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T. Sunderland [a], K. Rogers [b] & N. Coish [c]

[a] Natural England, Sheffield, UK

[b] University of Cumbria, National School of Forestry, Cumbria, UK

[c] Torbay Council, Torquay, UK

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What proportion of the costs of urban trees can be justified by the carbon sequestration and air-quality benefits they provide?

T. Sunderland[a]*, K. Rogers[b] and N. Coish[c]

[a]*Natural England, Sheffield, UK;* [b]*University of Cumbria, National School of Forestry, Cumbria, UK;* [c]*Torbay Council, Torquay, UK*

The i-Tree Eco programme estimates carbon sequestration and air pollution removal by urban forests. Previously we applied i-Tree Eco to the Torbay area of England; in this paper we use these results to assess the extent to which these benefits justify the costs of urban trees. We combined our benefits estimates with cost data to produce a single year "snapshot" comparison of costs and benefits for the urban forest. We then extended the discussion by modelling the lifetime benefits of four species of tree in the Torbay context. Two were assumed to be street trees: Lime (*Tilia cordata*) and cherry (*Prunus avium*). Two were assumed to be park trees: Maritime pine (*Pinus nigra var maritima*) and English oak (*Quercus robur*). We used this to produce an illustrative, partial, cost: benefit ratio for these trees. The central estimate of the "snapshot" comparison significantly exceeded costs and this remained the case when we sensitivity tested by halving the air-quality benefit to account for an uncertainty in the input data. The central cost-benefit ratios for the individual trees were cherry 1:0.01, lime 1:0.07, pine 1:0.12, and oak 1:0.21. We tested these results for sensitivity to the discount rate; reanalysing with a discount rate of 2.1% as opposed to the standard 3.5%. This produced the following results: Cherry 1:0.01, lime 1:0.76, pine 1:0.97, oak 1:4.96. These results suggest that, in common with other projects, cost-benefit analysis of investment in trees is very sensitive to the discount rate used, but that whilst carbon sequestration and air pollution removal may not justify tree planting by themselves, they do add to the justification. The significance of these benefits vary by tree, location and assumptions used, but larger and longer-lived trees appear to offer the greatest carbon sequestration and air-quality benefit, with the native oak performing particularly strongly.

Keywords: urban trees; air quality; carbon sequestration; cost-benefit

Introduction

Many of the benefits provided by trees in an urban environment are well-known and broadly acknowledged. Others are less well-known outside groups with a specific interest in the environment. Table 1 below, makes an attempt to list the main benefits in discrete categories. An important feature of the evidence for these benefits is that they are difficult or extremely difficult to quantify. Benefits that cannot be quantified cannot be included in cost-benefit analysis, except as a qualitative extension, which is often somewhat marginalised. Discussion of the state of this evidence with regard to quantification can be found in the MEBIE review from Natural England (Sunderland, 2011). By contrast costs, also shown in Table 1, are well-known and easy to quantify. The costs are therefore much clearer than the benefits, an imbalance which may disadvantage the funding case for urban trees.

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*Corresponding author. Email: tim.sunderland@naturalengland.org.uk

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Table 1. Costs and benefits of urban trees.

Costs	Benefits		
	Environmental	Social	Ecological
Planting (a)	Air Quality (a)	Aesthetic – including mental health/spiritual	Species habitat
Establishment (a)	Carbon storage and sequestration (a)	Increased attractiveness of streets for active travel	
Clearance of leaf litter (a)	Climate regulation/ amelioration	Increased attractiveness of streets for socialisation	
Damage to pavements and buildings	Erosion control	Education	
Removal of dead dying diseased trees (a)	Storm water attenuation	Attractiveness of locality for tourism and inward investment (b)	
Maintenance – trimming over carriageways (a)	Noise abatement		
Loss of light	Soil quality		
Release of Volatile Organic Compounds	Water quality		

Note: (a) These costs and benefits were included in this analysis, with the exception of the clearance of leaf litter which was only partially included; (b) This benefit is a relative benefit: That is to say, trees do not probably increase the level of tourism or inward investment in the UK, but may increase Torbay's attractiveness relative to other areas. For this reason it cannot be included in a cost-benefit analysis to national standards.

In a previous paper we applied i-Tree Eco (referred to as i-Tree from this point) to the trees within the Torbay Council area based on a sample survey (Rogers et al., 2011). This analysis produced estimated quantities of carbon sequestration and air pollution removed by the trees. It also produced automatic valuations of the public benefit of removing the carbon and other pollutants, based on standard values used in the United States. In this paper we improve on this analysis by calculating the value of the carbon and air pollution removal using appropriate official values for the UK.

Previous analyses using i-Tree report only the costs and benefits for a one-year "snapshot" of the urban forest (Peper et al., 2007). This provides an interesting perspective, and this approach is also followed here. However, this approach gives no indication of the efficiency of the investment. For example, Peper et al. (2007) report that New York receives $5.60 benefit for every dollar spent on trees during the study year. This is often misquoted as cost-benefit ratio, but the excess of benefits over costs may be due to higher levels of investment in the past, yielding current benefits. Only comparison of project-related costs and benefits over time can provide a meaningful cost-benefit ratio. We did not have the data to do this for the whole urban forest and so we extended the analysis by modelling lifetime carbon sequestration and air pollution for four trees in the Torbay context. This allows the construction of a cost-benefit analysis for these four trees. This is a very partial cost-benefit analysis, because most of the benefits cannot be included. It is also illustrative because there is no actual proposed planting to appraise, so there are no site-specific factors to take into account. The paper now proceeds with a description of the study site, followed by methods, results, discussion and conclusion.

Site

Torbay is a unitary authority in Devon, in the south-west of England. It is an east-facing bay on the south coast, between the major cities of Exeter and Plymouth. It is a unitary authority with a population of 134,000 (Torbay Council, 2011). The area contains three towns: Torquay, Paignton, and Brixham, but also contains some areas which could be classified as rural. The population density of 21.2 people per hectare is lower than that of Bristol (37.5), but similar to that of Cheltenham (23.9) (Torbay Council & Torbay NHS Trust, 2008).

The sampling of Torbay's trees covered the full council area. Torbay has approximately 11.8% forest cover made up of around 818, 000 trees, at an average density of 128 trees p/ha^{-1} (Rogers et al., 2011). The most common tree species found in Torbay are: Leyland Cypress (*Cupressocyparis leylandii*) at 14.5%, Ash (*Fraxinus excelsior*) at 11.6%, and Sycamore (*Acer pseudoplatanus*) at 10%. The most important by leaf area are: Ash at 19.5%, Sycamore at 16.4%, Beech (*Fagus sylvatica*) at 5.8% and Hazel (*Corylus avellana*) at 4.9% (Rogers et al., 2011). Some of the trees were in private ownership (71%), but these tend to be the smaller trees, and bushes/hedges which are captured in the sample (Rogers et al., 2011). Private ownership is important for later consideration of costs and benefits because private trees have low or zero public cost but offer public benefit. Trees from every continent are represented within the tree population of Torbay which is made up of 35% native species, 40% of European origin and 25% of exotic species from the rest of the world (Rogers et al., 2011). 102 species were sampled in Torbay equating to approximately 10 species p/ha (Rogers et al., 2011) with a calculated Shannon diversity index of 3.32 (1.5 being low and 3.5 being high). This represents a fairly diverse tree-scape, which one might hope will be more resilient than that represented by a more homogenous landscape.

Methods

Costs

Cost data was received directly from Torbay Council and from contractors' invoices to Torbay Council.

Benefits

Modelling the four trees

Four existing trees in Torbay were chosen for modelling:

- lime (*Tilia cordata*) – current age 94
- cherry (*Prunus avium*) – current age 26
- maritime pine (*Pinus nigra var. maritima*) – current age 70
- English oak (*Quercus robur*) – current age 133

Tree growth was modelled in four different life stages, with the fourth stage ending at functional obsolescence, with the exception of the oak which would still be growing strongly at 200 years old (full details in Appendices 1&2). For valuation, trees were assumed to shift from one modelled stage to the next at the midpoint between the ages.

Inputs from I-Tree modelling

For the UK, the appropriate way to monetise the carbon sequestration benefit is to multiply the tonnes of carbon stored by the non-traded price of carbon, because 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 (the abatement cost) in order to remain compliant with the Climate Change Act (Department of Energy and Climate, 2009). This approach gives higher values to carbon than the approach used in the previous paper, reflecting the UK Government's response to the latest science, which shows that deep cuts in emissions are required to avoid the worst effects of climate change (Department of Energy and Climate Change, 2009). Because carbon targets tighten in future years, the value of a tonne of carbon sequestered increases considerably. For example, the medium non-traded carbon value for the study year is £52 tCO_2e^{-1}, but this will increase to £200 tCO_2e^{-1} by 2050 (Department of Energy and Climate Change, 2009). We faced a particular challenge when it came to valuing carbon sequestration for our four modelled trees because we modelled them 200 years into the future. The Department of Environment Energy and Climate Change (DECC) offers values for 2050, which are described as interim, and we used these for this time period (Department of Energy and Climate Change, 2011). To take the analysis until two of the trees are 200 years old, however, it was necessary to have values to 2205. In preference to selecting arbitrary or zero values, the values for this time period were linearly extrapolated using data from the peak in value (2075–2077) until 2010, with value set to zero where this extrapolation became negative. We acknowledge that this greatly increases the levels of uncertainty in the analysis, but the impact on the results is minimal due to the practice of discounting, which will be described below.

In our previous paper US average values for air pollution removal were used, based on the cost of mechanical air scrubbing (abatement cost) (Rogers et al., 2011). In this paper we use the official UK values, based on the estimated social cost of the pollutant in terms of impact upon human health, damage to buildings and crops. Values were taken from the IIGCB economic analysis report to inform the Air Quality Strategy (Department for Environment, Food and Rural Affairs, 2007b). They are a conservative estimate because they do not include damage to ecosystems; SO_2 negatively impacts trees and freshwater and NO_x contributes to acidification and eutrophication (Department for Environment, Food and Rural Affairs, 2007a). 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 (i.e. densely populated) the area under consideration is (Department for Environment, Food and Rural Affairs, 2007b). We used the "transport outer conurbation" values as a conservative best fit, given the population density data above. Air pollution values are conservatively assumed to be a normal good, which means that the proportion of their income that individuals are willing to pay for them will remain constant as income increases. They are therefore increased by 2% each year, our study's assumed rate of economic growth (in line with the air-quality strategy (Department for Environment, Food and Rural Affairs, 2007a)). For both carbon and air pollution removal, we make the assumption that the benefit to society from a tonne of gas removed is the same as the cost of a tonne of the same gas emitted.

Sensitivity Analysis

High, low and medium values

There is considerable uncertainty about many of the economic values used in this analysis. For air pollution this stems from scientific uncertainties in the effect that these emissions have on human health (and also damage to buildings and crops). Official values include high and low values, which range either side of the medium value, to help analysts numerically express this uncertainty. We therefore calculated the results using each of these three values to test the sensitivity of our findings to this uncertainty (Department for Environment, Food and Rural Affairs, 2007b). With carbon this uncertainty is about the costs of following the carbon reduction pathway the UK is committed to. For this reason a sensitivity analysis was undertaken for all results using central, high and low scenarios (Department of Energy and Climate Change, 2009). For the central scenario the central economic value was applied to carbon sequestration and all air pollutants, for the low scenario low values were used for all emissions and for the high scenario high values were used. Costs remain the same through all three scenarios.

Uncertainty about the quantity of pollution removed

Torbay Council's air pollution monitoring is focused on Air Quality Management Areas: Small areas where there is a known problem. This makes it unrepresentative of the wider situation in Torbay and inappropriate for this analysis. We therefore used data from nearby Plymouth, which monitors background levels of air pollution, and therefore shows lower levels of pollution than Torbay's stations. However, there is a possibility that background air pollution is greater in Plymouth than Torbay because it is a larger conurbation. In order to account for this we conducted an additional sensitivity analysis on the one-year "snapshot", in which we arbitrarily reduced the air-quality benefits by 50%. For the four modelled trees we assume they are growing somewhere with the Plymouth background levels of air pollution.

Discount rate

In cost-benefit analysis it is necessary to compare the value of costs and benefits which fall in the future to those today, reducing future costs and benefits to their "present value". For example, the formula below calculates the present value of £1000 in one year's time at a discount rate of 3.5%. The effect of discounting is compound, so to work out the present value in two years' time you could apply the same process to £965.

$$PV = £1000 \times - \left(£1000 \times \left(\frac{3 \cdot 5}{100} \right) \right) = £965$$

A central challenge to cost-benefit analysis as a rational decision maker is that outcomes are highly sensitive to the discount rate chosen, and that discount rates are some of the hardest input values to justify objectively (Weitzman, 2001). This is particularly problematic for long-term environmental projects (Weitzman, 2001). Therefore this analysis uses two discount rates, the standard rate for UK Government analysis of 3.5% (HM Treasury, 2003), and a sensitivity discount rate with the pure time preference element removed of 2.1% (see Appendix 3 for justification).

Results

Costs

The costs of trees vary dramatically depending on context: A self-seeding tree in a forest may have no direct costs, whereas planting, maintaining and ultimately removing a street tree may require significantly more. Table 2 below provides the costs used for the modelling of the four trees. These vary by location as well as tree type. Location is the more significant effect. These data are typical, rather than average, and are taken from invoices to Torbay

Table 2. Costs for the four modelled trees.

Tree (a)	Year incurred	Lime	Cherry	Maritime Pine	Oak
Location		Street	Street	Park	Park
Supply	0	£199	£66	£103	£199
Delivery	0	£70	£70	£70	£70
Planting	0	£140	£140	£140	£140
Remove pre-existing grille	0	£170	£170		
Empty rubble from soil pit and refill with top soil	0	£300	£300		
Geo-textile membrane	0	£11	£11		
Apply resin-bonded surface (Sureset)	0	£370	£370		
Tree guards (incl. carriage)	0	£585	£585		
Traffic management (portable traffic lights, cones, etc.)	0	£155	£155		
Irrigation	0	£150	£150	£150	£150
Second year warranty	1	£105	£105	£105	£105
Crown pruning	96	£400			
End of life removal costs	28		£90		
End of life removal costs	95			£2000	
End of life removal costs	195	£2000			£2000

Note: (a) Details about the sizes and ages for the modelled trees is available in Appendix 1.

Council. Clearly costs will be, in practice, different for each individual tree. The section below discusses modelling of the individual trees and for the one-year snapshot analysis.

Trees must be purchased from the nursery, transported, planted and irrigated. Planting is significantly more expensive for street trees, as shown by the table above. A warranty is also purchased to protect the investment should the young tree need replacing. Our snapshot analysis uses Torbay Council's total cost of tree planting which was £38,400 in 2010/11. This is a significant increase of the year before in which it was £13,700, suggesting this is quite variable. Using a year with high costs makes our "snapshot" analysis conservative, but really points to the need for all costs and benefits to be considered over time.

Potentially leaf litter is beneficial natural compost, but in an urban environment it requires sweeping from the streets in order to avoid becoming a trip hazard and blocking drains. However, much of the leaf litter is too contaminated with other rubbish to be used for compost and is therefore sent to landfill. An estimated 342 tonnes of leaf litter, multiplied by the landfill tax (£48 tonne^{-1} in 2010), leads to an annual cost of £16,416 which is used in the snapshot analysis. This cost is considered too nugatory to consider for the individual tree modelling.

Pruning is done to maintain health, prevent the tree becoming too large, or prevent branches becoming dangerous. The actual tree on which our lime was modelled, was pruned to avoid it becoming too large and encroaching on the adjacent carriageway, at a cost of £400. Removal of the tree may be required when it becomes old, due to danger to the public, and the costs of these vary by size of tree. We have conservatively assumed this cost for all the modelled trees. In 2010/11 Torbay Council spent £67,200 on pruning and removal, of which £64,200 was on street trees and only £3,000 on park trees. This figure is broadly similar to proceeding years and will include planned regular pruning as well as work responding to storm damage. Also included in the model is £10,700 spent in 2010/11 on managing woodlands in the rural part of the district.

The annual Torbay Trees and Woodlands' (including park trees) staff costs are £289,900. This is included in the single-year snapshot analysis, but is not included in the individual tree modelling, because the marginal overhead cost of each tree would be too small to consider.

Benefits

Snapshot analysis

The i-Tree analysis estimated that 98,100 tonnes (approximately 15.4 t/ha^{-1}) of carbon is stored in Torbay's trees. Multiplying this by the non-traded price of carbon gives the figures in the second row of Table 3, which can be interpreted as the welfare loss if all the carbon stored in Torbay's trees was suddenly released. Notice that even the "low" figure is significantly higher than the value given in the previous paper of £1.4 million (Rogers et al., 2011), due to the higher importance ascribed to it by using official UK values. Because this is a measure of stock, rather than annual flow it does not feature in the one-year snapshot analysis.

Table 3. The value of the carbon stored in Torbay's trees.

	Low	Medium	High
Non-traded carbon value per tonne of carbon equivalent (£) (2010) taken from (DECC)	26	52	78
Value of stored carbon. (£ million)	2.6	5.1	7.7

The net carbon sequestration of Torbay's trees was estimated at 3,320tC yr^{-1} (based upon gross carbon sequestration of 4,279tC yr^{-1} minus calculated emissions of 959tC yr^{-1} due to tree death). Carbon sequestered is likely to be released in the long-term when trees decompose or are burnt (sometimes as a fossil fuel substitute), but can be stored for medium-term as wood. Multiplication for the non-traded price leads to the results below, a fairly significant welfare benefit.

Torbay's urban forest is estimated to remove 22.88 tonnes of O_3, 17.97 tonnes of PM_{10}, 7.91 tonnes of NO_2, and 1.3 tonnes of SO_2 annually (Rogers et al., 2011). O_3 is removed in the greatest quantity and O_3 is a significant health concern, particularly above a threshold of 35 parts per billion (AEA Technology, 2006), a threshold exceeded for an average of 74 days a year in Torbay (South West Environmental Observatory, n.d.). Unfortunately the scientific uncertainties are too great to give any quantified value to O_3 sequestration (N. Cape, personal communication, Summer 2011).

The table below shows the benefit from PM_{10} removal. The values produced are a very significant welfare benefit, but vary significantly between low and high estimates, due to the high levels of uncertainty about the health impacts.

Applying the same approach to NO_2 leads to a central estimate of £0.1 million. By comparison the level of SO_2 removed is negligible. The central estimate of the air-quality benefit of £1.33 million per year is more than four times the £281,000 calculated in the previous paper (Rogers et al., 2011). This is due to using health and other effects as a rationale for the value rather than abatement cost. The air-quality benefit dominates the annual carbon sequestration benefit of £0.17 million.

Table 4. The value of the carbon sequestration by Torbay's trees in the study year.

	Low	Medium	High
Non-traded carbon value per tonne of carbon equivalent (£) (2010)	26	52	78
Annual value of net carbon sequestration by Torbay's trees (£ million)	.08	.17	.26

Table 5. The value of the PM_{10} emissions removed by Torbay's trees in the study year.

Pollutant: PM_{10}: Amount removed (tonnes): 17.97	Low	Medium	High
UK social damage cost per tonne (£)	14,994	73,261	188,951
Annual value (£ million)	0.27	1.32	3.39

Table 6. The value of quantified pollutants removed by Torbay's trees in the study year.

Pollutant:	Low Annual Value (£million)	Medium Annual Value (£million)	High Annual Value (£million)
PM_{10}	.27	1.32	3.39
NO_2	.00	.01	.02
Total	.27	1.33	3.41

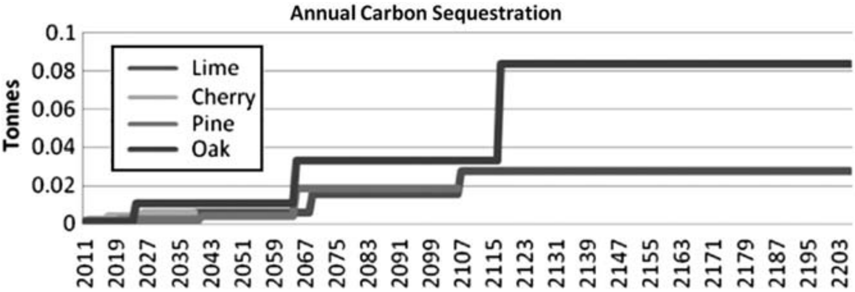

Figure 1. Carbon sequestration benefits of modelled trees over time.

Modelled trees

Figure 1 shows the annual carbon sequestration results for the lifespan of the trees. The cherry has the lowest lifespan and sequestration, followed by pine, lime and oak. It's clear that repeated planting of the trees with shorter lifespans would not achieve the same sequestration over the period as the longer-lived trees. Maximum benefits are achieved by allowing the larger trees to grow to maturity.

Figure 2, below, shows the air-quality benefits provided by the trees. The proportions of pollutants removed are the same across the trees (O_3, PM_{10}, NO_2 and then SO_2 in order of magnitude), which is the same as the whole forest analysis. The oak is the most effective, followed by the lime, then pine, then cherry, the same pattern as carbon analysis above. However, note that the performance of the lime diminishes for the last 100 years, whilst that of the oak continues to improve. This is because the actual lime that we

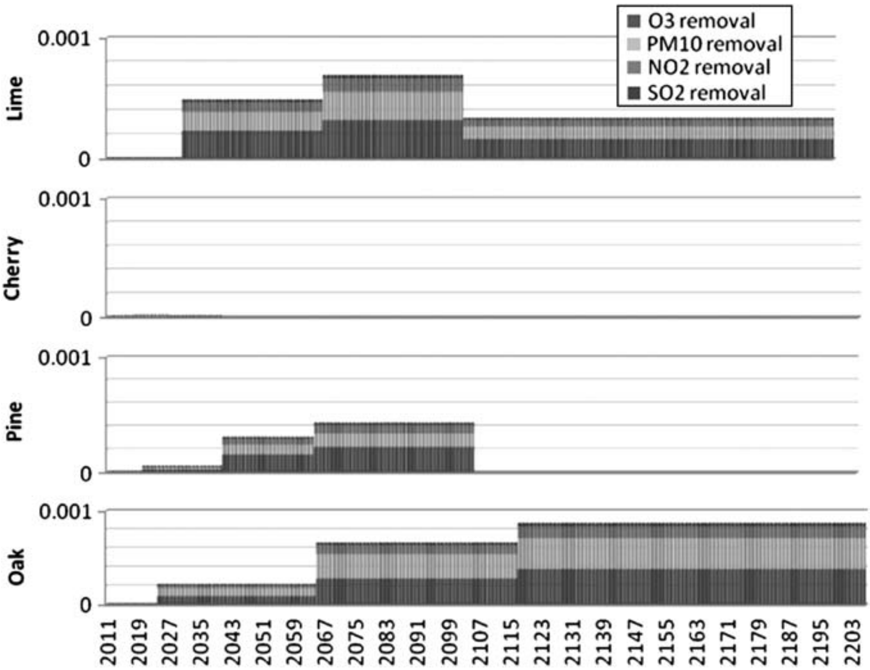

Figure 2. Annual air-quality benefits of modelled trees over time.

modelled had its crown pruned back because it was next to a road and encroaching on the carriageway. The reduced leaf area makes it less effective, but it continues to perform well in carbon terms, because it continues to increase in stem and branch wood. This therefore makes a point about the trade-offs required when managing street trees, rather than an issue intrinsic to the lime species.

Comparison of costs and benefits

Snapshot analysis

Figure 3, below, compares the annual costs and benefits of the trees within the Torbay area. Staff costs dominate the cost-side, and that the maintenance and planting of highway (street trees) is more costly than park trees. Total quantified costs are £0.42 million. The only significant public cost which is unlikely to be captured is the additional cost of cleaning up leaf litter. There will also be some private costs not captured, such as a neighbour's trees providing unwanted shade.

Removal of PM_{10}s from the atmosphere dominates the benefit-side with a central estimate of £1.32 million per year. This is followed by the annual carbon sequestration benefit of £0.17 million a year (central estimate). There are much smaller but quantified benefits from SO_2 and NO_2 removal and a further unquantified benefit from removal of ozone. The total quantified benefit is £1.55 million (central estimate). As discussed in the methodology section, we have included a sensitivity scenario in which the air pollution quantities are reduced by an arbitrary 50%, labelled S-Benefits. It is apparent from the graph that only the two low scenarios are below the costs, and only slightly below for the non-sensitivity benefits. Both the normal and S medium values are well above costs.

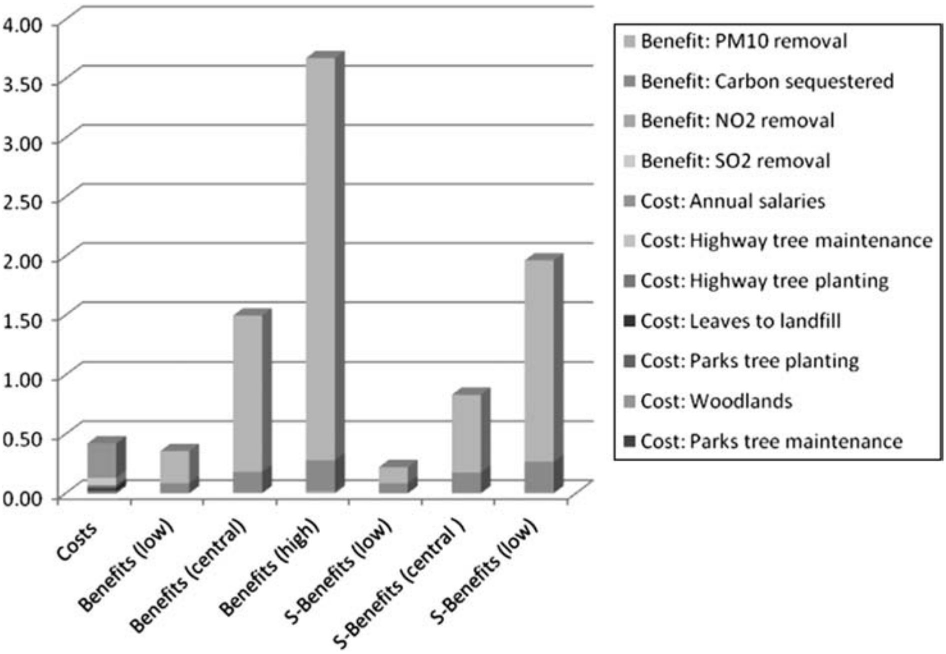

Figure 3. A comparison of selected quantifiable costs and benefits during the study year (£ millions).

Modelled tree cost: benefit ratios

The cost: benefit ratio for the modelled trees at the UK standard discount rate are shown in Table 7 below. The results show that the proportion of urban tree costs which can be justified through carbon sequestration and air pollution removal benefits varies dramatically from tree to tree. For oak trees planted in parks about one fifth of the cost can be justified this way, whereas for cherry trees planted on the street it's only one hundredth. The variation is driven partly by the qualities of the trees, with the larger longer-lived trees providing greater benefits. It is also partly driven by location, with street trees requiring greater levels of investment.

There is some apparent disjuncture between the annual snapshot, which shows that benefits are in excess of costs in the study year, and the cost-benefit analysis which shows the opposite for the lifetime of a tree. Some of this could be due to benefits now stemming from investment in previous years, but a very significant proportion is the effect of discounting. Accordingly, a sensitivity analysis for the discount rate was conducted and results for the analysis using the sensitivity rate (2.1%) are shown in the table below. This sensitivity analysis makes no change to the ranking of the trees, therefore, the findings above about tree size and location hold good. However, it is noticeable that the lime on the street comes much closer to the pine in the park using a 2.1% discount rate. This is because the lime is longer-lived and the lower discount rate gives greater weight to these long-term benefits.

The most noticeable thing about the sensitivity analysis cost-benefit ratios is how much more favourable they are, with the pine effectively justifying its costs, the lime justifying three-quarters of them and the oak justifying them more than four times over. This confirms the sensitivity of the analysis to the discount rate used.

Explanation for the significant difference in results can be found in Figure 4 below, which shows the path of the benefit flow at the two different discount rates. At 2.1% it is possible to clearly see the "jumps" at each modelled tree growth spurt, with the slopes in between them being the combined effect of the changing carbon prices and the discount rate. By contrast, at 3.5% the discounting has overridden these jumps and the benefit reaches zero by 2072. The difference between the two discount rates may seem too large at first examination. The explanation for this is that the air pollution benefits have been increased in line with expected economic growth of 2%. This is effectively cancelled out by the first 2% of the sensitivity discount rate which assumes the same level of economic growth (see Appendix 3). For the air-quality benefit (which is the larger benefit) the graph effectively shows the difference between discounting at 0.1% and 1.5%, which explains the significant difference.

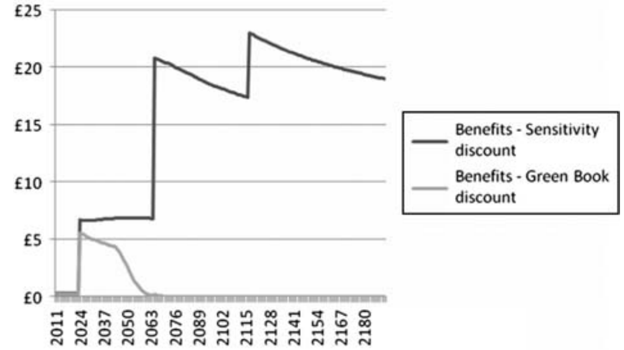

Figure 4. Comparing the flow of benefits at Green Book discount rate (3.5%) and sensitivity analysis discount rate (2.1%).

Table 7. Results for individual trees at Green Book discount rate (3.5%).

Tree	Location	Low			Central			High		
		Costs (£)	Benefits (£)	Cost: Benefit ratio	Costs (£)	Benefits (£)	Cost: Benefit ratio	Costs (£)	Benefits (£)	Cost: Benefit ratio
Lime	Street	2251.33	31.84	1:0.01	2251.33	168.20	1:0.07	2251.33	426.17	1:0.19
Cherry	Street	2151.52	4.55	1:0.00	2151.52	14.44	1:0.01	2151.52	41.02	1:0.02
Pine	Park	564.33	15.13	1:0.01	564.33	66.92	1:0.12	564.33	167.17	0:0.30
Oak	Park	660.33	31.84	1:0.05	660.33	135.58	1:0.21	660.33	334.42	0:0.51

Table 8. Results for individual trees at sensitivity discount rate (2.1%).

Tree	Location	Low			Central			High		
		Costs (£)	Benefits (£)	Cost: Benefit ratio	Costs (£)	Benefits (£)	Cost: Benefit ratio	Costs (£)	Benefits (£)	Cost: Benefit ratio
Lime	Street	2251.33	350.52	0.16	2251.33	1716.51	0.76	2251.33	4353.17	1.93
Cherry	Street	2151.52	5.62	0.00	2151.52	17.58	0.01	2151.52	47.48	0.02
Pine	Park	564.33	121.88	0.22	564.33	547.19	0.97	564.33	1352.82	2.40
Oak	Park	660.33	645.20	0.98	660.33	3094.92	4.69	660.33	7822.06	11.85

Discussion

The significant uncertainties which lie behind the production of the values used, mean that the wide "error" bands out to the high and low estimates, must also be taken into account. A precautionary approach to human health and climate change would take the "high" values seriously in decision making. Furthermore, we have noted some weaknesses in the methodology with regard to the "snapshot" approach. Firstly, we have been unable to get hold of an estimate of the additional sanitation cost of removing leaves from streets and pavements. Secondly, we are comparing public benefits with public costs, but a proportion of the public benefits will be produced by private trees. This means that private investment, which we have not considered, will play a part in producing the benefits. In this analysis we were unable to quantify which benefits were produced by private and public trees, although the majority of the benefits come from the larger trees, which tend to be in public hands.

Our illustrative cost-benefit analysis, stretching 200 years into the future, obviously relies on a large number of assumptions about future values. There is not space to make all of these explicit as many stem from the official values used (the References section should be consulted for details). For example, not considered is the effect of climate change which could alter tree performance significantly. Clearly the analysis is only as good as the estimates of quantity of pollution removed, and we discussed the methodology for this in the last paper (Rogers et al., 2011). These limitations must be born in mind when using the data and mean that it is the magnitude, rather than the detail of the value calculations which is significant.

The analysis has followed Weitzman (2001) in highlighting the importance of discounting to cost-benefit analysis of this sort. Discounting and the role of cost-benefit analysis should be carefully considered when making decisions with international and intergenerational distributional and ethical issues. It is worth noting in this context that the benefits currently received by Torbay are due to planting from 200 years ago.

In our previous paper we reported that i-Tree can produce quantitative elements for other ecosystem services such as storm water management, shading (to reduce air-conditioning) and sheltering from wind (to reduce heating) (Rogers et al., 2011). At time of writing there are difficulties in applying these approaches to the UK, but if these difficulties are overcome these results could be used to produce fuller cost-benefit analyses. However, the wide range of benefits catalogued in the introduction, and the very great difficulty in quantifying them, suggest that decision-making tools other than cost-benefit analysis have a role to play if the full suite of benefits is to be considered. Social Return on Investment and Multi-Criteria Analysis are two possibilities.

Conclusion

The one-year snapshot analysis shows the magnitude of the carbon sequestration and air-quality benefits for Torbay, showing that they are large enough to be taken into account by government and planning. It also found that these compare well with annual costs. This, however, cannot tell us whether this makes trees an efficient investment or whether we are benefiting from investment in earlier decades and centuries. In common with other long-term projects, the results of illustrative cost-benefit analysis are highly sensitive to the assumptions used, in particular the discount rate. Nevertheless, the results show that whilst at the standard UK discount rate urban tree planting cannot be financially justified by the carbon sequestration and air-quality benefits alone, these benefits make a significant contribution to the justification for planting some trees in an urban context, particularly larger, longer-lived trees. The native oak performs particularly well. This partial cost-benefit analysis should not by itself be used to decide whether or not to plant trees in urban environments, but does draw attention to some benefits which are not often considered.

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Notes on contributors

Tim Sunderland is an Economist at Natural England, a non-departmental public body sponsored by the Department for Environment Food and Rural Affairs to promote nature conservation, protect biodiversity, conserve landscape and promote access to the countryside. His education is from the University of Leeds (BA Development Studies & MSC Ecological Economics). He has previously worked in local government, skills policy and international development.

Kenton Rogers is the principal consultant at Hi-line, a tree work contracting company, based in South West England. He leads the consultancy team whose focus is on trees and woodlands, ecology and the environment. He has worked in forestry and arboriculture for 20 years. Currently he is undertaking a Masters Degree in Forest Ecosystem Management at the National School of Forestry with a particular interest in how the Urban Forest functions and delivers benefits.

Neil Coish is Principal Natural Environment Officer at Torbay Council.

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Appendix 1. Results of tree growth modelling

Table 9.

		Lime	Cherry	Maritime Pine	English Oak
Age of tree on which modelling is based		94	26	70	133
Stage 1	Age	5	8	5	5
	Diameter at breast height (cm)	5	5	3	5
	Carbon sequestration (kg – gross)	.56	1.26	1.26	0.72
	PM_{10} removed (g)	3.302	3.435	3.146	2.661
	NO_2 removed (g)	1.139	1.257	1.347	0.678
	SO_2 removed (g)	0.231	0.255	0.274	0.138
	O_3 removed (g)	3.295	3.637	3.899	1.962
Stage 2	Age	43	10	23	30
	Diameter at breast height (cm)	30	8	20	44
	Carbon sequestration (kg – gross)	5.93	2.17	2.17	10.32
	PM_{10} removed (g)	156.639	5.455	15.877	84.819
	NO_2 removed (g)	80.645	2.017	9.514	32.292
	SO_2 removed (g)	16.392	0.41	1.934	6.564
	O_3 removed (g)	233.377	5.837	27.533	93.449
Stage 3	Age	80	17	46	88
	Diameter at breast height (cm)	81	10	45	65
	Carbon sequestration (kg – gross)	15.77	3.94	3.94	33.42
	PM_{10} removed (g)	231.372	7.712	82.825	259.215
	NO_2 removed (g)	111.558	2.818	54.736	97.844
	SO_2 removed (g)	22.675	0.573	11.125	19.887
	O_3 removed (g)	322.834	8.154	158.399	283.149
Stage 4	Age	120	26	70	133
	Diameter at breast height (cm)	94	13	70	90
	Carbon sequestration (kg – gross)	27.69	5.66	18.39	83.94
	PM_{10} removed (g)	104.042	3.419	115.172	327.998
	NO_2 removed (g)	54.811	1.68	74.023	127.097
	SO_2 removed (g)	11.763	0.361	15.887	27.277
	O_3 removed (g)	165.316	5.067	223.264	383.341

Appendix 2. Tree growth modelling method

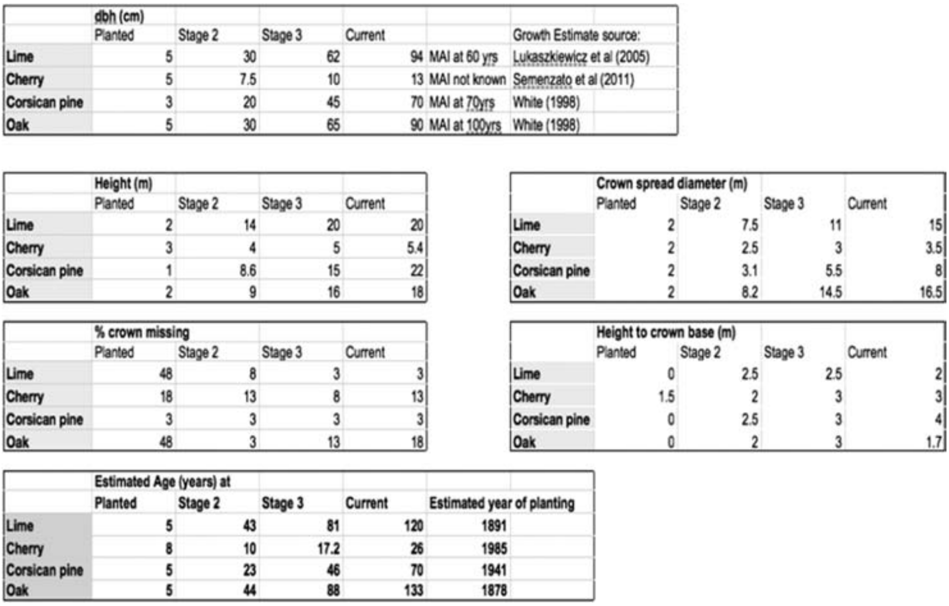
In order to model the cost and benefits of the individual trees chosen for this study through time, it was also necessary to model the growth of these trees back to the point of planting and also forward to a theoretical point of functional obsolescence: Described as the state of being which occurs when an object, service or practice is no longer wanted even though it may still be in good working order (Hollis, 2007). This is with the exception of the oak tree which would still be growing strongly at 200 years old. We did not model the oak tree beyond 200 years because of the difficulty in applying meaningful values to the long-term future.

Firstly, it was necessary to establish the current age of the chosen trees. This could not be done by taking a core sample and counting the rings without damaging the tree. There were no records as to planting date of tree either. Therefore, the trees' current ages where estimated by using the diameter at breast height and available models in the literature. For the oak and pine the method outlined in White (1998) is used, for the lime Lukaszkiewicz et al. (2005), and for the cherry Semensato, Cattaneo, and Dainese (2011). This allowed us to estimate a feasible estimated planting date for the trees (see Figure 5 below).

Tree growth curves were then plotted for the four trees using: The methods outlined in Lukaszkiewicz et al. (2005), White (1998) and Semensato et al. (2011), the current tree dimensions and an assumed deliberate planting of the trees at an assumed planting size. UK forest growth models were not applied because all of the trees presented were open grown with no competition from neighbouring species, and this was assumed to be the case since time of planting. An adjustment was made for the crown dimensions of the lime, however, as it has been subject to repeated highways pruning.

Appendix 3. Choosing a senstivity discount rate

For UK government policy appraisal there is a standard discount rate, which has been used for the main modelled trees cost-benefit ratio. This rate is 3.5% for years zero to 30, at which point it falls to 3.0% for years 31 to 75 years, 2.5% for years 76 to 125 years and 2% for years 126 to 200 (HM Treasury, 2003). Time-declining (known as hyperbolic discounting) is used to recognise the uncertainty about the appropriate discount rate increases further into the future (HM Treasury, 2003; Weitzman, 2001).



	dbh (cm)					
	Planted	Stage 2	Stage 3	Current		Growth Estimate source:
Lime	5	30	62	94	MAI at 60 yrs	Lukaszkiewicz et al (2005)
Cherry	5	7.5	10	13	MAI not known	Semenzato et al (2011)
Corsican pine	3	20	45	70	MAI at 70yrs	White (1998)
Oak	5	30	65	90	MAI at 100yrs	White (1998)

	Height (m)			
	Planted	Stage 2	Stage 3	Current
Lime	2	14	20	20
Cherry	3	4	5	5.4
Corsican pine	1	8.6	15	22
Oak	2	9	16	18

	Crown spread diameter (m)			
	Planted	Stage 2	Stage 3	Current
Lime	2	7.5	11	15
Cherry	2	2.5	3	3.5
Corsican pine	2	3.1	5.5	8
Oak	2	8.2	14.5	16.5

	% crown missing			
	Planted	Stage 2	Stage 3	Current
Lime	48	8	3	3
Cherry	18	13	8	13
Corsican pine	3	3	3	3
Oak	48	3	13	18

	Height to crown base (m)			
	Planted	Stage 2	Stage 3	Current
Lime	0	2.5	2.5	2
Cherry	1.5	2	3	3
Corsican pine	0	2.5	3	4
Oak	0	2	3	1.7

	Estimated Age (years) at				
	Planted	Stage 2	Stage 3	Current	Estimated year of planting
Lime	5	43	81	120	1891
Cherry	8	10	17.2	26	1985
Corsican pine	5	23	46	70	1941
Oak	5	44	88	133	1878

Figure 5. Growth estimate models.

However, it is important to note that values at 30 years are already discounted by two-thirds, meaning the time-declining nature of the discount can only impact on the remaining third.

The discount rate is made up of a number of elements which can be expressed formally:

$$r = \rho + \mu g$$

Where ρ represents the extent to which future consumption is valued less than current consumption, to which we will return in the next paragraph. g represents the predicted long-term growth rate, and is 2% (HM Treasury, 2003). This is multiplied by μ which compensates for the marginal utility of income. This follows from the economic theory of marginal utility of income which expects that each additional pound of income to be worth less to you the more income you already have. For example, an extra £100 is worth a lot more to someone earning a thousand pounds than someone earning a million. The Green Book uses an estimated of 1 for μ (HM Treasury, 2003) making μg 2%.

We now turn to ρ which is made up of two parameters: δ – pure time preference and L – catastrophe risk. δ can be understood as a pure preference to have something now rather than later, which can be pejoratively termed impatience. This is not due to risk or changes in consumption over time (HM Treasury, 2003). Normally in cost-benefit analysis estimates for δ will be observed from market behaviour and thus the approach adopted in the Green Book (HM Treasury, 2003). However, in his review of the economics of climate change, Stern argues that the application of pure time preference to cost-benefits analyses which cover the lifespan of more than one generation is inappropriate because it contravenes the principle of intergenerational equity (Stern, 2006). Following this argument pure time preference (δ) equates to the sensitivity discount rate. This leaves L – catastrophe risk. The appropriate value for this depends on the project. For Stern's climate change review this was understood in terms of a worldwide cataclysmic event, such as an asteroid hitting the Earth, which would render all benefits after that time null and void (Stern, 2006). Stern used a value of 0.1 for this (Stern, 2006). For our smaller project some rather smaller project-specific catastrophes should be considered, such as the possibility of a lorry destroying the tree. This, however, seems very unlikely to happen to one particular tree, even if it may happen occasionally within the area, and also insurance for the young tree is built into the calculations. Therefore, in the absence of any specific evidence as to an appropriate value 0.1 has been used. Setting δ to zero and L to 0.1 gives a value of 0.1 for ρ in the initial equation. When added to 2.0, our value for μg, this gives our sensitivity discount rate a value of 2.1.

Table 10.

Year	Low	Central	High	Year	Low	Central	High	Year	Low	Central	High	Year	Low	Central	High
2101	69.86	271.90	478.10	2121	37.67	239.16	452.20	2141	5.49	206.42	426.31	2161	0.00	173.69	400.42
2102	68.25	270.26	476.80	2122	36.06	237.53	450.91	2142	3.88	204.79	425.02	2162	0.00	172.05	399.12
2103	66.64	268.63	475.51	2123	34.45	235.89	449.62	2143	2.27	203.15	423.72	2163	0.00	170.41	397.83
2104	65.03	266.99	474.21	2124	32.84	234.25	448.32	2144	0.66	201.51	422.43	2164	0.00	168.78	396.53
2105	63.42	265.35	472.92	2125	31.23	232.62	447.03	2145	0.00	199.88	421.13	2165	0.00	167.14	395.24
2106	61.81	263.72	471.62	2126	29.62	230.98	445.73	2146	0.00	198.24	419.84	2166	0.00	165.50	393.94
2107	60.20	262.08	470.33	2127	28.02	229.34	444.44	2147	0.00	196.60	418.54	2167	0.00	163.86	392.65
2108	58.59	260.44	469.04	2128	26.41	227.70	443.14	2148	0.00	194.97	417.25	2168	0.00	162.23	391.35
2109	56.98	258.81	467.74	2129	24.80	226.07	441.85	2149	0.00	193.33	415.95	2169	0.00	160.59	390.06
2110	55.37	257.17	466.45	2130	23.19	224.43	440.55	2150	0.00	191.69	414.66	2170	0.00	158.95	388.76
2111	53.76	255.53	465.15	2131	21.58	222.79	439.26	2151	0.00	190.06	413.36	2171	0.00	157.32	387.47
2112	52.15	253.90	463.86	2132	19.97	221.16	437.96	2152	0.00	188.42	412.07	2172	0.00	155.68	386.17
2113	50.55	252.26	462.56	2133	18.36	219.52	436.67	2153	0.00	186.78	410.77	2173	0.00	154.04	384.88
2114	48.94	250.62	461.27	2134	16.75	217.88	435.37	2154	0.00	185.14	409.48	2174	0.00	152.41	383.59
2115	47.33	248.98	459.97	2135	15.14	216.25	434.08	2155	0.00	183.51	408.18	2175	0.00	150.77	382.29
2116	45.72	247.35	458.68	2136	13.53	214.61	432.78	2156	0.00	181.87	406.89	2176	0.00	149.13	381.00
2117	44.11	245.71	457.38	2137	11.92	212.97	431.49	2157	0.00	180.23	405.60	2177	0.00	147.50	379.70
2118	42.50	244.07	456.09	2138	10.31	211.34	430.19	2158	0.00	178.60	404.30	2178	0.00	145.86	378.41
2119	40.89	242.44	454.79	2139	8.70	209.70	428.90	2159	0.00	176.96	403.01	2179	0.00	144.22	377.11
2120	39.28	240.80	453.50	2140	7.10	208.06	427.61	2160	0.00	175.32	401.71	2180	0.00	142.58	375.82

Table 11.

Year	Low	Central	High	Year	Low	Central	High
2181	0.00	140.95	374.52	2201	0.00	108.21	348.63
2182	0.00	139.31	373.23	2202	0.00	106.57	347.33
2183	0.00	137.67	371.93	2203	0.00	104.94	346.04
2184	0.00	136.04	370.64	2204	0.00	103.30	344.74
2185	0.00	134.40	369.34	2205	0.00	101.66	343.45
2186	0.00	132.76	368.05				
2187	0.00	131.13	366.75				
2188	0.00	129.49	365.46				
2189	0.00	127.85	364.16				
2190	0.00	126.22	362.87				
2191	0.00	124.58	361.58				
2192	0.00	122.94	360.28				
2193	0.00	121.30	358.99				
2194	0.00	119.67	357.69				
2195	0.00	118.03	356.40				
2196	0.00	116.39	355.10				
2197	0.00	114.76	353.81				
2198	0.00	113.12	352.51				
2199	0.00	111.48	351.22				
2200	0.00	109.85	349.92				