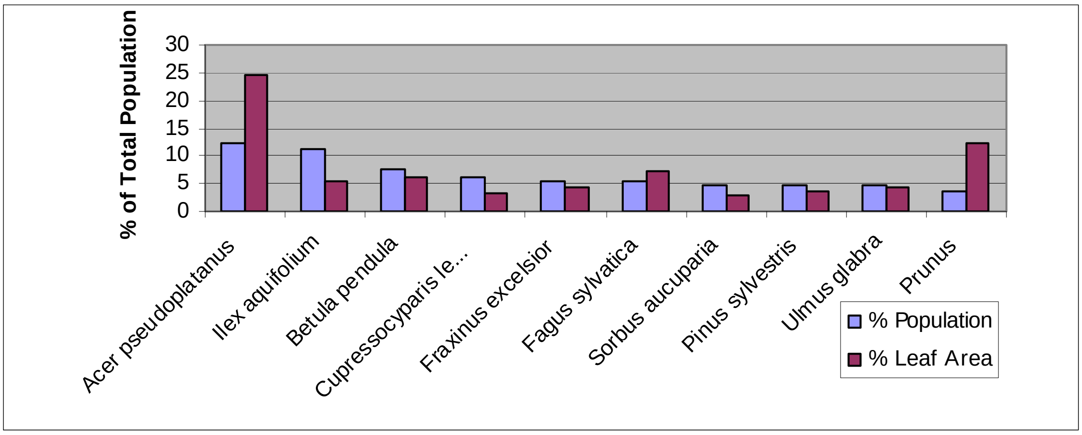

Figure 5. Percentage population and leaf area of the ten most important tree species in Edinburgh

Table 3. Most important species in Edinburgh

Tree Species	% population	% Leaf Area	Importance Value (IV)
Acer pseudoplatanus	12.1	24.5	36.6
Ilex aquifolium	11.1	5.4	16.5
Prunus	3.7	12.3	16.0
Betula pendula	7.6	6.2	13.8
Fagus sylvatica	5.3	7.2	12.6
Fraxinus excelsior	5.6	4.5	10.1
Cupressocyparis leylandii	6.2	3.1	9.3
Ulmus glabra	4.5	4.4	8.9
Pinus sylvestris	4.5	3.5	8.0
Sorbus aucuparia	4.7	2.9	7.7
Quercus petraea	1.9	0.8	2.7
Quercus robur	1.6	1.7	3.4
Malus	1.6	1.0	2.6
Crataegus monogyna	1.6	0.7	2.3
Tilia platyphyllos	1.0	1.3	2.4

The two most dominant ground cover types are grass (25.6%) and tar (tarmac; 19.4%) (Figure 6).

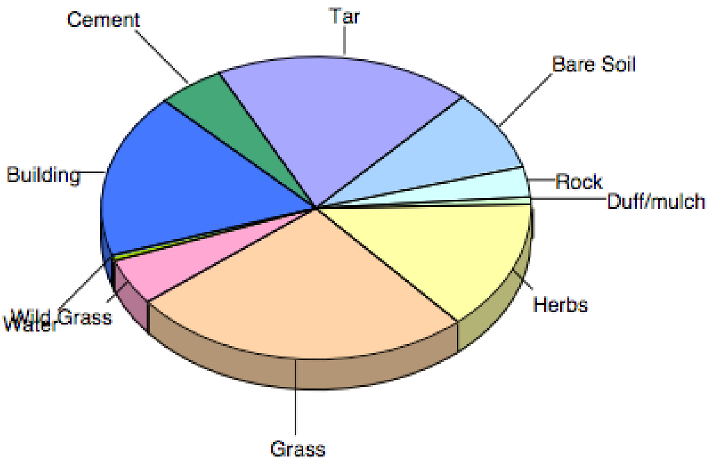

Figure 6. Breakdown of percentage ground cover in Edinburgh

Tree Condition

Overall, 71% of the trees in Edinburgh are in an 'excellent' condition, exhibiting less than 5% crown dieback[4]. With 8% in 'good' and 16% in 'fair' condition. A total of 15% of Edinburgh's trees are estimated as being in 'critical', 'dying' or 'dead' condition (Figure 7).

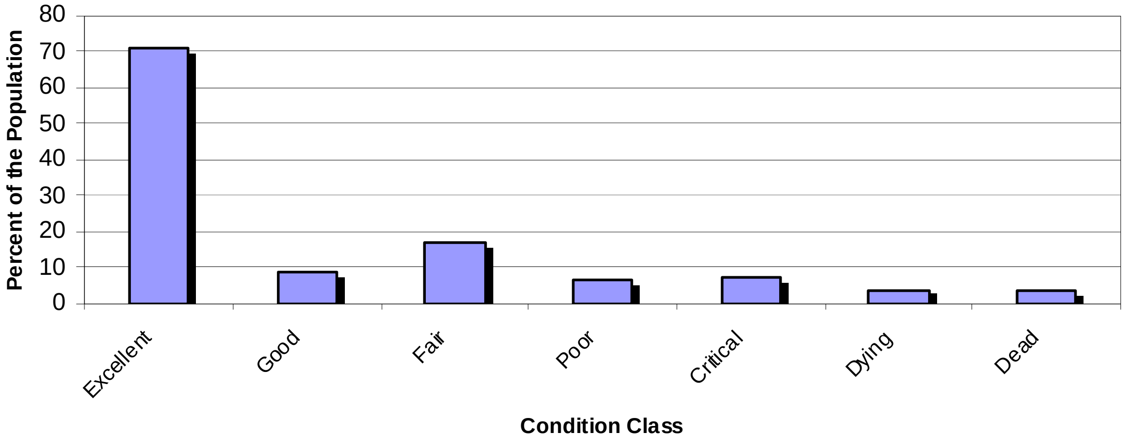

Figure 7. Condition Edinburgh's trees

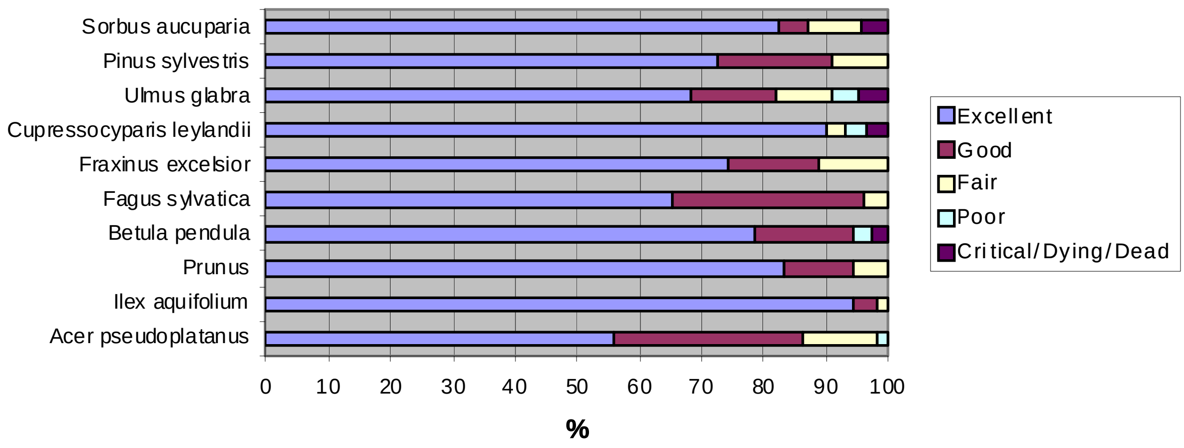

Figure 8. Condition of the top ten species in Edinburgh

Phenology

Mean average leaf-on/leaf-off dates were calculated using datasets from the UK phenology records (Natures Calendar, 2010). The data from 10 species were selected to calculate an average (*Acer campestre*, *Acer pseudoplatanus*, *Aeseculus hippocastanum*, *Alnus glutinosa)*, *Betula pendula*, *Fagus sylvatica*, *Fraxinus excelsior*, *Quercus petraea*, *Quercus robur* and *Sorbus aucuparia*) over a 5 year period (2006-2010) from data collected from two counties (Midlothian and Lanarkshire) in Scotland 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 to provide an average date for the leaf off event. The average dates calculated for these events used in the study were: leaf-on was 9th May and leaf-off was Nov 12th.

Table 4. Average leaf on and leaf off day for broadleaf species of Edinburgh

Species	First leaf average day number	First leaf falling average day number	Bare tree average day number	Calculated average number of days to lose leaves
Acer campestre	112 (14)	288 (13)	318 (10)	29
Acer pseudoplatanus	109 (53)	290 (55)	315 (55)	25
Aesculus hippocastanum	103 (56)	284 (58)	313 (57)	28
Alnus glutinosa	111 (21)	No data	No data	-
Betula pendula	112 (56)	287 (60)	314 (62)	28
Fagus sylvatica	118 (57)	292 (54)	317 (54)	25
Fraxinus excelsior	133 (55)	291 (56)	309 (56)	18
Quercus petraea	122 (11)	306 (9)	330 (9)	23
Quercus robur	125 (20)	296 (15)	331 (14)	34
Sorbus aucuparia	112 (57)	284 (6)	306 (8)	22
Average for all species	**116**	**291**	**317**	**26**
Average leaf off day	**317**		**12-Nov**	(average leaf off date normal year)
Average leaf on day assuming two weeks to full leaf	**130**		**09-May**	(average leaf on date normal year)

Carbon storage and sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings and consequently altering carbon dioxide emissions from fossil-fuel based power plants (Abdollahi et al., 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. As trees grow they store more carbon as wood. As trees die and decay, they release much of the stored carbon back to the atmosphere.

Carbon storage refers to the total carbon stored within one or more species or genus over their lifetime, expressed in metric tonnes. Carbon sequestration refers to the amount of carbon captured (sequestered) by trees over the course of a year. Some of the sequestered carbon will be used for short term physiological process within the tree and some will go into long term storage within the tissues of the tree.

Edinburgh's trees are estimated to store 145,611 metric tonnes of carbon within their tissues, at around 12,697 kg per hectare. Edinburgh's trees are estimated to sequester 5,329 metric tonnes of gross carbon per year at around 465 kg per hectare per year, with net carbon sequestered estimated at 4,721 metric tonnes per year. Caution should be taken when using the carbon sequestration data for predicting future value, as iTree only provides a single estimation of net incremental value per year. As such the iTree output does not present a true reflection of carbon sequestration over a tree's lifetime.

The UK Government concluded a major review of the carbon valuation approach to be used in UK policy appraisal in July 2009. The revised approach moves away from a valuation based on the damages associated with impacts, instead using the cost of mitigation as its basis (DECC, 2011). The new approach set the valuation of carbon over the 2008-2050 period at a level that is consistent with the UK Government's targets in the short and long term. The EU Climate and Energy Package introduced separate emissions reduction targets for the traded sector (i.e. emissions covered by the EU Emission Trading System) and for the non-traded sector (i.e. emissions outside the EU Emission Trading System). The presence of separate targets in the Traded and Non-Traded sectors implies that emissions in the two sectors are essentially different commodities. We have used non-traded values to estimate the value of carbon both stored and sequestered in Edinburgh's tree stock.

Standard Green Book guidance encourages analysts to perform sensitivity analyses in order to assess how future uncertainties can affect the choice between the policy options. In the area of energy and climate change, the net costs of a policy are sensitive to the fossil fuel price assumptions. For example, in a 'low' fossil fuel price scenario, the net costs of an energy efficiency policy are likely to be higher because the energy savings will be worth less than in a scenario with high fossil fuel prices. Government has therefore produced 'low', 'central' and 'high' traded/non traded carbon values over the 2008-2100 period to be used in sensitivity analysis (Table 5; showing unit values (£/tCO_2e) for 2011 to 2050).

A 3.5% discount rate per year has been applied on the value of stored carbon over the period 2011 to 2041, reducing to 3% from 2042 to 2050. Table 5 shows the total value (£) of stored carbon (expressed in tCO_2e) over the 2011 to 2050 timeframe. The value of net sequestered carbon per annum has also been calculated for each of the scenarios over a 2011 to 2050 timeframe (Table 6).

Under the 'low' scenario the trees of Edinburgh were estimated to store carbon with a non-traded value of £14.9 million in 2011 and were providing £484,689 per annum of non-traded value through net carbon sequestration. Using the same scenario ('low') the total value of carbon stored in Edinburgh's trees would accrue to £35 million by 2050 (Table 5). Value based on the 'central' scenario are twice that of the low, whilst those under a 'high' scenario are three times that of the 'low'.

Of the species sampled, *Acer pseudoplatanus* is estimated to store and sequester the most carbon (approximately 33.9% of the total carbon stored and 22.5% of all sequestered carbon.) Other species in the top 10 overall for carbon sequestration are *Betula pendula, Fagus sylvatica, Ilex aquifolium, Prunus, Populus, Sorbus aucuparia, Fraxinus excelsior, Cupressocyparis leylandii and Quercus robur* (Figure 9).

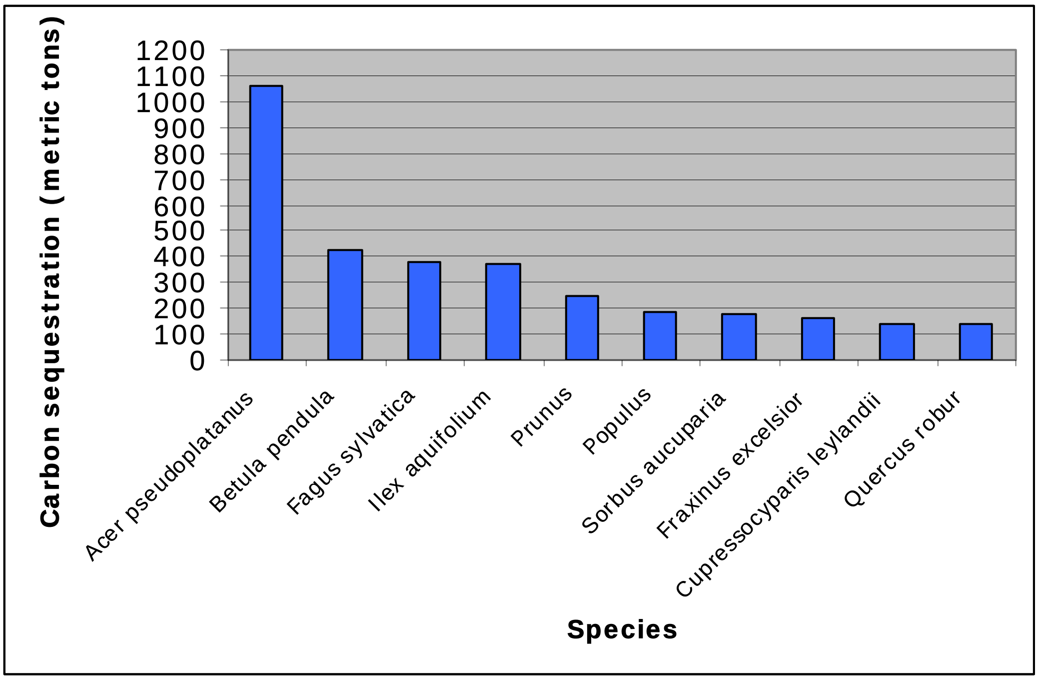

Figure 9. Carbon sequestration for species with greatest overall carbon sequestration in Edinburgh

Table 5. Estimated UK value of stored carbon in Edinburgh's trees from 2011 to 2050

Year	Stored C (t)	Net Sequestered C (t)	Stored C (tCO_2e)	Net Sequestered C (tCO_2e)	Non-traded Unit Value (£ / tCO_2e) Low	Central	High	Discount Rate	Discount Factor	Value of Discounted Stored tCO_2e (£) Low	Central	High
2011	145,611	4,721	533,907	17,310	28	56	83	3.5%	1.00	£14,949,396	£29,898,792	£44,314,281
2012	150,332	4,721	551,217	17,310	28	56	85	3.5%	0.97	£14,912,160	£29,824,319	£45,269,056
2013	155,053	4,721	568,528	17,310	29	57	86	3.5%	0.93	£15,391,073	£30,251,420	£45,642,493
2014	159,774	4,721	585,838	17,310	29	58	87	3.5%	0.90	£15,323,377	£30,646,754	£45,970,131
2015	164,495	4,721	603,148	17,310	30	59	89	3.5%	0.87	£15,768,268	£31,010,927	£46,779,195
2016	169,216	4,721	620,459	17,310	30	60	90	3.5%	0.84	£15,672,286	£31,344,573	£47,016,859
2017	173,937	4,721	637,769	17,310	30	61	91	3.5%	0.81	£15,564,765	£31,648,355	£47,213,120
2018	178,658	4,721	655,079	17,310	31	62	93	3.5%	0.79	£15,961,479	£31,922,959	£47,884,438
2019	183,379	4,721	672,390	17,310	31	63	94	3.5%	0.76	£15,829,235	£32,169,090	£47,998,325
2020	188,100	4,721	689,700	17,310	32	64	95	3.5%	0.73	£16,193,736	£32,387,472	£48,075,154
2021	192,821	4,721	707,010	17,310	32	65	97	3.5%	0.71	£16,038,814	£32,578,840	£48,617,654
2022	197,542	4,721	724,321	17,310	33	66	99	3.5%	0.68	£16,371,971	£32,743,942	£49,115,913
2023					33	67	100	3.5%	0.66	£16,196,367	£32,883,534	£49,079,901

					Non-traded Unit Value (£ / tCO_2e)					Low	Central	High
Year	**Stored C (t)**	**Net Sequestered C (t)**	**Stored C (tCO_2e)**	**Net Sequestered C (tCO_2e)**	**Low**	**Central**	**High**	**Discount Rate**	**Discount Factor**	**Value of Discounted Stored tCO_2e (£)**		
	202,263	4,721	741,631	17,310								
2024	206,984	4,721	758,941	17,310	34	68	102	3.5%	0.64	£16,499,188	£32,998,376	£49,497,565
2025	211,705	4,721	776,252	17,310	34	69	103	3.5%	0.62	£16,304,841	£33,089,236	£49,394,077
2026	216,426	4,721	793,562	17,310	35	70	105	3.5%	0.60	£16,578,440	£33,156,880	£49,735,320
2027	221,147	4,721	810,872	17,310	36	71	107	3.5%	0.58	£16,834,855	£33,202,076	£50,036,931
2028	225,868	4,721	828,183	17,310	36	72	108	3.5%	0.56	£16,612,794	£33,225,589	£49,838,383
2029	230,589	4,721	845,493	17,310	37	73	110	3.5%	0.54	£16,841,681	£33,228,182	£50,069,863
2030	235,310	4,721	862,803	17,310	37	74	111	3.5%	0.52	£16,605,306	£33,210,613	£49,815,919
2031	240,031	4,721	880,114	17,310	41	81	122	3.5%	0.50	£18,134,919	£35,827,523	£53,962,443
2032	244,752	4,721	897,424	17,310	44	88	132	3.5%	0.49	£19,173,571	£38,347,142	£57,520,714
2033	249,473	4,721	914,734	17,310	47	95	142	3.5%	0.47	£20,169,965	£40,769,078	£60,939,043
2034	254,194	4,721	932,045	17,310	51	102	153	3.5%	0.45	£21,546,605	£43,093,211	£64,639,816
2035	258,915	4,721	949,355	17,310	54	109	163	3.5%	0.44	£22,451,947	£45,319,671	£67,771,618
2036	263,636	4,721	966,665	17,310	58	116	173	3.5%	0.42	£23,724,408	£47,448,817	£70,764,184
2037	268,357	4,721	983,976	17,310	61	122	184	3.5%	0.41	£24,539,466	£49,078,931	£74,020,683
2038					65	129	194	3.5%	0.40	£25,708,815	£51,022,109	£76,730,924

					Non-traded Unit Value (£ / tCO_2e)					Low	Central	High
Year	Stored C (t)	Net Sequestered C (t)	Stored C (tCO_2e)	Net Sequestered C (tCO_2e)	Low	Central	High	Discount Rate	Discount Factor	Value of Discounted Stored tCO_2e (£)		
	273,078	4,721	1,001,286	17,310								
2039	277,799	4,721	1,018,596	17,310	68	136	204	3.5%	0.38	£26,435,116	£52,870,233	£79,305,349
2040	282,520	4,721	1,035,907	17,310	72	143	215	3.5%	0.37	£27,503,184	£54,624,380	£82,127,564
2041	287,241	4,721	1,053,217	17,310	75	150	225	3.5%	0.36	£28,142,886	£56,285,772	£84,428,658
2042	291,962	4,721	1,070,527	17,310	78	157	235	3.0%	0.35	£28,883,156	£58,136,609	£87,019,765
2043	296,683	4,721	1,087,838	17,310	82	164	246	3.0%	0.34	£29,956,633	£59,913,266	£89,869,900
2044	301,404	4,721	1,105,148	17,310	85	171	256	3.0%	0.33	£30,627,899	£61,616,125	£92,244,024
2045	306,125	4,721	1,122,458	17,310	89	178	266	3.0%	0.32	£31,622,838	£63,245,676	£94,513,201
2046	310,846	4,721	1,139,769	17,310	92	184	277	3.0%	0.31	£32,226,113	£64,452,226	£97,028,622
2047	315,567	4,721	1,157,079	17,310	96	191	287	3.0%	0.30	£33,143,655	£65,942,064	£99,085,719
2048	320,288	4,721	1,174,389	17,310	99	198	297	3.0%	0.29	£33,680,321	£67,360,643	£101,040,964
2049	325,009	4,721	1,191,700	17,310	103	205	308	3.0%	0.28	£34,521,984	£68,708,804	£103,230,788
2050	329,730	4,721	1,209,010	17,310	106	212	318	3.0%	0.27	£34,993,730	£69,987,461	£104,981,191

Table 6. Estimated UK value of net annually sequestered carbon in Edinburgh's trees from 2011 to 2050

	Value of Discounted Annually Sequestered tCO_2e (£)		
Year	**Low**	**Central**	**High**
2011	£484,689	£969,379	£1,436,758
2012	£468,299	£936,598	£1,421,622
2013	£468,622	£921,085	£1,389,707
2014	£452,775	£905,550	£1,358,325
2015	£452,549	£890,012	£1,342,561
2016	£437,245	£874,490	£1,311,735
2017	£422,459	£859,000	£1,281,459
2018	£421,779	£843,557	£1,265,336
2019	£407,516	£828,177	£1,235,693
2020	£406,436	£812,872	£1,206,607
2021	£392,692	£797,655	£1,190,347
2022	£391,269	£782,538	£1,173,807
2023	£378,038	£767,531	£1,145,569
2024	£376,322	£752,644	£1,128,967
2025	£363,596	£737,887	£1,101,483
2026	£361,633	£723,266	£1,084,899
2027	£359,387	£708,791	£1,068,178
2028	£347,234	£694,468	£1,041,701
2029	£344,811	£680,302	£1,025,113
2030	£333,151	£666,301	£999,452
2031	£356,683	£704,666	£1,061,349
2032	£369,837	£739,675	£1,109,512
2033	£381,694	£771,510	£1,153,204
2034	£400,173	£800,346	£1,200,518
2035	£409,384	£826,349	£1,235,733
2036	£424,839	£849,679	£1,267,193
2037	£431,704	£863,408	£1,302,189
2038	£444,457	£882,075	£1,326,532
2039	£449,246	£898,493	£1,347,739
2040	£459,587	£912,791	£1,372,378
2041	£462,547	£925,095	£1,387,642
2042	£467,038	£940,064	£1,407,102
2043	£476,688	£953,376	£1,430,064
2044	£479,736	£965,116	£1,444,852
2045	£487,681	£975,362	£1,457,564
2046	£489,437	£978,874	£1,473,630
2047	£495,841	£986,518	£1,482,359
2048	£496,443	£992,886	£1,489,330
2049	£501,458	£998,047	£1,499,505
2050	£501,032	£1,002,065	£1,503,097

Air Pollution Removal

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to buildings and ecosystem processes and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power plants. Many trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak D.J. and Dwyer, 2000).

Estimates of pollution removal were attained by combining tree inventory data with pollution data from the DEFRA (2010b) network for 2010 for Edinburgh. Edinburgh's trees were calculated to remove 100 metric tonnes of the following pollutants: ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter less than 10 microns (PM_{10}) and sulphur dioxide (SO_2) per year with an associated value of £547,265[*] ($879,000) per year based on US valuation (based on national median externality costs associated with pollutants (Murray *et al.*, 1994)).

The UK has published UK Social Damage Costs (UKSDC) for air particulates (PM_{10}), NO_x and sulphur dioxide (SO_2). Using these values to supplement the US externality values for ozone (O_3), carbon monoxide (CO) gives an estimated value of pollutants removed by Edinburgh's trees of £2.3 million per year. Table 7 shows a breakdown of value of Edinburgh's trees per year by air pollutant. The UK valuations are based on the central estimates of damage cost presented in DEFRA (2010a). These are derived from the lag probability distribution developed for Monte Carlo analysis to reflect the fact that, although evidence is limited, COMEAP tend towards a greater proportion of the health effect occurring in the years sooner after the pollution rather than later. This estimate is intended for use only where a single point estimate is necessary and should always be accompanied by the central range.

Table 7. Value of the air pollutants removed and quantity per annum. Valuation methods used are US externality cost (USEC) and UK data (DEFRA, 2010) where available

Pollutant	Tonnes Removed per Year	Unit Value (£/t)	Value per year	Valuation Source
Carbon monoxide (CO)	1	915	£1,129	USEC*
Nitrogen dioxide (NO_2)	20	955	£18,626	UK IGCB; based on NOx value using Central Scenario
Ozone (O_3)	45	6,443	£288,971	USEC*
Particulates (PM_{10})	28	70,351	£1,983,757	UK IGCB; based on PM Transport Urban Large and Central Scenario
Sulphur dioxide (SO_2)	6	1,633	£10,557	UK IGCB; based on Central Scenario

[*] Using a currency conversion of 0.6226 Pounds sterling (£) to the US Dollar ($)

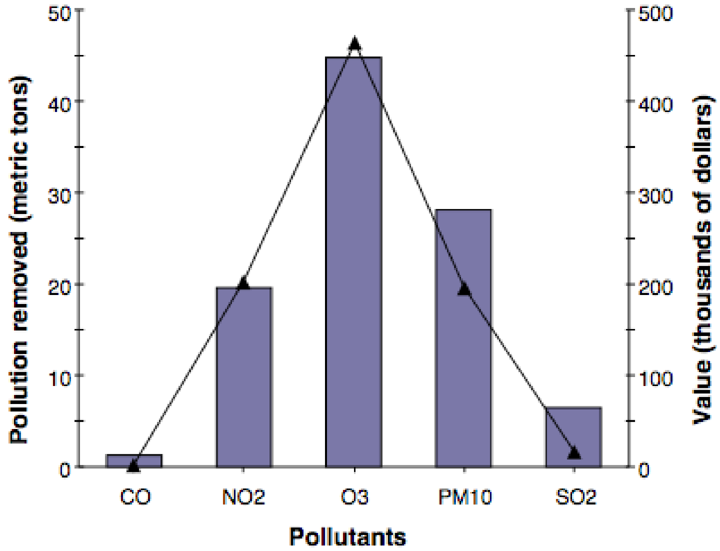

Figure 10. Pollution removal (column data) and associated monetary value (line graph) USEC method for the trees in Edinburgh

General Recommendations for Air Quality Improvement

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmosphere environment. Four main ways that urban trees affect air quality are (Nowak, 1995):

- Temperature reduction and other microclimate effects
- Removal of air pollutants
- Emission of volatile organic compounds (VOC)
- Tree maintenance emissions
- Energy effects on buildings

The cumulative and interactive effects of trees on climate, pollution removal and VOC and power plant emissions determine the impact of trees on air pollution. Cumulative studies involving urban tree impacts on ozone have revealed that increased urban canopy cover, particularly with low VOC emitting species, leads to reduced ozone concentrations in cities (Nowak and Dwyer, 2007). Local urban management decisions also can help improve air quality.

Potential strategies for increasing the air pollution removal value of trees are listed in Table 8.

Table 8. Potential strategies to increase the air pollution removal value of trees

Strategy	Result
Increase the number of healthy trees	Increase pollution removal
Sustain existing tree cover	Maintain pollution removal levels
Maximize use of low VOC-emitting trees	Reduces ozone and carbon monoxide formation
Sustain large, healthy trees	Large trees have greatest per-tree effects
Use long-lived trees	Reduce long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduce pollutants emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduce pollutant emissions
Plant trees in energy conserving locations	Reduce pollutant emissions from power plants
Plant trees to shade parked cars	Reduce vehicular VOC emissions
Supply ample water to vegetation	Enhance pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improve tree health
Utilize evergreen trees for particulate matter	Year-round removal of particles

Structural Value

Urban trees have a structural value based on the cost of having to replace a tree with a similar tree; they also have functional values (either positive or negative) based on the functions the trees perform.

The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees (Nowak *et al*., 2002). Annual functional values also tend to increase with increased number and size of healthy trees. Through proper management, urban forest values can be increased; however, the values and benefits also can decrease as the amount of healthy tree cover declines.

Structural values for 2011:

- Structural value: £382 million (based on the iTree US valuation of $614 million)
- Carbon storage: £15 million (under the 'low' scenario) to £44 million (under the 'high' scenario)

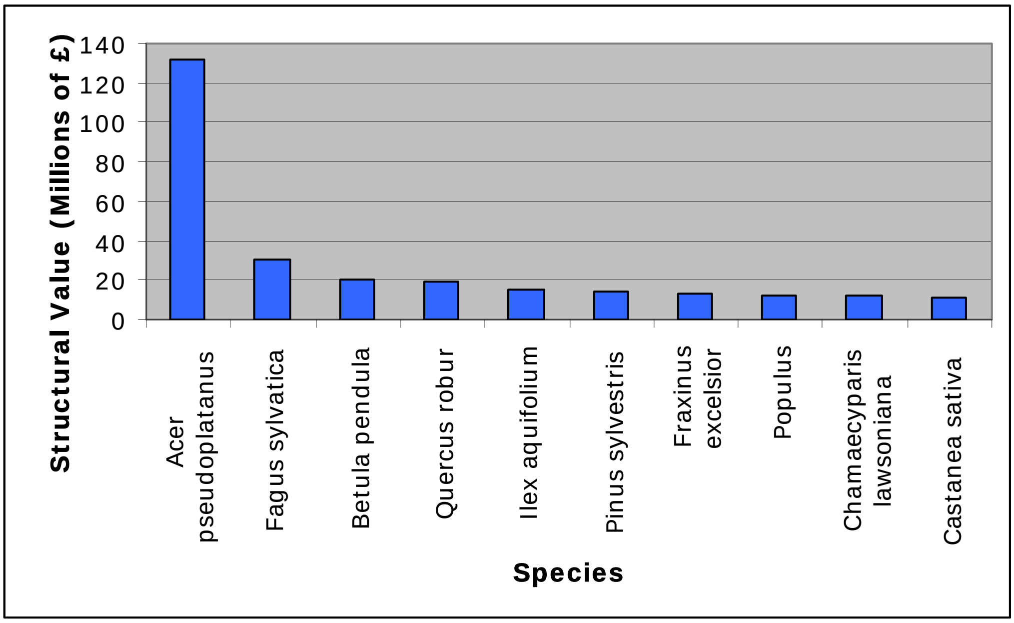

Figure 11. UK structural value (£) of the 10 most valuable tree species in Edinburgh

Risks of Pests and Disease

Various insects and diseases can infest urban forests, potentially killing trees and reducing the health, value and sustainability of the urban forest. As pests tend to have differing tree hosts, the potential damage or risk of each pest will differ. Ten exotic pests were analysed for their potential impact: Asian longhorned beetle (ALB), emerald ash borer (EAB), gypsy moth (GM), oak processionary moth (OPM), red band needle blight (RBNB), acute oak decline (AOD), bleeding canker of horse chestnuts (BCHC*), Phytophthora ramorum* (PR), *Phytophthora kernoviae* (PK) and *Phytophthora lateralis* (PL). The results are summarised in Table 9.

Asian Longhorn Beetle

Asian Longhorn Beetle (ALB) is a major pest in China, Japan and Korea where it kills many species of broadleaved trees. In America, ALB has established populations in Chicago and New York where the damage to street trees is high. The damage to the urban environment has been high where felling, sanitation and quarantine are the only viable management options. Analysis of climate data by scientists at the central science laboratory suggests that England and Wales and some warmer coastal areas of Scotland are suitable for ALB establishment and breeding. We can expect extensive damage to urban trees if the ALB establishes in the UK.

In March 2012 the ALB has been found in the Paddock Wood area of Maidstone in Kent. Forestry Commission and Fera surveyors have now confirmed that 22 trees in the area are infested with larvae (grubs) of Asian longhorn beetle and five more are considered highly likely to be infested. The infestation zone (i.e. the area within a 100m radius of each infested tree) currently covers about 8 hectares. It must be noted that there are no reported cases of ALB in Scotland. If an ALB outbreak occurred in Edinburgh it would pose a significant threat to 51.9% of Edinburgh's trees.

The known host tree and shrub species include:

- *Acer* (maples and sycamores)
- *Aesculus* (horse chestnut)
- *Albizia* (Mimosa, silk tree)
- *Alnus* (alder)
- *Betula* (birch)
- *Carpinus* (hornbeam)
- *Cercidiphyllum japonicum* (Katsura tree)
- *Corylus* (hazel)
- *Fagus* (beech)
- *Fraxinus* (ash)
- *Koelreuteria paniculata*
- *Platanus* (plane)
- *Populus* (poplar)
- *Prunus* (cherry, plum)
- *Robinia pseudoacacia* (false acacia/black locust)
- *Salix* (willow, sallow)
- *Sophora* (Pagoda tree)
- *Sorbus* (mountain ash/rowan, whitebeam etc)
- *Quercus palustris* (American pin oak)
- *Quercus rubra* (North American red oak)
- *Ulmus* (elm).

Emerald Ash Borer

Although there is no evidence to date that the emerald ash borer is present in the UK, the increase in global movement of imported wood, wood packaging and dunnage poses a significant risk of its accidental introduction. Emerald Ash borer poses a potential future threat to 5.8% of the Edinburgh urban forest.

Gypsy Moth

Gypsy moth, *Lymantria dispar*, is an important defoliator of a very wide range of trees and shrubs in mainland Europe, where it periodically reaches outbreak numbers. A small colony has persisted in northeast London since 1995 and a second breeding colony was found in Aylesbury, Buckinghamshire in the summer of 2005. No cases of GM have been reported in Scotland. If GM spread to Edinburgh, it would pose a threat to 4.1% of the Edinburgh urban trees.

Oak Processionary Moth

In 2006, the Oak Processionary Moth (*Thaumetopoea processionea*) was found in west London along a stretch of the A40 and in Kew and East Sheen. This was the first recorded breeding population in

Great Britain. Adult male moths have occasionally been found along the south coast of England and also on the Channel Islands, where they have presumably either flown in or been blown across from the Continent. The caterpillars can also 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 which 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 in recent years. Oak Processionary Moth poses a threat to 4.1% of the Edinburgh urban forest.

Red Band Needle Blight

Dothistroma (red band) needle blight is the most significant disease of coniferous trees in Scotland, with 11% of pine crops known to be infected on the national forest estate. In addition to the levels of mortality found on inland origins of lodgepole pine, the increasing incidence and severity of this fungal disease on Scots pine is of particular concern.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 pine (*Pinus nigra* ssp. *laricio*), lodgepole pine (*Pinus contorta* var. *latifolia*) and more recently Scots pine (*Pinus sylvestris*) all being affected. However, there are no reported cases of red band needle blight on urban trees and there is unlikely to be a significant risk to the future of Scots Pine in Edinburgh (Brown, A., 2012 pers. comm., 26 April). Red band needle blight poses a threat to 4.5% of the Edinburgh urban forest.

Acute Oak Decline

Acute oak decline (AOD) affects mature trees (>50 years old) of both native oak species (*Quercus robur*, known as pedunculate or English oak and *Quercus petraea* - sessile oak). Over the past three to four years there have been a growing number of reports on oak trees with symptoms of stem bleeding. The incidence of AOD in Britain is unquantified at this stage but estimates put the figure at a few thousand affected trees. The condition appears to be most prevalent in the Midlands and the South East. Acute Oak Decline poses a threat to 3.5% of the Edinburgh urban forest.

Bleeding Canker of Horse Chestnut

Bleeding Canker of Horse Chestnuts primary casual agent is the pathogen, *Pseudomonas syringae* pv *aesculi*. Over the past four years the Tree Health Diagnostic and Advisory Service of Forest Research has received increasing numbers of reports about the disease. In 2000, only four reports had been received but by 2003 more than 60 reports of stem bleeding in horse chestnut were recorded. In 2004, 90 reports were received, around 75 in 2005 and more than 110 in 2006. Affected trees have been recorded as far north as Lancashire, Glasgow and Fife. Trees of all ages have been affected by the recent disease upsurge. Young trees with a stem diameter of only 10 cm (4 inches) have been found with advanced symptoms. However, the impact on the environment can be particularly profound when large, mature trees are infected and disfigured by the disease. If the disease is severe and the areas of bark which are killed are extensive, large trees can undoubtedly be killed.

However, younger trees (10-30 years old) are at greater risk and can succumb to the disease in just a few years (3-5) as the smaller diameter of their trunks means that they can be girdled more quickly. Horse Chestnut bleeding canker poses a threat to 0.4% of the Edinburgh urban forest.

Phytophthora ramorum

Phytophthora ramorum (PR) was first found in the UK in 2002. Since 2007 it has been found on ornamental shrubs in Western Scotland. Rhododendron is a major host which aids the spread of the disease. In 2009, however, it was reported on Japanese Larch (*Larix kaempferi)* in the SW of England. PR infections were confirmed on over 70 sites in Southern England. By 2010, PR was found on Japanese Larch in Wales, Northern Ireland and one site in Western Scotland. *Phytophthora ramorum* deemed to pose a low risk to 47.7% of the Edinburgh urban forest.

Phytophthora kernoviae

Phytophthora kernoviae (PK) was first discovered in Cornwall in 2003. The disease infects Rhododendron and Bilberry (*Vaccinium*) and can cause lethal stem cankers on Beech. It was found in the West of Scotland in 2008. The west of Scotland has been classified as a high risk area for both PR and PK due to the climatic conditions. The east of Scotland including Edinburgh has been classified as a low risk area.

At present Scotland has 25 locations with confirmed PR, 13 with PK and 4 have both, all in western Scotland. *Phytophthora kernoviae* is deemed to pose a low risk to 9.8% of the Edinburgh urban forest.

Phytophthora lateralis

The main host of *Phytophthora lateralis* (PL) is Lawson Cypress (*Chamaecyparis lawsonia*) but also infects Yew (*Taxus baccata*). It was detected in France in 1998, particularly in Brittany, has resulted in the decline of Lawson Cypress hedgerows. The disease was first noted in the UK in 2009 and became more prevalent in 2010. The lesions spread up the lower stem, kill the phloem and disrupt the xylem resulting in crown death.

Although there is less than 2200 hectares of commercially grown Lawson Cypress in Britain there is a huge risk to amenity and garden Lawson Cypress. PL has recently been found on *Thuja occidentals*, part of the Cypress family, on nursery stock in Scotland.

PL was found in Balloch (on the shores of Loch Lomond), Dumbartonshire. A 2010 survey noted there were 82 dead/dying Lawson Cypress, 27 dead/dying Yew trees and 20 plus Yew hedgerow dead. It has also been found at a cemetery in Greenock (on the south bank of the Firth of Clyde, 25 miles west of Glasgow) where 23 Lawson Cypress are dead or dying. The disease has also been found in a public park in Glasgow. *Phytophthora lateralis* is deemed to pose a high risk to 2% of the Edinburgh urban forest.

Table 9. Risks of emerging pests and pathogens

Pest / Pathogen	Species effected	Prevalence in the UK	Prevalence in Scotland	Risk of Spreading to Scotland	Number of Trees at Risk	% of Tree Popul-ation at Risk	Structural value of trees at risk (£million)	Stored carbon value of trees at risk (£)
Asian Longhorn Beetle	Many broadleaf species (see above)	Small outbreak in Kent	None	Medium risk in Warmer coastal areas of Scotland	366,021	57.4%	256	10,505,517
Gypsy Moth	Primary - Oak Secondary - hornbeam, beech, chestnut, birch and poplar.	2 outbreaks London and Buckinghamshire	None	Low risk	26,238	4.1%	29	1,462,283
Emerald Ash Borer	Ash sp.	None	None	Medium risk – through imported wood	36,733	5.8%	16	489,342
Red Band Needle Blight	Pine sp.	Increasing	3,300 hectares infected and increasing.	Low risk to urban trees	28,862	4.5%	14	317,773

Pest / Pathogen	Species effected	Prevalence in the UK	Prevalence in Scotland	Risk of Spreading to Scotland	Number of Trees at Risk	% of Tree Popul-ation at Risk	Structural value of trees at risk (£million)	Stored carbon value of trees at risk (£)
Acute Oak Decline	*Quercus robur* & *petraea* (pedunculate and sessile oak)	Midlands and the South East	None	Low risk	22,302	3.5%	23	1,235,642
Bleeding Canker	*Aeseculus hippocastanum* (Horse Chestnut)	Increasing	Reported in Glasgow and Fife	High risk to urban trees	2624	0.4%	7	453,714
Phytophthora ramorum	Variety of broadleaf and evergreen species	South West England, Wales	West Scotland	Low risk of spreading to the East of Scotland	304,360	47.7	264	10,646,810
Phytophthora kernoviae	Horse and Sweet Chestnut, Beech, Cherry, Laurel and English Oak	South West England, Wales	West Scotland	Low risk of spreading to the East of Scotland	62,971	9.8	69	3,362,369
Phytophthora lateralis	*Chamaecyparis lawsonia* &*Taxus baccata* (Lawsons Cypress and Yew)	Increasing	Infections on 3 sites near Glasgow.	High risk to urban/ garden trees	13,119	2%	13	408,200
Oak Processionary Moth	Primary Oak Secondary hornbeam, hazel, beech, sweet chestnut & birch	London and South Coast	None	Low risk	26,238	4.1%	29	1,462,283

The Importance of Planting and Maintaining a Diverse Tree Population

Encouraging a high diversity of species and genera is generally regarded as a mean of providing a more healthy and sustainable urban tree population (Duhme and Pauleit, 2000; Raupp et al., 2006; Bassuk et al., 2009). A diverse tree population is more likely to be more resilient to outbreaks of existing and emerging pests and diseases and extreme climatic events causing heat waves, excessive periods of drought, flooding, or gales. There is some discrepancy over the advisable maximum percentage of the total tree population which should be made up of any one species, with figures of 5 to 20% being suggested (Barker, 1975; Smiley et al., 1986; Miller and Miller, 1991; Grey and Deneke, 1986; Moll, 1989). The most extensive system reviewed provides a recommended maximum use of species and genera from the same family (Santamour, 1990). This suggests no species should represent more than 10%, no genus more than 20%, and no family more than 30% of the total tree population. There is also a growing amount of research testing whether planting trees of one species with a diverse provenance would provide greater resilience to future pests, diseases and climatic induced events. In Edinburgh, only Sycamore and Holly (12% and 11% respectively) exceed 10% of the total population. No genus in Edinburgh's tree population exceeds 20% and no family exceeds 30% with the highest family of Rosaceae at 17.5%.

A further consideration when assessing which tree species to plant is the relative cost-benefit of large versus smaller trees. Such an assessment uses the total economic cost of planting trees and their management versus the ecosystem benefits the trees provide over their lifetime. A US study (USDA Forest Service, 2003; Maco & McPherson, 2003) quantified the costs and benefits of large, medium and small tree species to determine their relative cost-benefits. Benefits assessed included net annual energy savings, annual net air quality improvement, carbon dioxide reductions, annual stormwater runoff reductions and aesthetic values. Costs included tree planting, pruning, tree related repair works, legal costs, litter removal and disposal. The results of the study (Table 10) clearly demonstrate that planting any size class of tree provides a positive cost-benefit i.e. the benefits which a tree provides are always greater than the costs of planting and maintaining the tree as long as its growth and condition are unhampered by abiotic (e.g. light or more generally radiation, temperature, water, atmospheric gases, and soil conditions) or biotic (e.g. pests and diseases) factors. For small tree species the cost-benefit ratio was found to be 2.88, which rises to 5.25 and 4.75 for medium and large tree species respectively. This clearly indicates that investment in planting larger and medium sized tree species pays higher dividends over planting smaller tree species. If data became available on the planting and maintenance costs of Edinburgh's trees the cost-benefit of the tree population down to the species specific level could be assessed.

Although there is a very compelling argument for increasing the diversity of Edinburgh's tree population, important considerations should not be overlooked in the rush to diversify. Planting new tree species that are untested for the region is not the right course where adaptability and longevity of species in Edinburgh has not been properly assessed. However, the i-Tree survey identified that Edinburgh has a minimum of 50 tree species and gives invaluable data on their condition. These data provide an excellent resource to determine what species will grow effectively. This, coupled with information on relative importance to create ecosystem services (Table 3) and risks of pests and disease (Table 9), provides The City of Edinburgh and partners a means to strategically plan a more resilient urban forest which provides an increasingly valuable service to society.

Table 10. Cost-benefit analysis of small, medium and large tree species (USDA Forest Service, 2003)

Size of Tree	Benefit (US $)	Cost (US $)	Cost Benefit Ratio
Large	65.18	13.72	4.75
Medium	36.04	6.87	5.25
Small	17.96	6.23	2.88

Comparison with other Cities

A common question asked is, "How does this city compare to other cities?" Although comparison among cities should be made with caution as there are many attributes of a city that affect urban forest structure and functions, summary data are provided from other cities analysed using the UFORE model in Tables 11 and 12 below.

Table 11. City Totals for trees

City	% Tree Cover	Number of trees	Carbon Storage (T)	Carbon sequestration (T/yr)	Air Pollution Removal (T/yr)
Calgary, Canada*	7.2	11,889,000	404,000	19,400	296
Atlanta, GA*	36.8	9,415,000	1,220,000	42,100	1,508
Toronto, Canada*	20.5	7,542,000	900,000	36,600	1,100
New York, NY*	21	5,212,000	1,226,000	38,400	1,521
Baltimore, MD*	21	2,627,000	541,000	14,600	390
Philadelphia, PA*	15.7	2,113,000	481,000	14,600	523
Washington, DC*	28.6	1,928,000	474,000	14,600	379
Boston, MA*	22.3	1,183,000	289,000	9,500	258
Woodbridge, NJ*	29.5	986,000	145,000	5,000	191
Minneapolis, MN*	26.5	979,000	227,000	8,100	277
Syracuse, NY*	23.1	876,000	157,000	4,900	99
Torbay, UK**	11.2	818,000	98,100	4,279	50
Morgantown, WV*	35.9	661,000	85,000	2,700	60
Edinburgh, UK	**17**	**638,000**	**145,611**	**5,329**	**100**
Moorestown, NJ	28	583,000	106,000	3,400	107
Udine, Italy	10	162,000	19,100	888	80
Jersey City, NJ	11.5	136,000	19,000	800	37
Freehold, NJ	34.4	48,000	18,000	500	19

Source: *USDA Forest Service; **Rogers et al., 2011

Table 12. Per hectare values of tree effects by city

City	No. of trees per ha	Carbon Storage (T)	Carbon sequestration (T/Yr)	Pollution Removal (kg/yr)
Calgary, Canada	164.8	5.6	0.13	4
Atlanta, GA	275.8	35.64	0.62	44.2
Toronto, Canada	119.4	14.35	0.29	17.5
New York, NY	65.2	15.24	0.24	19.1
Baltimore, MD	125.5	25.78	0.35	18.6
Philadelphia, PA	61.8	14.12	0.21	15.2
Washington, DC	121.1	29.81	0.46	23.8
Boston, MA	82.8	20.18	0.33	17.9
Woodbridge, NJ	164.3	24.21	0.42	31.8
Minneapolis, MN	64.7	15.02	0.27	18.4
Syracuse, NY	134.7	24.21	0.38	15.2
Morgantown, WV	295.8	38.11	0.6	26.7
Edinburgh, UK	**55.6**	**12.73**	**0.46**	**8.7**
Moorestown, NJ	153.2	28.02	0.45	28.2
Jersey City, NJ	35.3	4.93	0.11	9.6
Freehold, NJ	95.1	35.87	0.49	37.7

Source: USDA Forest Service

Placing the benefits of Edinburgh's trees in context

The urban forest in Edinburgh provides benefits that include carbon storage and sequestration and air pollutant removal. To estimate the relative value of these benefits, tree benefits were compared to estimates of average municipal carbon emissions, average passenger motor car emissions and average household emissions.

US Comparison

Carbon storage is equivalent to:

- Amount of carbon emitted in Edinburgh in 22 days
- Annual carbon (C) emissions from 96,300 automobiles
- Annual C emissions from 48,400 single-family houses

Carbon monoxide removal is equivalent to:

- Annual carbon monoxide emissions from 5 automobiles
- Annual carbon monoxide emissions from 22 single-family houses

Nitrogen dioxide removal is equivalent to:

- Annual nitrogen dioxide emissions from 1,360 automobiles

- Annual nitrogen dioxide emissions from 905 single-family houses

Sulfur dioxide removal is equivalent to:

- Annual sulphur dioxide emissions from 10,400 automobiles
- Annual sulphur dioxide emissions from 175 single-family houses

Particulate matter less than 10 micron (PM_{10}) removal is equivalent to:

- Annual PM_{10} emissions from 82,800 automobiles
- Annual PM_{10} emissions from 7,990 single-family houses

Annual carbon sequestration is equivalent to:

- Amount of carbon emitted in Edinburgh in .8 days
- Annual C emissions from 3,500 automobiles
- Annual C emissions from 1,800 single-family houses

Note: estimates above are partially based on the user-supplied information on human population total for study area

Total carbon emitted per capita in Scotland for 2009 is estimated at 7.0 tCO_2 per annum (DECC, 2011b) which is marginally lower than the UK average of 7.4 tCO_2 per annum.

The carbon dioxide equivalent sequestered annually by Edinburgh's trees is equivalent to total emitted to that of the total CO_2 emissions across Scotland for the equivalent of 2,473 capita.

Stored CO_2e = 533907/7.0 eqv to 76,272 capita

Estimated carbon dioxide emissions per capita for Scotland break down as 3 tCO_2 from industrial, commercial and public emissions; 3 tCO_2 for transport emissions; and 2 tCO_2 for domestic emissions.

Comparison of Stored and Sequestered Carbon to Typical Carbon Emissions of a Range of UK Travel Modes

Travel by different modes has differing impacts in terms of emissions of CO_2e per passenger kilometre. Table 13 below provides a relative comparison of the stored and annually sequestered carbon by Edinburgh's trees, expressed as equivalent passenger kilometres for a range of transport types. All figures are estimated using data for GB/UK as a whole so do not specifically relate to Scotland. The car figures in brackets are taken from the 2008 DfT publication 'Carbon Pathways Analysis: Informing Development of a Carbon Reduction Strategy for the Transport Sector' (Department for Transport, 2008). This calculates efficiency figures using a traffic weighted average car emission factor to take account of the fact that lower CO_2 emitting cars such as newer cars and diesel cars, are on average driven more than higher CO_2 emitting cars such as older cars or sports cars. The emission figures used are those quoted on the Scottish Government website (http://www.scotland.gov.uk/Publications/2009/08/27143705/2)

Table 13. Stored and annually sequestered carbon by Edinburgh's trees expressed as equivalent CO_2 emissions per passenger kilometre (pkme) for a range of travel modes

Sector	Mode	CO_2 equivalent emissions per passenger km (gCO_2e/pkm)	Total tCO_2e stored in trees expressed as equivalent distance travelled (pkme)	Total sequestered tCO_2e by trees per annum expressed as equivalent distance travelled (pkme)
Road*	**Average petrol car**	130 (109)	4,106,976,923 (4,898,229,358)	133,153,846 (158,807,339)
	Average diesel car	124 (96)	4,305,701,613 (5,561,531,250)	139,596,774 (180,312,500)
	Average car (all)	128 (106)	4,171,148,438 (5,036,858,491)	135,234,375 (163,301,887)
	Average petrol motorbike	119	4,486,613,445	145,462,185
	Average bus	105	5,084,828,571	164,857,143
	Average coach	31	17,222,806,452	558,387,097
Rail	**National rail**	61	8,752,573,770	283,770,492
	Light rail and tram	84	6,356,035,714	206,071,429
Ferry (Large)	**Average foot and car passengers**	116	4,602,646,552	149,224,138
Aviation**	**Domestic flights**	173	3,086,167,630	100,057,803
	Short haul international	99	5,393,000,000	174,848,485
	Long haul international	113	4,724,840,708	153,185,841

* All Car figures assume an average car occupancy rate of 1.6 passengers.

** The long haul estimate is based on a flight length from the Guidelines of 6482 km, short haul 1108 km and domestic 463 km. In keeping with evidence from the IPCC, a 9% uplift factor has been applied to account for non-direct routes, circling and congestion. The emission factors refer to aviation's direct carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions only. There is currently uncertainty over the other non-CO_2 climate change effects of aviation (including water vapour, contrails, NO_x etc.) which may indicatively be accounted for by applying a multiplier. The appropriate factor to apply is subject to uncertainty but was estimated by the IPCC in 1999 to be in the range 2-4, with current best scientific evidence suggesting a factor of 1.9. If used, this factor would be applied to the emissions factors set out here.

Conclusions

The survey demonstrated the extensive ecosystem services contribution Edinburgh's trees make to improved environmental quality. The iTree modelling exercise coupled with UK valuation methods indicate the significant economic value of such services. The survey and modelling system has significant potential to inform current and future tree planting and management strategies for improving both the resilience of the tree population, and optimisation of the ecosystem services trees provide. Further refinement of the approach would allow such predictions to be made.

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Appendix 1. Tree Species List

Latin Name	Common Name
Acer Campestre	Field Maple
Acer pseudoplatanus	Sycamore
Aesculus hippocastanum	Horse Chestnut
Alnus glutinosa	European Alder
Betula pendula	Silver Birch
Castanea sativa	Sweet Chestnut
Chamaecyparis lawsoniana	Lawson's Cypress
Crataegus monogyna	Hawthorn
Cupressocyparis leylandii	Leyland Cypress
Fagus sylvatica	Beech
Fraxinus excelsior	Ash
Ilex aquifolium	Holly
Malus spp.	Apple species
Pinus sylvestris	Scots Pine
Populus spp.	Poplar species
Prunus spp.	Cherry species
Quercus petraea	Sessile Oak
Quercus robur	English Oak
Sorbus aucuparia	Rowan
Tilia platypyllos	Large Leaf Lime
Ulmus glabra	Wych Elm

Glossary

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

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

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

Ecosystem services - The benefits people obtain from ecosystems

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.

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

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

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.

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

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

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

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

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 1 m.

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

Particulate matter - he 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, and they are formed in the atmosphere by transformation of gaseous emissions.

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

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

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.

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

Physiological process - Refers to the functions of a living organism and its parts, and the physical and chemical factors involved.

Incremental value - the increase or decrease in costs as a result of one more or one less unit of output

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.

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

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

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

Girdled - (Girdling) removing the bark from a woody stem to kill the plant. Encircling a stem with a material so that the cambium layer is destroyed, killing the plant.

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

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

Phloem - The vascular tissue in plants that conducts sugars and other metabolic products downward from the leaves.

Xylem - The vascular tissue in plants that conducts water and dissolved nutrients upward from the root and also helps to form the woody element

Microclimate - The climate of a very small or restricted area.

Equivalent CO_2 emissions (CO2e) - One tonne of carbon dioxide equivalent (CO2e) is used as the standard measurement in the carbon market. It is a measure of the global warming potential of various greenhouse gases.

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