Measuring the ecosystem services of Torbay's trees: the Torbay i-Tree Eco pilot project

Abstract

Trees are an integral part of urban ecosystems. They provide a myriad of services that benefit urban communities, such as offsetting carbon emissions, improving air quality by filtering pollutants and regulating local climate. These services improve the environmental quality of urban areas as well as human health and wellbeing.

This paper presents a quantitative valuation of a range of benefits delivered by Torbay's urban forest. Using collected field data, the i-Tree Eco model and existing scientific literature the value of Torbay's urban forest was estimated. Torbay has approximately 11.8% forest cover made up of around 818 000 trees at a density of 128 trees/ha; these trees represent an estimated structural asset worth over £280 million. In addition, Torbay's urban forest provides the equivalent of £345 811 in ecosystem services annually. An estimated 98 100 tonnes (approximately 15.4 tonnes/ha) of carbon is stored in Torbay's trees, with an additional gross carbon sequestration rate of 4279 tonnes carbon per year, every year (approximately 671 kg/ha/year). This equates to £1 474 508 in storage and £64 316 in annual sequestration. Contributions to improving the air quality of Torbay total over 50 tonnes of pollutants removed every year, which equates to an annual estimated value of £281 495.

This paper explains the current limitations of the model, where research scope and methods can be improved and which UK-specific data we were able to incorporate. It also presents a framework for applying the model in a wider UK context. The study demonstrates that i-Tree Eco can be meaningfully applied to the UK, and there is therefore the potential for similar studies in other urban areas.

Introduction

Trees in the urban forest provide multiple ecosystem benefits (Nowak, 2006; Stenger *et al.*, 2009). Without measuring these ecosystem services no baseline can be established from which to monitor trends or to identify where additional resources are required. With increasing urbanisation there is a need to incorporate the role of the urban forest into long-term planning and climate adaptation strategies in order to improve environmental quality (Gill *et al.*, 2007).

Many studies have assessed the environmental value of an ecosystem qualitatively, listing the animals and plants found there and describing the network of systems – water, air, nutrients – that provide the underlying function. Some studies have also valued these services using contingent valuation (willingness to pay, willingness to accept), hedonic pricing, or avoided cost methods. Yet, to incorporate the role of the urban forest in environmental policies the impacts of trees need to be quantified. However, there have been few quantitative studies undertaken (Jim and Chen, 2009; de Groot *et al.*, 2010) and whilst there are systems that quantitatively measure the value of trees in the UK, none of these take an ecosystem services approach.

Since the release of the Millennium Ecosystem Assessment (2005a) there has been increased interest in defining and valuing our ecosystem services because, as a direct result of undervaluation, over two thirds of our natural ecosystems have been degraded (Millennium Ecosystem Assessment, 2005b). In order to develop viable strategies for conserving ecosystem services, it is important to estimate the monetary value so the importance can be demonstrated to the main stakeholders and beneficiaries (The Economics of Ecosystems and

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Kenton Rogers,[1] David Hansford,[1] Tim Sunderland,[2] Andrew Brunt[3] and Neil Coish[4]

[1] Hi-line Consultancy, Exeter, UK
[2] Natural England, Sheffield, UK
[3] Forest Research, Alice Holt Lodge, Surrey, UK
[4] Torbay Council, Devon, UK

Biodiversity, 2009). Furthermore, the ecological state of a city depends heavily on the state of its urban trees (Whitford *et al.*, 2001; Dobbs *et al.*, 2011) and to estimate the structure, function and value of the urban forest is an important first step in the sustainable management of natural capital.

Study area

The study took place in the coastal borough of Torbay, comprising the towns of Torquay, Paignton and Brixham. The study area covers 63.75 km² centred at 50° 27′ N and 3° 33′ W and lies in the southwest of England. Torbay has a mild temperate climate due to its sheltered position and the effect of the Gulf Stream, with mean annual precipitation of 1000 mm and a mean average maximum and minimum temperature of 14ºC and 7ºC respectively (Met Office, 2010). The population is *circa* 134 000 (Torbay Council, 2010).

Materials and methods

The basic process used by the i-Tree Eco model (also known as the Urban Forest Effects model or UFORE) is to calculate the correct number of survey plots needed to give a representative sample of an urban tree population. Survey data from these plots is 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 model can also estimate the predicted future benefits of the existing urban forest by applying growth rate calculations to the current stock.

Field sampling

During the summer of 2010, 250 random 0.04 ha plots were distributed across the borough of Torbay. Plots were allocated using randomised grid sampling. The borough (study area) was divided into 250 equal grid cells with one plot randomly located within each grid cell. The study area was then sub-divided into smaller units of analysis (or strata) after the plots had been distributed (post-stratification). This approach better allows for future assessment to measure changes through time and space but at the cost of increased variance of the population estimates, because pre-stratification can focus more plots in areas of higher variability (Nowak *et al.*, 2008a).

Out of the 250 plots, 241 were measured following field methods outlined in the i-Tree Eco user manual v 3.1. (i-Tree, 2010). Of the remaining 9 plots, 2 were inaccessible and 7 were located on private property, where permission to conduct the field measurements had been refused.

The 241 plots equate to 1 plot every 26.45 ha, which yields a relative standard error (of tree population) of ±11%. Details of how the number of plots influences the relative standard error over area are given in Nowak *et al.* (2008a). Other studies have frequently used 200, 0.04 ha plots yielding different variances (Nowak *et al.*, 2008b). However, the number of plots chosen for this size study area has been determined to be sufficient to address the objectives of the project. By way of comparison the Chicago study used 745 plots equating to 1 plot every 80.2 ha, producing a standard error of ±10% (Nowak *et al.*, 2010).

Following the protocol specified in the i-Tree Eco user manual v 3.1 (i-Tree, 2010), data was collected for each tree on every plot. Tree measurements included species, number of stems, diameter at breast height (dbh), total height, height to base of live crown, crown width, percentage crown die-back, crown light exposure and the position of the tree relative to the plot centre. Other information on the plot included percentage ground cover types, land use, percentage tree cover and plantable space. Shrub data (species and leaf volume) were also collected and their contribution included in the calculations for pollution removal – but not for carbon storage and sequestration. Full details of field data collection procedures are given in Nowak *et al.* (2008a).

Analysis

We used i-Tree Eco to calculate and describe the structure of Torbay's urban forest, including species composition, tree density and condition, leaf area and biomass. This data was combined with additional data, including local climate and hourly pollution, and an estimated local leaf-on/leaf-off date. These variables were then analysed to quantify the ecosystem functions, including carbon sequestration and storage, air pollution removal and structural value. Full methodologies are included in Nowak and Crane (2000) and Nowak *et al.* (2008a).

We did not carry out any analysis of tree shading and evaporative cooling on building energy use and subsequent avoided carbon emissions. This component of the i-Tree Eco model is designed for US building types, energy use and emissions factors, limiting its use in international applications (i-Tree, 2010).

The model provides values in dollars. Pound values were first converted to dollars with the submitted data, and returned dollar values were converted back into pounds using the HM Revenue and Customs average for year spot rate to 31 March 2010 (£-$ = 1.517 and $-£ 0.659).

A number of UK-specific datasets were needed to run the model for the Torbay study area.

Climate data

Weather data was obtained from the National Climatic Data Centre (2010), which although based in the USA provides datasets which are available for most major cities worldwide. This study used hourly climatic data from the Brixham weather station, which lies within the study area. Albedo (solar radiation) coefficients are also required. These do not vary much across the USA (Nowak *et al*., 2006) and 'best fit' values were used for Torbay based on the local climatic and geographical data supplied. Work is currently being undertaken in the USA to test how sensitive the model is to these coefficients in order to assess how accurate these values need to be; it is currently thought that they will not affect final figures very much (Nowak, personal communication, 8 February 2011).

Pollution data

We obtained hourly pollution data from Defra (2010a). Archived pollution data is available online for pollution monitoring stations across the UK. Monitoring stations located in Torbay did not collect data on the complete set of pollutants required by the i-Tree Eco model, therefore proxy data was obtained from a monitoring station in Plymouth town centre for the years 1997 onwards. This proxy dataset was also incomplete due to the station being periodically inactive or out of service. Therefore data for the various pollutants over a five-year period (2005–2009) was obtained. This data was then spliced where there were gaps in order to provide a continuous hourly pollution dataset for O_3, SO_2, NO_2, CO_2, and PM_{10} for one year.

Leaf-on, leaf-off dates

Mean average leaf-on/leaf-off dates were calculated using datasets from the UK phenology records (Nature's Calendar, 2010). The data from eight species were selected to calculate an average (field maple (*Acer campestre*), sycamore (*Acer pseudoplatanus*), birch (*Betula pendula*), hawthorn (*Crataegus monogyna*), beech (*Fagus sylvatica*), ash (*Fraxinus excelsior*), sessile oak (*Quercus petraea*) and English oak (*Quercus robur*)) over a five-year period (2005–2009) from data collected across the UK, 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 eight 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, 19 April 2010 and leaf-off, 27 October 2010. As these are UK averages the estimate is likely to be conservative when applied to Torbay, which is widely understood to be subject to a milder microclimate.

Structural data

For transplantable trees the United Kingdom and Ireland Regional Plant Appraisal Committee (UKI RPAC) – Guidance note: 1 (Hollis, 2007) was used with the average installed replacement cost (£500.00) and average transplantable size (30–35cm) of replacement trees in Torbay to determine a basic replacement price of £12.42/cm² (of cross sectional area of tree). These averages were calculated by obtaining the cost of supply of each replacement tree species and associated planting and maintenance costs to derive the installed replacement cost. Where no price existed for a given tree species then the 16–18cm class price from the UKI RPAC – Guidance note: 1 (Hollis, 2007) was used. This installed replacement unit cost is multiplied by trunk area and local species factor (0–1) to determine a tree's basic value.

Local species factors for the USA are determined by the Council of Tree and Landscape Appraisers (CLTA) regional groups and published by the International Society of Arboriculture. However, there is no published data for the UK. To undertake a full appraisal of local species factors would be a significant task (Hollis, 2007). Therefore, using the list of recorded tree species from the field study, knowledge of the locality and the species adaptability table (6.1) in Hibberd (1989), the growth characteristics, pest and disease susceptibility and environmental adaptability were determined to broadly gauge the local species factor into the following categories; low 0.33, medium 0.66 and high 1.

Carbon storage and sequestration

The UFORE model quantifies composition and biomass for each tree using allometric equations from the literature. Where no equation can be found for an individual species, the average results from equations of the same genus are used. If no genus equations are found then the model uses average results from all broadleaf or conifer equations (Nowak, 1994; Nowak *et al*., 2008a).

Where equations estimate total above-ground tree wood biomass, the below-ground biomass was estimated using a root-to-shoot ratio of 0.26 (Nowak *et al*., 2008a). Where equations calculate fresh weight biomass, species or genus specific conversion factors were used to calculate the dry weight.

Urban trees tend to have less above-ground biomass than trees in forests. Therefore, biomass results for urban trees were adjusted accordingly by reducing biomass estimates by 20%, although no adjustment is made for trees in more natural stands (Nowak *et al*., 2008a). Estimates of annual carbon storage are calculated by converting tree dry-weight biomass by multiplying by 0.5 (Nowak *et al*., 2008a). Full methodologies are included in Nowak and Crane (2002) and Nowak *et al*. (2008a).

Gross carbon sequestration was estimated from average diameter growth per year for individual trees, land use types, diameter classes and dbh from field measurements (Nowak *et al*., 2008a). Adjusting for tree condition, gross carbon sequestration was calculated as the difference in the amount of carbon storage between a measured tree's actual and predicted carbon storage in one year.

Net carbon sequestration includes released carbon due to tree death and subsequent decomposition based on actual land use categories, mortality estimates, tree size and condition (Nowak *et al*., 2008a).

The model uses biomass formulas and standardised growth rates derived from US data and therefore our estimates for Torbay are sensitive to this. However, as the base growth rates used are from northern US areas (Nowak *et al*., 2008a), the growth and carbon sequestration rates are likely to be conservative when applied to Torbay.

Since population carbon estimates are based on individual trees, the model estimated the percentage of the measured tree that will die and decompose as opposed to a percentage of the tree population to die and decompose. These individual estimates were aggregated to estimate decomposition for the total population, based on field land use and two types of decomposition rates, rapid and delayed release (Nowak *et al*., 2008a). This assumes that urban trees release carbon soon after removal, whereas trees in forest or vacant areas are likely left standing for prolonged periods, thus delaying release (Escobedo *et al*., 2010); again, this is likely to result in a more conservative estimate of carbon stored. Additional methods and assumptions on standardised growth, decomposition rates and related carbon emissions are presented in Nowak and Crane (2002).

The value of the carbon stored and sequestered annually is a multiplication of the unit cost. The model uses the estimated marginal social cost of carbon dioxide based on a stochastic greenhouse damage model from a paper by Fankhauser (1994). This estimates a social cost of carbon in the order of $20.00 per ton carbon for emissions between 1991 and 2000 rising to $28.00 per ton carbon by 2021 (imperial). The value used in the study was calculated for 2010 at $22.80 per tonne carbon (metric).

Air pollution filtration

Air pollution removal is modelled within UFORE as a function of dry deposition and pollution concentration. Estimates of hourly pollution removal and its value are based on the local weather and solar radiation data, pollution data, leaf area index, leaf-on, leaf-off dates and geographical factors (Nowak *et al*., 2006).

Leaf area index (LAI) is calculated for trees and shrubs from the field data. The UFORE model estimates leaf area using regression equations (Nowak, 1994; Nowak and Crane, 2002; Nowak, Crane and Stevens, 2006) based on the input variables from the field data. Because trees can also emit volatile organic compounds (VOC's) – emissions that contribute to the formation of O_3 and CO – biogenic emissions from different tree species were accounted for in the calculations (Nowak *et al*., 2008a).

The value attributed to the pollution removal by trees is estimated within the model using the median externality values for the USA for each pollutant. These values are given in $ per metric tonne as O_3 and NO_2 = $9906 per metric tonne, CO = $1407 per metric tonne, PM_{10} = $6614 per metric tonne and SO_2 = $2425 per metric tonne (Nowak *et al*., 2008a). These values are considered as the estimated cost of pollution to society that is not accounted for in the market place of the goods or services that produced the pollution (Nowak *et al*., 2006).

Structural value

The structural value is based on methods from the Council of Tree and Landscape Appraisers and is based on four variables: trunk area (cross sectional area at dbh), species, condition and location (local species factors). The field measurements (species, cross sectional area at dbh) are used to determine a basic value that is then multiplied by condition and local species factors to determine the final compensatory value (UFORE, 2010).

For trees larger than transplantable size the basic value (*BV*) was:

$$BV = RC+(BPx[TAa- TAr]x\ SF)$$

where *RC* is the replacement cost at its largest transplantable size, *BP* (basic price) is the local average cost per unit trunk area (£/cm²), *TAa* is the trunk area of the tree being appraised, *TAr* is the trunk area of the largest transplantable tree and *SF* is the local species factor.

For trees larger than 76.2 cm dbh, trunk area is adjusted downwards based on the assumption that a large mature tree will not increase in value as rapidly as its trunk area due to factors such as anticipated maintenance and structural safety (Council of Tree and Landscape Appraisers, 1992). The adjustment is:

$$ATA = -0.335d^2 + 176d - 7020$$

where *ATA* = adjusted trunk area, and *d* = the trunk diameter in inches.

Basic values for the trees were then multiplied by condition factors based on crown die-back and local species factors (UFORE, 2010). Data from all measured trees was used to determine the total compensatory value (structural value) of the tree population (Nowak *et al*., 2008a).

Results and discussion

Urban forest structure

There are approximately 818 000 trees in Torbay, situated on both private and public property. The results of the survey found that the private/public ownership split for the plots is 71.1% private, 28.9% public ownership. This is higher than the national average revealed in the results of *Trees in Towns II* (Britt and Johnston, 2008), where two-thirds of all trees and shrubs were found on private property (public ownership indicates that the land falls under the duty assigned to Torbay Borough Council to maintain at the public expense). Data for land ownership under these headings is not included within the parameters for i-Tree data collection. Instead, additional data was collected at the time of survey by way of assigning a percentage to each plot (rounded to the nearest 5%) for the area in private/public ownership.

The most common tree species found in Torbay are Leyland cypress (118 306 trees, 14.5%), ash (94 776 trees, 11.6%) and sycamore (81 703 trees, 10%). Total tree leaf area in Torbay is 51.7 km². (NB. whilst this is related to, it does not substitute for canopy cover.) The most dominant tree species in terms of total leaf area are ash (10.1 km², 19.5%), sycamore (8.5 km², 16.4%) and beech (3 km², 5.8%) (results are taken for trees only; results for shrubs are not included within these values).

The most important species (calculated as the sum of relative leaf area and relative composition) are those trees which have attained a larger stature and therefore larger stem diameters and total leaf areas (Table 1 shows the top ten trees by importance value). The top ten trees account for 67.6% of the total leaf area. While being the most numerous tree, Leyland cypress accounts for only 3.1% of the total leaf area. The dominance of ash as the climax community large canopy tree within Torbay's woodlands accounts for its status as the most important tree.

The recent *Trees in Towns II* survey (Britt and Johnston, 2008) used aerial photography to report mean average canopy cover for towns in England to be 8.2%. Mean canopy areas per plot were calculated at 11.1% for the South West and 11.8% for the South East. The Torbay study estimated tree canopy cover over the area of Torbay at 11.8% (a total of 752 ha). For comparison, canopy cover for Chicago and New York, USA, were estimated at 17% and 24% respectively (Rodbell and Marshall, 2009). Shrub cover for Torbay was 6.4%.

Table 1 Species importance within Torbay.

Rank	Species	Percentage population	Percentage leaf area	Importance value
1	Ash	11.6	19.5	31.1
2	Sycamore	10.0	16.4	26.4
3	Leyland cypress	14.5	3.1	17.5
4	Hazel	7.4	4.9	12.4
5	Beech	3.7	5.8	9.4
6	Holm oak	4.4	4.9	9.3
7	Elm	5.5	2.2	7.7
8	Lawson cypress	2.5	3.7	6.2
9	Hawthorn	5.4	0.8	6.2
10	English oak	2.2	3.7	6.0

Of trees in Torbay 57.1% are less than 15.2 cm diameter at breast height. This distribution (although normal) is skewed (Figure 1). Ideally one would expect a normal distribution with most trees in the middle diameter classes. However, it must be taken into account that because any stem over 2.5 cm diameter was included in the study, many small hedgerow trees were included within the analysis. This is especially relevant for one of the most commonly used amenity hedge species, Leyland cypress (with 65.8% of trees within the population at less than 15.2 cm stem diameter). Large numbers of hedgerow Leyland cypress trees were recorded with small stem-diameters and crown-volumes (due to their repeated clipping as hedges). Also, within woodland plots, many small trees in the understorey were also included.

In terms of continental origin, Table 2 shows percentages for each of the six continents from which the 102 species found in Torbay originate. By far the most dominant continent of origin is Europe. It is interesting to note that of the species of European origin, 51.4% are native to the UK, which represents 35.3% of all species found.

Table 2 Origin of species within Torbay.

Origin	Percentage
Europe	68.9
N. America	14.6
Asia	6.8
Australasia	5.8
S. America	2.9
Africa	1.0
UK (as % of European species)	51.4
UK (as % of total species)	35.3

The structural value of Torbay's trees amounts to £280 million. The CTLA value is a conservative value based on a tree in average condition, which will overestimate the value of some trees, and underestimate others. This approach serves to give a credible value for all the trees in Torbay. CTLA methodology does not apply a value to the trees as an amenity, and this is not considered here. The value of each tree applies to its replacement cost only, and is partially theoretical, as it is not possible to buy and transplant large trees in the event that they are lost. Through depreciating the values for the trees by species (i.e. suitability to the environment), condition (physiological and structural defects, life expectancy) and location (as trees contribute to the market value of property in an area, they can be assigned a proportion of this value; larger trees are effectively 'worth more'), a realistic value for trees is obtained, which realises the significance of the contribution of a tree to its environment. See Hollis (2009) for a thorough evaluation of the system.

Climate change, carbon storage and sequestration

Climate change is now recognised as one of the most serious challenges facing us today (Wilby, 2007; Lindner *et al*., 2010) and its potential impacts for trees and forests are well documented (Freer-Smith *et al.*, 2007). The UK climate change scenarios (UKCIP, 2009) indicate average annual temperature increases of between 1 and 5°C by 2080. However, these scenarios do not take urban surfaces into account (Gill *et al*., 2007), which have the potential to further increase these predicted temperatures due to the urban heat island effect.

Urban trees help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue, by altering energy use in buildings, thereby altering carbon dioxide emissions from fossil fuel based power plants and also by protecting soils, one of the largest terrestrial sinks of carbon (Reichstein in Freer-Smith *et al*., 2007). They will also be useful in adapting to climate change through evaporative cooling of the urban environment (Gill *et al*., 2007; Escobedo *et al*., 2010).

The model estimated that Torbay's trees store 98 100 tonnes of carbon (15 tonnes of carbon per ha) and sequester a further 4279 tonnes per year (0.7 tonnes of carbon per ha). Net carbon sequestration is estimated at 3320 tonnes taking into account tree mortality. As trees die and decay they release much of the stored carbon back into the atmosphere. This is illustrated most significantly in the net amount for elm (Table 3), which despite a large population have a negative net sequestration rate due to their short lifespan; a consequence of Dutch elm disease.

Torbay's baseline (2005/6) total emissions were estimated at 750 000 tonnes of carbon (Torbay Council, 2008), over seven times more than the total carbon stored in the borough's urban forest and equating to 5.6 tonnes of carbon per capita. Based on these figures the urban forest can offset the emissions from 592 residents, which accounts for less than 0.5% of total emissions.

The direct impacts of trees on CO_2 seem at first glance to be negligible. However, the potential for the urban forest to reduce CO_2 emissions through energy reduction, and its role in climate adaptation, lowering urban temperatures through

Figure 1 Tree composition in Torbay by diameter class.

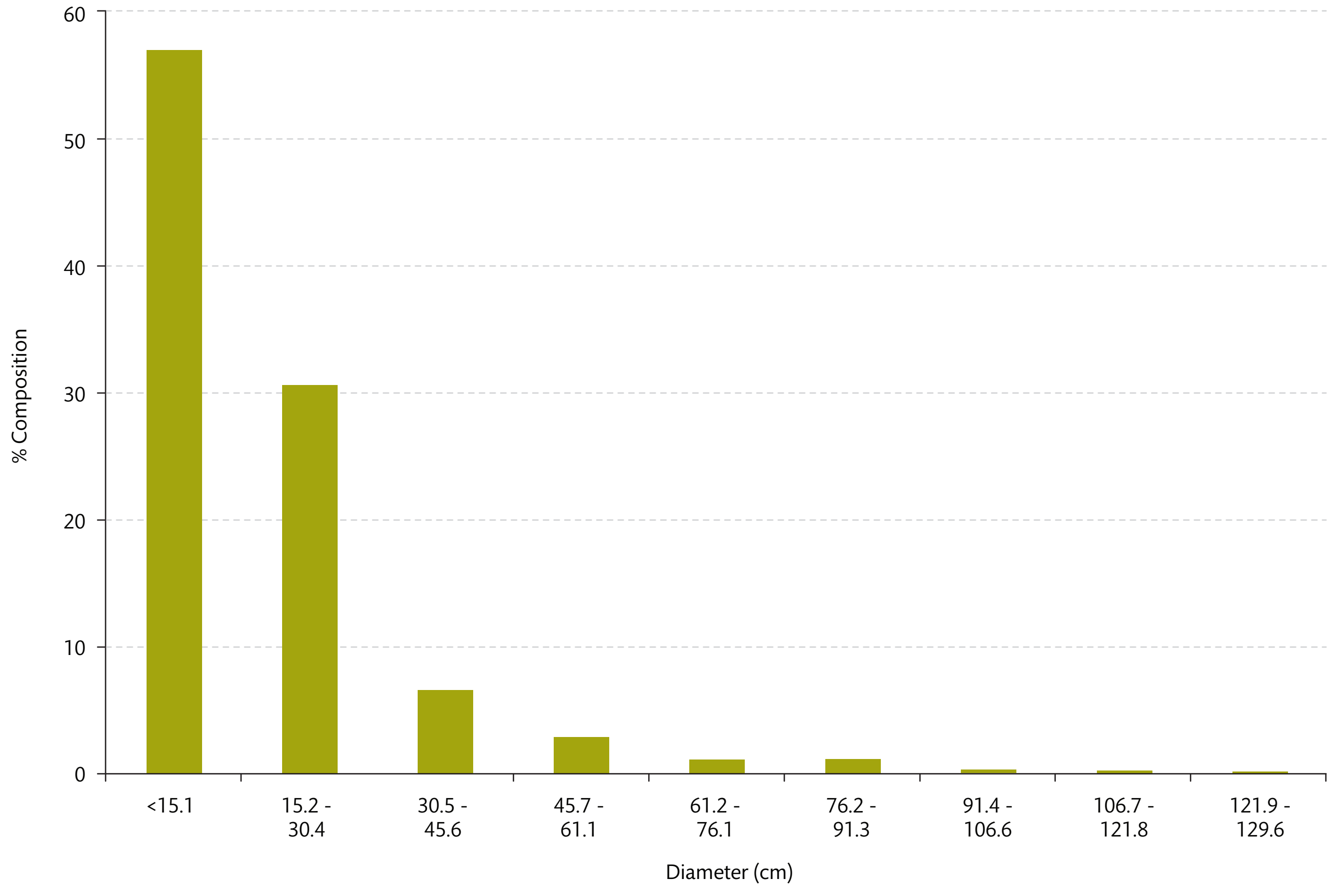


Table 3 Carbon storage and sequestration of the ten most significant trees in Torbay.

Species	Number of trees		Carbon (mt)		Gross seq (mt/yr)		Net seq (mt/yr)		Leaf area (km^2)		Leaf biomass (mt)		Carbon	Net seq
	Val	SE	Val	SE	Val	SE	Val	SE	Val	SE	Val	SE	Value (£)	Value (£)
Leyland cypress	118 306	35 361	2430.77	662.22	268.75	74.93	255.68	71.12	1.581	0.433	370.55	101.43	36 536	3843
Ash	94 776	32 088	11 399.19	3771.22	506.6	145.48	470.61	134.75	10.091	2.976	1 073.56	316.56	171 337	7074
Sycamore	81 703	23 197	18 142.32	7048.52	661.7	197.74	597.8	174.52	8.493	2.466	593.94	172.46	272 691	8985
Hazel	60 787	22 128	2344.55	963.41	186.59	67.86	160.9	64.64	2.549	0.899	177	62.41	35 240	2418
Elm	45 100	21 600	3466.27	1675.56	112.98	53.7	-289.69	263.14	1.147	0.559	78.09	38.07	52 100	-4354
Hawthorn	43 793	18 142	800.52	299.41	87.54	31.14	84.47	29.69	0.432	0.151	54.4	19.04	12 032	1270
Holm oak	35 949	12 999	9934.76	3845.19	425.14	160.98	291.65	158.86	2.54	0.974	233.13	89.34	149 326	4384
Beech	30 067	14 147	7385.11	3960.2	260.32	111.87	222.25	92.25	2.984	1.169	149.34	58.5	111 003	3341
Lawson cypress	20 262	5818	3945.47	2567.21	115.78	58.13	94.19	48.52	1.936	1.107	484.02	276.76	59 303	1416
English oak	18 302	7484	6713.92	3572.15	211.87	96.12	192.47	86.62	1.937	0.887	128.98	59.07	100 915	2893

evaporative cooling and protecting soil carbon, should not be overlooked. Although these particular ecosystem functions were not quantified as part of this study, Gill *et al.*, (2007) reported that increasing green cover by 10% within urban areas in Manchester could reduce surface temperatures by 2.2 to 2.5 °C.

Torbay has a large proportion of smaller (both in age and ultimate size potential) trees and carbon sequestration from small trees is minimal (Escobedo *et al.*, 2010). However a proportion of these trees will grow, thus offsetting the decomposition from tree mortality.

The estimates of carbon stored in the urban forest are likely to be conservative as soil carbon has not been factored into the evaluation. Furthermore, the urban forest can also reduce emissions indirectly, and if more trees able to achieve a larger size are planted, additional carbon can be stored in the urban forest. However, tree establishment and maintenance operations will offset some of these gains.

Air pollution removal

Air pollution from transportation and industry is a major public health issue in urban areas (Beckett *et al.*, 1998; Bolund and Hunhammar, 1999; Tiwary *et al.*, 2009). Urban trees can make significant contributions to improving urban air quality (Freer-Smith *et al.*, 2005) by removing air pollution through dry deposition, a mechanism by which gaseous and particulate pollutants are captured on plant surfaces and are either absorbed into the plant through the stomata (Jim and Chen, 2008), or introduced to the soil through leaf fall. Trees are capable of higher rates of dry deposition than other land types (McDonald *et al.*, 2007) and also alter the urban atmosphere by reducing levels of ozone, because although some species can contribute to VOC emissions, the cooling effect of the urban forest on air temperature reduces ozone to greater effect (Nowak *et al.*, 2000).

Torbay's trees remove 50 tons of pollutants every year with an estimated value of £281 000 (Figure 2). Pollution removal was greatest for ozone, O_3, followed by PM_{10}, NO_2 and SO_2. Recorded CO levels were negligible.

Figure 2 Total pollution removed.

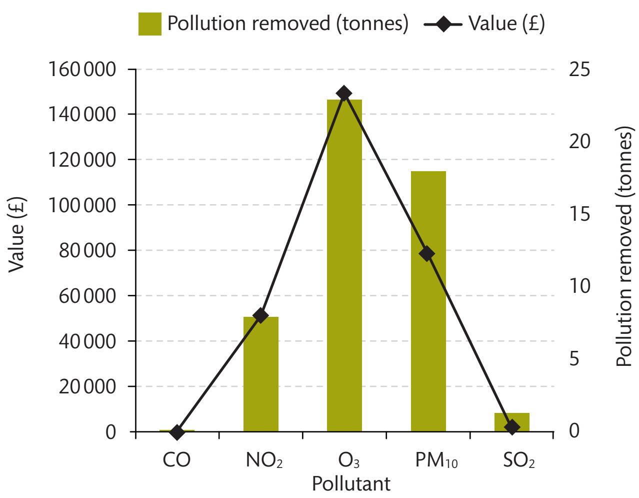
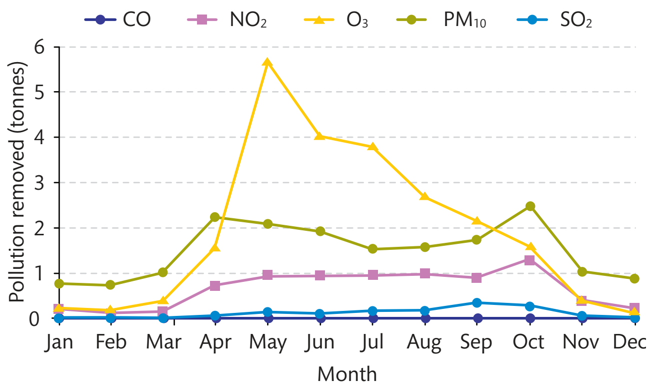


Figure 3 shows monthly removal, which varied, peaking in May for O_3 and in October for other pollutants. The monthly pattern of removal differed from observations in the USA in which peak removal rates tend to occur in the summer months (Nowak, 1994). These differences could be attributed to the poor summers of 2007–2009 from which the climatic and pollution datasets were taken, as one would typically expect pollution levels to build over the summer months, peaking at the end of the summer.

Figure 3 Monthly pollution removal.



Total pollution removal in Torbay is 0.002 tonnes per ha per year. These values were lower than have been recorded by other studies; 0.009 tonnes per ha per year in Tiwary *et al.* (2009) for a site in London (PM_{10} only) and 0.023 tonnes per ha per year in Jim and Chen (2008) for a site in Guangzhou, China. However, the greater pollution concentrations and canopy cover areas observed in these studies will result in more pollutants being removed. Greater tree cover, pollution concentrations and LAI are the main factors influencing pollution filtration and therefore increasing areas of tree planting has been shown to make further improvements to air quality (Escobedo and Nowak, 2009). Furthermore, because filtering capacity is closely linked to leaf area (Nowak, 1994) it is generally trees with larger canopy potential that provide the most benefits.

Available planting space in Torbay has been estimated from the study at 8%. McDonald *et al.* (2007) reported in a modelling study that by increasing tree cover by 13% in the West Midlands, PM_{10} concentrations alone could be reduced by up to 10%. Species selection is an important consideration; for example, conifers are capable of capturing more particulates but are not considered to be as tolerant as broadleaves (Beckett *et al.*, 1998). As different species can capture different sizes of particulate (Freer-Smith *et al.*, 2005) a broad range of species should be considered for planting in any air quality strategy. Donovan (2003), quoted in McDonald *et al.* (2007), developed an Urban Air Tree Quality Score as a decision support tool for this purpose.

Uncertainties in the quantification have been acknowledged, such as the application of US externality values on the pollutants and the use of a local proxy site for pollution data. While the USA uses abatement cost values (based on what it would cost to clean the air by mechanical means), in the UK pollution values are based on damage costs, which were not suitable for local modelling without further work and did not cover all the pollutants monitored in the UK (Defra, 2010b). Furthermore, dry deposition rates were modelled based on generic values due to lack of empirical data and no account is made of wet deposition.

Tiwary *et al*. (2009) reported that although the UFORE method has limitations based on these inherent assumptions, a different methodology used by Broadmeadow *et al*. (1998) in the UK gave results that would suggest that the models being evaluated as part of that study were reasonably reliable.

Conclusions

The UFORE model was originally developed using geographically specific US growth rates. Tree species in the UK have different growth rates, and therefore biomass and leaf area estimates, and the subsequent provision of ecosystem services will also differ. Applying i-Tree Eco to British conditions could result in the over or under estimation of the reported values. As the UFORE model has been applied in other non-US cities, it would be interesting to compare results. However, for the most accurate use of the model, the algorithms should be adapted to suit UK conditions.

The values presented in this study represent only a portion of the total value of the urban forest of Torbay because only a proportion of the total benefits have been evaluated. Trees confer many other benefits. Benefits such as avoided energy costs for cooling and heating, visual amenity, human health, tourism, ecological benefits, and other provisioning and regulating services such as timber and natural hazard mitigation (de Groot *et al.*, 2010) remain unquantified.

The importance of several of these benefits will increase as the predicted effects of climate change (such as increased summer droughts and winter rainfall) become more apparent. Under these scenarios, a healthy and diverse urban forest using appropriate species will be more resilient to change.

Although there is scope to improve the approach used in this study with UK-specific data, it still provides a useful indicator of the monetary value of urban trees, and allows for a better analysis of tree planting costs and benefits to be undertaken. The findings should also raise awareness of the wide range of ecosystem services delivered by trees in urban areas, strengthening the case for increasing urban greening, and promoting the sustainability of urban ecosystems.

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