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Ecosystem services delivery by large stature urban trees

Research Report

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Contents

Summary

This Research Report illustrates the change in provision of four ecosystem services (carbon storage, carbon sequestration, avoided storm water run-off and air pollution removal) through the life stages of large stature trees common to towns and cities in Great Britain. Provision of ecosystem services was calculated using the i-Tree Eco model. Field data for 3259 urban trees sampled in Great Britain from 10 i-Tree Eco surveys was used in conjunction with simulated trees where field data were not available. Aggregating the results according to an age classification approach for the 12 tree species (common ash, common beech, English elm, holm oak, Leyland cypress, lime spp., London plane, Norway maple, oak spp., Scots pine, sycamore and wych elm) demonstrated both a change in ecosystem services provision over the lifespan of these tree species and a relative difference between tree species. The results indicate that young trees (with a trunk diameter of <15 cm) of all species provide low amounts of ecosystem services. Ecosystem services provision increased as the trees matured, most notably between the semi-mature and mature age classifications. The results demonstrate the importance of allowing large stature trees to attain maturity in order to maximise ecosystem service provision in the urban environment.

Introduction

Urban forest is defined as 'all the trees in the urban realm – in public and private spaces, along linear routes and waterways and in amenity areas. It contributes to green infrastructure and the wider urban ecosystem' and can provide a range of services that help alleviate problems associated with urbanisation (Urban Forestry and Woodlands Advisory Committees Network, 2016; Davies *et al.*, 2017). They improve local air quality, capture carbon, reduce flooding and cool urban environments. Urban forests provide habitats for animals and can improve social cohesion in communities (Davies *et al.*, 2017). These benefits are widely referred to as ecosystem services, and have been classified as supporting, provisioning, cultural, and regulating ecosystem services (Millennium Ecosystem Assessment, 2005). Supporting services include essential natural processes such as nutrient recycling and soil formation. Provisioning services refers to the supply of products such as food and raw materials. Cultural services arise through the interaction of humans with environmental spaces, and they are grouped into six categories: health; nature and landscape connections; education and learning; economy; social development and connections; and symbolic and cultural significance (O'Brien and Morris, 2013). Regulating services are those that help balance the ecosystem. These include carbon storage, carbon sequestration, flood risk mitigation and air pollution removal (Millennium Ecosystem Assessment, 2005; Davies *et al.*, 2017).

The extent to which urban trees deliver regulating ecosystem services can be quantified with tools such as i-Tree Eco (www.itreetools.org/eco/); i-Tree Eco was developed by the US Department of Agriculture Forest Service to describe the structure and composition of urban forests, to quantify a range of ecosystem services provided by urban trees, and to inform future management of the urban forest. By quantifying and valuing some of the ecosystem services provided by trees, i-Tree Eco provides a valuable insight into urban trees, their importance to urban society, and a rationale for their protection and maintenance. By January 2018, i-Tree Eco surveys had been carried out in 22 urban areas across Great Britain. Gathering together the survey data from these studies creates a rich database of urban trees in Great Britain. This database includes many common species at different stages of maturity and condition that can be used to assess the ecosystem services provision of urban trees and how it varies over their lifetimes. Such information can help guide management of urban forests, as ecosystem services delivery can vary by species, stature, condition and location (Davies *et al.*, 2017). The location of planting not only affects the growth of trees, it also influences the demand for different services. For example, trees in areas of higher precipitation will intercept greater amounts of rainfall, thereby providing a greater service in that area. Therefore, decisions on which trees to plant, where to plant them and how to manage them, as well as external factors such as climate and pest and disease outbreaks, all affect the ecosystem services delivery of urban forests.

This Research Report is the first of two investigating how regulating ecosystem services provision varies with tree stature and age. The focus of this report is large stature tree species, defined as a species for which a healthy, isolated 20-year-old specimen growing in good soil conditions is typically over 12 m high (Stokes *et al.*, 2005); note that it is the species that is defined herein as being of large stature, and not the tree: it is independent of age. A second Research Report will focus on ecosystem services provision by small and medium stature tree species. By reporting ecosystem services provision over the lifetime of a tree and comparing it to trees of similar stature, these reports can help to inform species selection for future tree planting, as well as the preparation of local authority urban tree management plans to enhance the benefits that society receives from the urban forest.

Specifically, this study aims to:

- model ecosystem services provision over the lifetime of a range of large stature tree species common to the urban environment of Great Britain, based on calculations incorporated within the i-Tree Eco tool;
- assess how ecosystem services provision changes under different climate regions of Great Britain.

Methodology: quantifying ecosystem services provision by large stature trees

Data collection

Data from 10 i-Tree Eco surveys conducted across Great Britain between 2010 and 2016 were used in this study (Table 1); i-Tree Eco uses a standardised field collection method which is described in the i-Tree Eco version 6.0 Field Manual (www.itreetools.org). All of the measurements in each of these i-Tree Eco studies were carried out as defined in the manual. The consistency in field data collection methodology provides confidence in the analysis of the tree data as a contiguous dataset. Therefore, the data from the 10 surveys were collated into a single database, totalling 8881 trees. Table 2 presents a description of the key parameters included in the database that are used by i-Tree Eco when modelling ecosystem services provision.

Species selection

The most common tree species found in the i-Tree Eco surveys were selected from the unified database as those species with more than 40 trees represented, and grouped according to stature following Stokes *et al.* (2005) and the Royal Horticultural Society (2016). Fourteen of these tree species were categorised as large stature and extracted into a discrete dataset containing 3273 surveyed trees. The tree species considered in this study are presented in Table 3. Due to species similarity, some species were grouped for the purpose of this study: pedunculate oak and sessile oak are aggregated as oak spp. and small-leaved lime and common lime are aggregated as lime spp. Prior to analysis, a quality check was carried out for incorrectly entered or missing data: 14 trees were removed due to missing data or data inconsistencies that could not be reconciled. This left a final sample of 3259 surveyed trees.

Table 1 List of the i-Tree Eco studies used in this study.

i-Tree Eco study	Reference
Bridgend	Doick *et al.*, 2016a
Area 1 Highways (Cornwall and South Devon)	Rogers and Evans 2015
Edinburgh	Hutchings, Lawrence and Brunt, 2012
Glasgow	Rumble *et al.*, 2015a
Greater London	Rogers *et al.*, 2015
Southampton	Mutch *et al.*, 2017
Tawe catchment (encompassing Swansea City and the towns of Neath Port Talbot and Powys)	Doick *et al.*, 2016b
Torbay	Rogers, Jarratt and Hansford, 2011
Victoria Business Improvement District	Rogers, Jaluzot and Neilan, n.d.
Wrexham	Rumble *et al.*, 2015b

Table 2 Descriptions of tree characteristics and environment used within i-Tree Eco to estimate ecosystem services delivery.

Parameter	Description
Diameter at breast height (cm)	The diameter at breast height of the tree at 1.37 m above ground
Height (m)	The tree height measured using a clinometer
Crown width (m)	The width of the tree crown, an average of the measured width along the north-south and east-west axes.
Percentage dieback (%)	Estimated percentage of crown area showing bare and dead branches; this does not include natural dieback from self-pruning due to shading.
Crown light exposure	The number of sides of the tree exposed to sunlight, including the four sides and the top; ranges from 0–5, where a score of 5 indicates that all four sides of the tree and the top are exposed to sunlight.

Table 3 The large stature tree species commonly occurring in towns and cities of Great Britain used in this study.

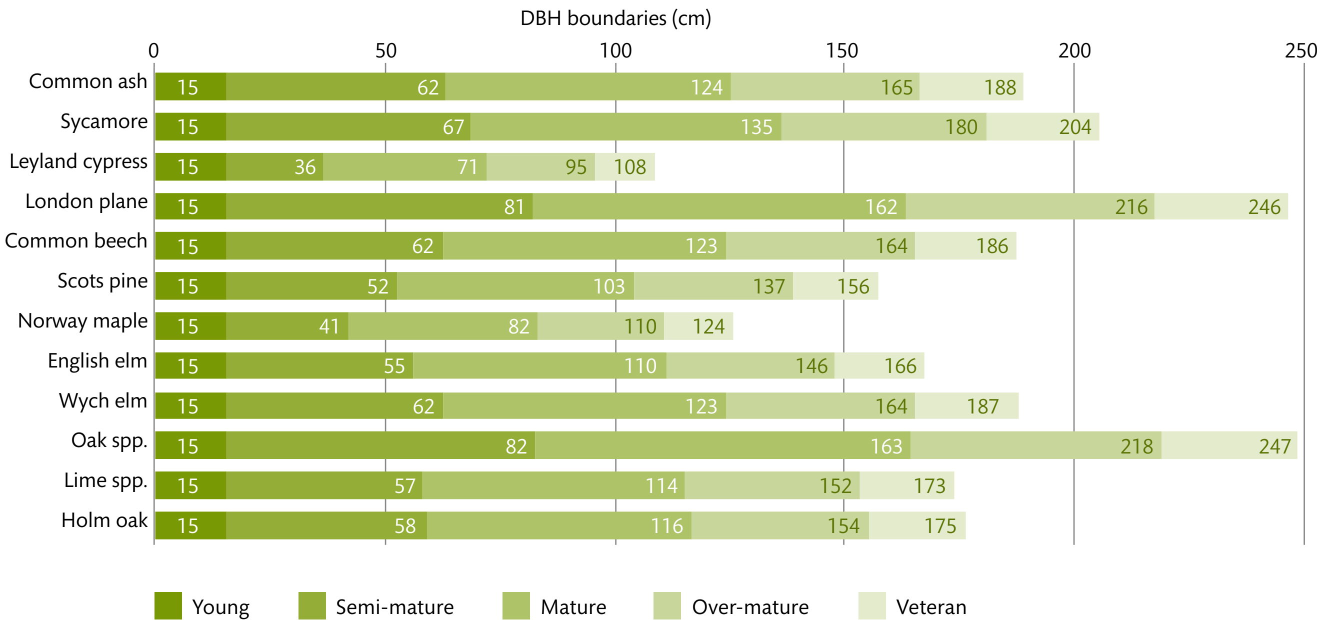
Common name	Scientific name
Common ash	*Fraxinus excelsior*
Sycamore	*Acer pseudoplatanus*
Leyland cypress	*Cupressocyparis leylandii*
London plane	*Platanus x acerifolia*
Common beech	*Fagus sylvatica*
Scots pine	*Pinus sylvestris*
Norway maple	*Acer platanoides*
English elm	*Ulmus procera*
Wych elm	*Ulmus glabra*
Oak spp. Pedunculate oak Sessile oak	*Quercus spp.* *Quercus robur* *Quercus petraea*
Lime spp. Small-leaved lime Common lime	*Tilia spp.* *Tilia cordata* *Tilia x europaea*
Holm oak	*Quercus ilex*

Age classification

Ecosystem service delivery varies over the lifetime of a tree (Nowak *et al.*, 2008). To illustrate these changes, two approaches were used, namely, trunk diameter (diameter at breast height) and age classification. First, measurements of trunk diameter were used as an indicator of tree age (White, 1998) because information regarding the age of urban trees is rarely available (McPherson, Van Doorn and Peper, 2016). This approach was used to assess the strength of relationship between tree diameter at breast height (DBH) as a proxy of time and ecosystem services delivery. Second, age classification was used to enable comparison of ecosystem services provision for tree species with different potential maximum ages.

For the age classification approach, the lifespan of a tree was initially described according to three phases: early life, maturity, and over-maturity. Each phase was assigned a DBH range based upon the maximum achievable size and age recorded for each species in Great Britain (i.e. a champion tree) (Mitchell, 1974; Mitchell, Schilling and White, 1994). The early life phase was identified as a DBH of up to 33% of the champion tree DBH, mature as a DBH of 33–66% of the champion tree DBH, and over-mature as a DBH of 66–100% of the champion tree DBH. Next, the early life phase was divided into young (<15 cm) and semi-mature (>15 cm to 33% of the champion tree DBH). Finally, the over-maturity phase was divided into over-mature (66–88%) and veteran (88–100%), thus providing a total of five age classifications, which were named young, semi-mature, mature, over-mature and veteran. Using tree size as an indicator of tree age to define age bands mirrors the approach of Lukaszkiewicz and Kosmala (2008), and enabled each tree from the database to be assigned to an age classification according to their DBH. The DBH boundaries for each species are provided in Figure 1. The age classifications enable the estimated ecosystem services provision of the

Figure 1 DBH boundaries calculated by age classification for each species. The numbers within bars represent the upper limit of that particular range.

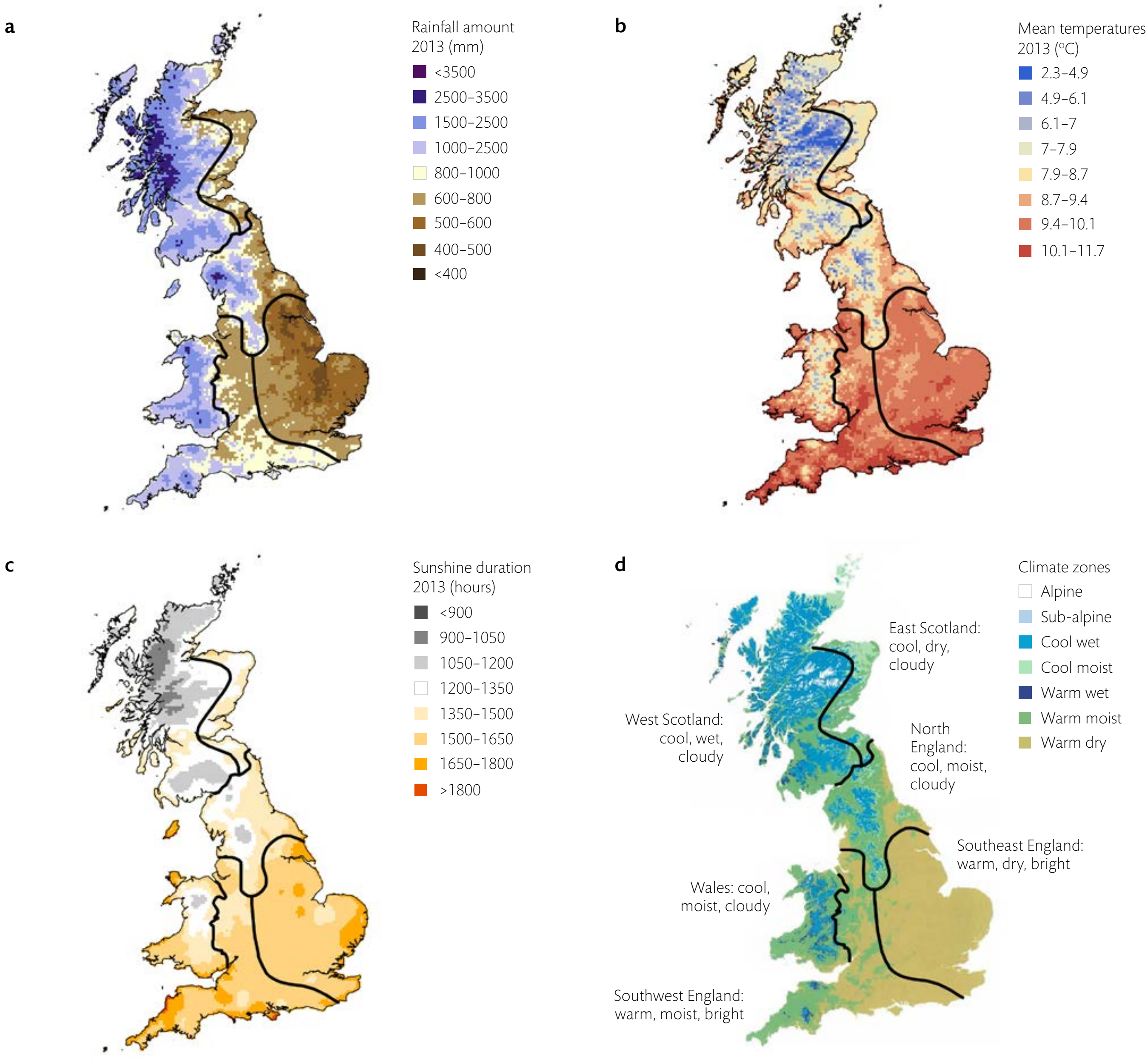


field sampled trees, calculated using the i-Tree Eco model (see Modelling ecosystem service delivery using i-Tree Eco, page 5), to be summarised. Ecosystem services provision throughout the lifespan of each tree species can then be assessed across the five age classifications

Classification of climate regions in Great Britain

To demonstrate the variation in ecosystem services provision with regard to changes in climate across Great Britain, the country was segmented into zones. Maps of the annual averages for each of temperature, rainfall and sunlight hours in Great Britain were collected for 2011–2015 (Met Office, 2016). A climate zone map based on accumulated temperature and moisture deficit was also gathered for comparison (Pyatt, Ray and Fletcher, 2001). The climate zones were selected first along political boundaries, to provide ease of comparison for each country, then second by visual comparison of the four maps listed. In this way six climate zones were formed. These maps and selected climate zones are shown in Figure 2.

Figure 2 (a) Annual total rainfall for 2013 (Met Office, 2016); (b) annual mean temperature for 2013 (Met Office, 2016); (c) total hours of sunshine for 2013 (Met Office, 2016); (d) climate zone classifications (Pyatt, Ray and Fletcher, 2001).



Note: Met Office maps were chosen for 2013 as this is the weather dataset used within i-Tree Eco, and all the maps were overlaid with the climate region division lines selected for this study.

Scotland was divided into two areas: the cold-wet west and the cool-dry east (Figure 2). The division broadly marks a sunlight exposure boundary of 1200–1350 hours per year, and an annual rainfall boundary of approximately 1000–1500 mm (based on 2011–2015 Met Office measurements, 2016; Figure 2).

England was divided into three areas. The north was separated from the south along the Humber and the bottom of the Pennines, broadly representing a 9–11°C annual average temperature, where north of this boundary is typically cooler than to the south of it (as an annual average based on 2011–2015 Met Office measurements, 2016). Next, the warmer southern portion of England was then divided according to rainfall. The east of the country is generally dryer than the west and was divided by a broad boundary at 600–800 mm annual rainfall (Figure 2). For the colder northern portion of England, although there is a similar division in rainfall as seen in the south between east and west, a lack of weather station data within i-Tree Eco for this region meant that no further division could be made.

Wales was not subdivided because its climate does not vary significantly among its major urban population areas, which are generally located along the coast (Figure 2). The Welsh climate zone was characterised by an average annual rainfall of approximately 1000–1500 mm, a mean annual temperature of 9–11°C, and a sunlight exposure boundary of approximately 1500–1650 hours per year (Figure 2).

Modelling ecosystem service delivery using i-Tree Eco

The quantification of ecosystem services delivery was performed in i-Tree Eco version 6.0.6; i-Tree Eco contains a database of weather and pollution data from 2013 for locations across Great Britain. Ecosystem services provision by urban trees was modelled for a single urban area in each of the six climate regions (i.e. six model runs per tree species). The results for each single urban area were assumed to be representative for that region.

i-Tree Eco utilises the data collected in the field to model each individual tree's leaf area, biomass, basal area, crown projection and general condition. Together with the in-built climate, air pollution and phenology data, ecosystem services provision is then modelled. Table 4 provides a summary of how each ecosystem service is estimated; a complete methodology is provided in Nowak *et al.* (2008) and the i-Tree manual (i-Tree, 2016). The ecosystem services modelled by i-Tree Eco which are robust for reporting within Great Britain (Rogers, Jarratt and Hansford, 2011; Natural England, 2013) are carbon storage (both above and below ground), gross carbon sequestration, avoided storm water run-off, and air pollution removal. Gross carbon sequestration is calculated from the change in tree biomass between each year, and does not take into account tree death or decay (Nowak and Crane, 2002). Air pollution removal is quantified for ozone, sulphur dioxide, and oxides of nitrogen and particulate matter which are less than 2.5 µm ($PM_{2.5}$), and are reported both individually and as a total by i-Tree Eco; total pollution removal values are used herein. The i-Tree Eco model returns an output for each

Table 4 Description of input variables used within i-Tree Eco to calculate carbon storage, gross carbon sequestration, avoided storm water run-off and air pollution removal.

Ecosystem service	Parameters	Calculation description
Carbon storage	Species, DBH, total height, land use, crown width, crown height, % crown missing	Yearly increases in total tree biomass (excluding leaves for deciduous species) are estimated through species-specific annual growth increments which are then converted into above and below-ground carbon storage.
Gross carbon sequestration	Species, DBH, total height, land use, CLE, crown health	Calculated as the change in carbon storage from this year to the next; it does not account for CO_2 emissions due to decomposition after the tree dies.
Avoided run-off	% tree cover, species, total height, crown base height, crown width, % crown missing	Leaf area is calculated from species and crown parameters and assessed with existing relationships to estimate interception of rainfall.
Air pollution removal	% tree cover, species, total height, crown base height, crown width, % crown missing	Leaf area is calculated from species and crown parameters and assessed with existing relationships to estimate the interception of air pollutants.

Note: A simplified description of the calculation performed in i-Tree is provided (after: i-Tree, 2016). For detailed descriptions of each calculation refer to Nowak *et al.* (2008).

ecosystem service for each tree. These data were grouped by species and the mean average determined for each age classification, unless otherwise stated.

i-Tree Eco allows for the monetary evaluation of services, but this is not reported here. In i-Tree Eco, valuation is simply the quantity of ecosystem service provided multiplied by the unit value for that ecosystem service. For example, litres of rainfall intercepted multiplied by a water treatment company's referenced unit cost of treating surface water run-off. Such unit costs vary over time, typically increasing annually, as is the case for water treatment and the value for a tonne of carbon sequestered. Furthermore, the cost may vary regionally or locally, as is the case for the treatment of surface water run-off. Economic values of the quantified ecosystem service are therefore not presented in this report.

In addition to the database of field-sampled trees, data were generated for simulated trees for each age classification of each species and modelled within i-Tree Eco (as above). The ecosystem services provision of simulated trees was used to project ecosystem services provision for trees where no field data were available. For modelling, DBH was set as the mean DBH for each age classification range; condition was set to 5% dieback, except for the veteran age classification, where dieback was set to 20%; and crown light exposure (CLE) was set to 4, representing an obstruction to sunlight exposure on one side of the tree canopy, a common situation for urban trees and typical of the field-surveyed trees. Canopy width was not defined but was calculated within i-Tree Eco from DBH. The simulated tree results for each age classification were summarised as the average value for that classification, as in the field data trees.

To assess ecosystem services delivery, all 3259 field trees and all simulated trees were modelled in the southwest England climate. The strength of the relationship between tree DBH and ecosystem services delivery was investigated by selecting best-fit trendlines. The regression coefficient (R^2) was determined in 'R' (R Core Team, 2017) and reported as a measure of data variability around the trendline. For ecosystem services delivery against different age classifications, the mean value for each age classification was reported. The field trees were then also modelled in the other five climates of Great Britain to assess the role of regional climate in ecosystem services delivery. Comparisons among climates were assessed using a repeated measures analysis of variance (ANOVA) with Tukey's post-hoc test in R. Ash and sycamore were selected for this comparison because both were recorded in each of the 10 i-Tree Eco surveys, indicating suitability to climates across all of the English, Scottish and Welsh urban areas.

Results

Descriptive statistics of surveyed trees

Table 5 presents descriptive statistics for mean tree height, leaf area and % crown dieback for each tree species by age classification; % crown dieback (an indicator of tree health) and height are both field measurements used in i-Tree Eco to estimate total canopy area. Taller trees with wider crowns and less crown dieback have larger canopy areas. Leaf area is related to canopy area and is calculated within i-Tree Eco based on the tree's field measurements. Leaf area is a strong determinant of the ability of a tree to deliver ecosystem services (McPherson *et al.*, 1997). Field trees in our dataset were found to increase in height and leaf area with successive age classifications, while crown dieback did not show a clear trend with increasing age classification.

For example, between the young and mature age classifications of beech and London plane, height increased from 8 to 21 m and 7 to 22 m, respectively, and leaf area from 31 to 658 m^2 and 198 to 1161 m^2, respectively. These positive trends in height and leaf area age class were common to all species. Five species showed increasing dieback with each successive age classification (ash, English elm, holm oak, Scots pine and sycamore) while for wych elm and London plane dieback declined with age (Table 5). For the other five species (beech, Leyland cypress, lime spp., Norway maple and oak spp.), dieback increased between the young and semi-mature age classification before decreasing again.

Sample sizes varied between species and also between age classifications (Table 5). Sample sizes were large for many of

Table 5 Descriptive statistics of surveyed tree data for each species.

Species (sample size)	Mean % dieback (sample size)					Mean height (m)					Mean leaf area (m^2)*				
	Y	SM	M	OM	V	Y	SM	M	OM	V	Y	SM	M	OM	V
Ash (677)	1.7±0.4 (333)	3.2±0.5 (323)	8±2.5 (21)	-	-	9.7 ±0.1	15.3 ±0.3	20.8 ±1.3	-	-	29 ±1.6	153.4 ±9	477.2 ±50.1	-	-
Beech (193)	4.9±1.9 (62)	6.7±1 (121)	2.1±1.4 (10)	-	-	8.3 ±0.5	15.1 ±0.5	20.7 ±2.3	-	-	33.6 ±3.5	186.1 ±13.6	657.5 ±146.9	-	-
English elm (48)	0.3±0.2 (26)	7.4±3.7 (22)		-	-	7.9 ±0.5	10.1 ±0.6	-	-	-	17.2 ±2.1	87.1 ±21.5	-	-	-
Holm oak (57)	0 (14)	0±0 (39)	4.5±4.5 (4)	-	-	6 ±0.5	9.2 ±0.4	13.8 ±2.3	-	-	12.4 ±1.9	78.4 ±10.9	372.4 ±94.6	-	-
Leyland cypress (378)	3.2±0.7 (232)	5.8±1.8 (128)	14.3 ±4.6 (16)	0 (2)	-	3.4 ±0.1	6.4 ±0.4	13 ±1.3	17 ±5.1	-	10.7 ±0.6	40 ±4.8	152.7 ±21.0	578.7 ±188.4	-
Lime spp. (163)	1.1±0.8 (42)	7.2±2.5 (96)	1.9±1 (25)	-	-	5.6 ±0.3	12.1 ±0.6	18.1 ±1	-	-	43.1 ±5.5	212.8 ±20.3	605.7 ±60.9	-	-
London plane (389)	9±3.1 (22)	0.6±0.3 (244)	0.2±0.1 (123)	-	-	7.6 ±0.6	15.4 ±0.2	22 ±0.3	-	-	197.6 ±118.9	479.5 ±31.5	1161.2 ±47.3	-	-
Norway maple (81)	0.1±0.1 (28)	3.3±1.6 (30)	1.3±1.0 (23)	-	-	7.3 ±0.4	11.3 ±0.6	17.2 ±1.3	-	-	21.2 ±4.3	325.1 ±33.2	511.3 ±55.6	-	-
Oak spp. (482)	6.3±1 (173)	8±0.7 (299)	3.9±1.2 (10)	-	-	7.9 ±0.2	15.4 ±0.3	27.9 ±2.3	-	-	29.3 ±3.6	171.6 ±8.8	810.7 ±149.1	-	-
Scots pine (80)	4±1.9 (21)	6.6±2.2 (42)	9.3±2.3 (14)	16.3 ±4.4 (3)	-	7.9 ±0.9	18.1 ±0.9	25.2 ±1.5	26.7 ±7.0	-	60.1 ±14.4	118.2 ±14.6	230.9 ±65.2	528.5 ±328.4	-
Sycamore (655)	5.2±0.2 (198)	4.5±0.5 (409)	8.3±1.6 (48)	-	-	8.2 ±0.2	14.1 ±0.3	20.7 ±0.8	-	-	36 ±2.7	194.9 ±11.1	576.6 ±28.2	-	-
Wych elm (56)	5.5±2.2 (31)	1.2±0.8 (24)	0±0 (1)	-	-	8.4 ±0.6	11.8 ±0.9	18.5 (-)	-	-	69.8 ±12.7	116.7 ±18	745(-)	-	-

* Leaf area is an i-Tree Eco modelled output based on field measurements.
Note: Data are presented by age classification: Y = Young, SM = Semi-mature, M= Mature, OM = Over-mature and V = Veteran. Mean values are ± 1 standard error. Numbers presented in parenthesis are the sample size. A dash (-) represents where survey data was not available for that age classification.

the species, especially in the young and semi-mature age classifications. For example, several hundred in the case of ash, oak spp. and sycamore. Sample populations are more modest – tens of samples – for other species, including holm oak, Norway maple, Scots pine and elm. Fewer trees were found in the mature age classification than the younger classes and, despite the large initial number of trees in the database, only five trees were found in the over-mature age classification and none in the veteran age classification reflecting the lack of larger, older trees in urban areas (London Assembly, 2007).

Association between ecosystem service delivery and DBH

In this section, variability in modelled ecosystem services delivery was explored to demonstrate the suitability of this approach for modelling ecosystem services provision over the course of a tree's lifespan, using DBH as a proxy for change in time. Results showed that ecosystem services provision by the 12 different species changed in the same relative order in each of the climate regions investigated (data not shown); therefore, only the results for southwest England are shown, presented in Figures 3 and 4, where only three species are illustrated in each plot to ensure clarity. The species presented in this section provide a representative picture of the data variability observed. For a full comparison of differences in ecosystem services provision among tree species refer to the Ecosystem service provision by large stature tree species in urban environments section, page 9.

Figure 3a shows modelled carbon storage against time for ash, London plane and Scots pine. For each tree species the results showed a low level of variation in estimated carbon stored by each tree of similar size and species, and the trendlines indicated that a very high proportion of the variability in modelled carbon storage was associated with DBH (R^2 = 0.99). Similarly, trendlines for the relationship between carbon storage and increasing DBH accounted for a very high degree of the variability for each of the other eight tree species under consideration (R^2 = 0.99; data not shown).

Figure 3b shows the variability in the modelled carbon sequestration rate with increasing tree DBH for London plane, oak spp. and sycamore. The trendlines indicated that carbon sequestration increased to a peak (when tree growth is fastest), after which it declined with increased DBH. Across the 12 species considered, the trendlines explained a high proportion of the variability in the data (R^2 ranged from 0.71 for London plane to 0.96 for Scots pine; median = 0.82, data not shown). The variation visible in Figure 3b within species was primarily due to tree condition and different CLE values, which are used in i-Tree Eco to estimate growth (Nowak *et al.*, 2008).

Figure 4a presents the increase in avoided storm water run-off ecosystem services provision with increasing DBH for English elm, lime spp. and Norway maple. Figure 4b presents the pollution removal values for beech, Leyland cypress and wych elm against increasing DBH. Considerable variation was observed in the spread of data around the trendline in both Figures 4a and 4b; this was represented in the moderate R^2 values reported. The median R^2 value for all species was 0.58 for avoided run-off and 0.58 for pollution removal (data not shown). The higher variation associated

Figure 3 (a) Carbon storage and (b) gross carbon sequestration of individual trees, modelled for southwest England.

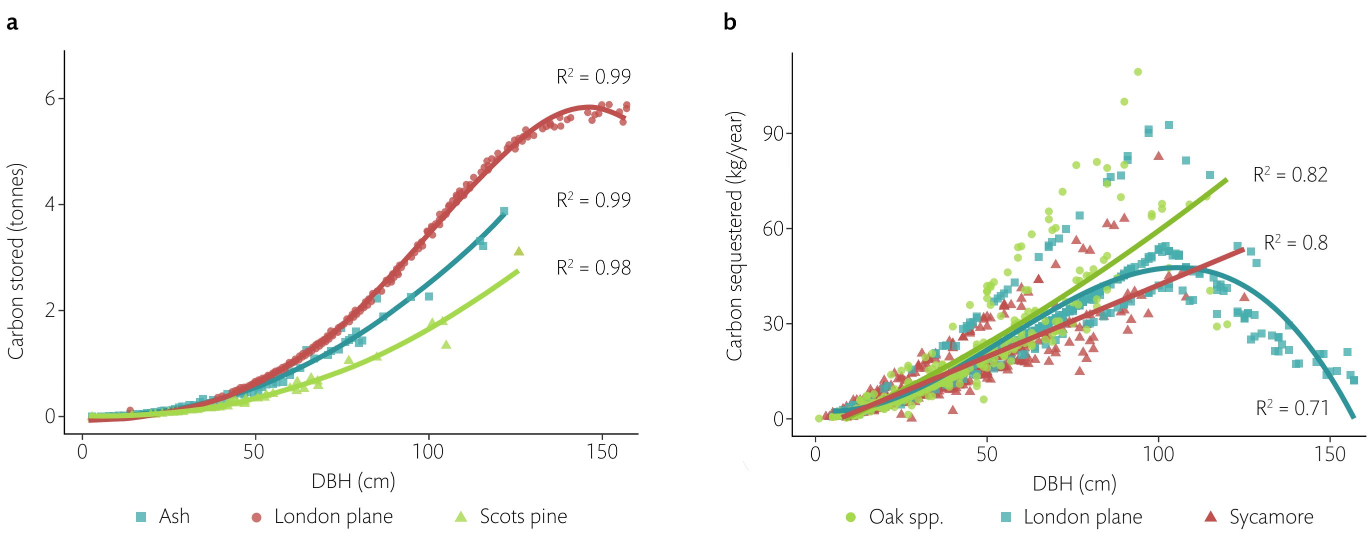
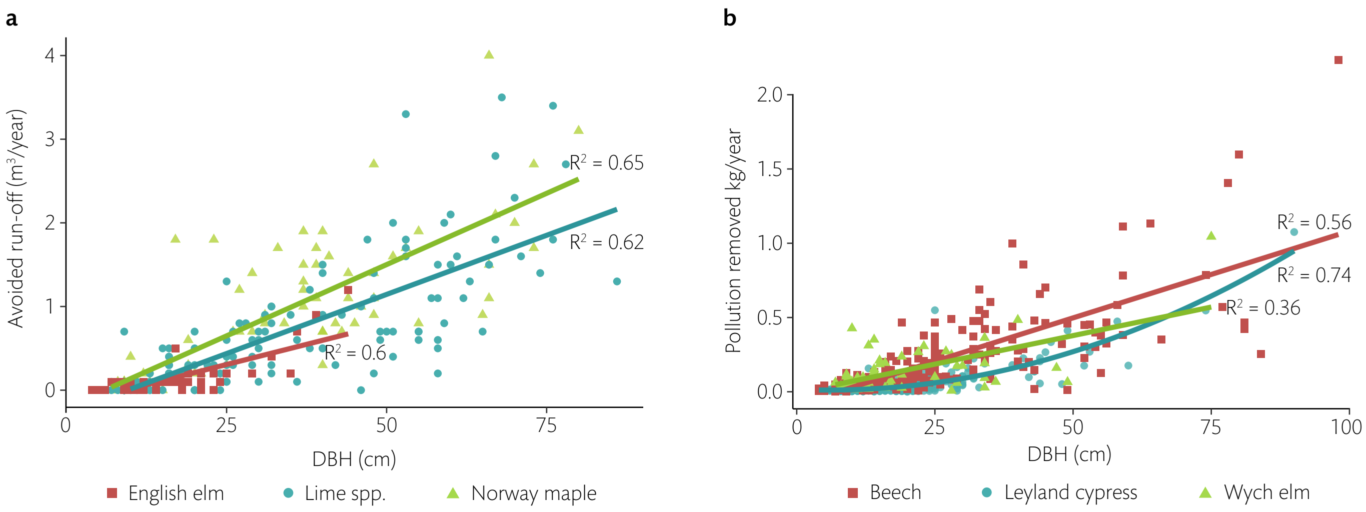


Figure 4 (a) Avoided storm water run-off and (b) pollution removal for a subset of the species studied, modelled for southwest England.



with delivery of these two ecosystem services than observed in Figure 3 was due to leaf area variability (as illustrated in Table 3) and may be linked to tree health, and thus canopy dieback, or management practices such as pruning or pollarding that reduce crown size. In each case, the data indicated that avoided storm water run-off and pollution removal capacity of trees increases with the size and age of a tree, although local factors will have a significant impact on the amount of service that each tree will deliver.

Ecosystem service provision by large stature tree species in urban environments

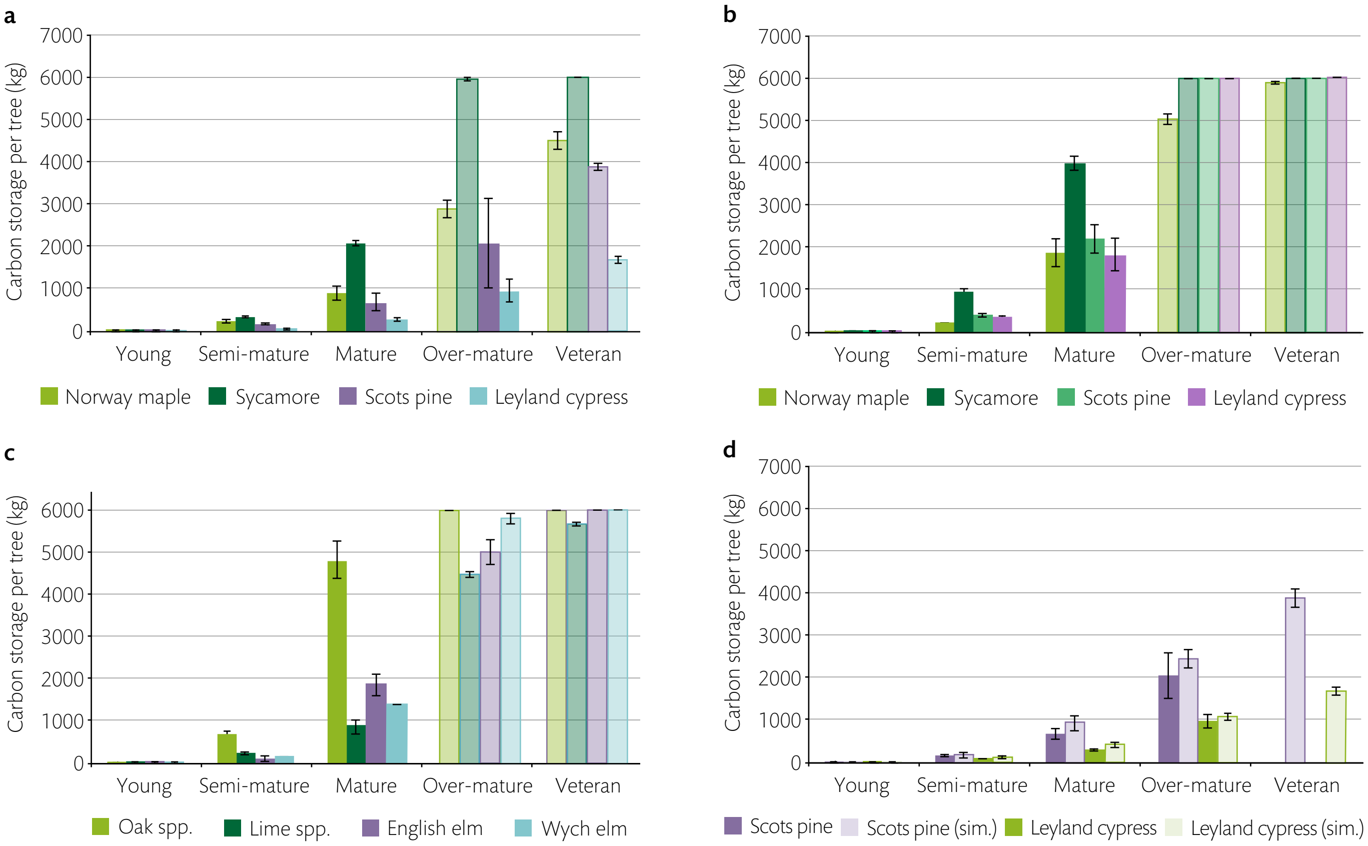
In this section, ecosystem services provision by 12 large stature tree species common to towns and cities in Great Britain is presented. The data presented are the average of each tree species in each of the five age classifications, based upon the database of field-sampled trees. Results are presented for the southwest England region only. Where field data were not available for a particular age classification, values are those determined for a simulated tree (see the Modelling ecosystem service delivery using i-Tree Eco section, page 5).

Carbon storage

Figures 5a–c show the above-ground carbon storage for each of the 12 tree species modelled. The data demonstrate that the amount of carbon stored was low in the young and semi-mature age classifications, and highest in the over-mature and veteran classifications. Carbon storage is proportional to tree volume and therefore was expected to increase as it gained in girth and height with increasing age (Yoon *et al.*, 2013). For most of the species modelled, carbon storage increased with each successive age classification, slowly in some species (e.g. wych elm and Scots pine) and faster in others (London plane and oak spp.). In some species, carbon storage peaked in the over-mature age classification and remained static into veteran age (e.g. sycamore and London plane), based on data from simulated trees. In the mature age classification, oak spp. and London plane stored the most carbon: i-Tree Eco predicted that each species stored on average more than 3000 kg of carbon per tree.

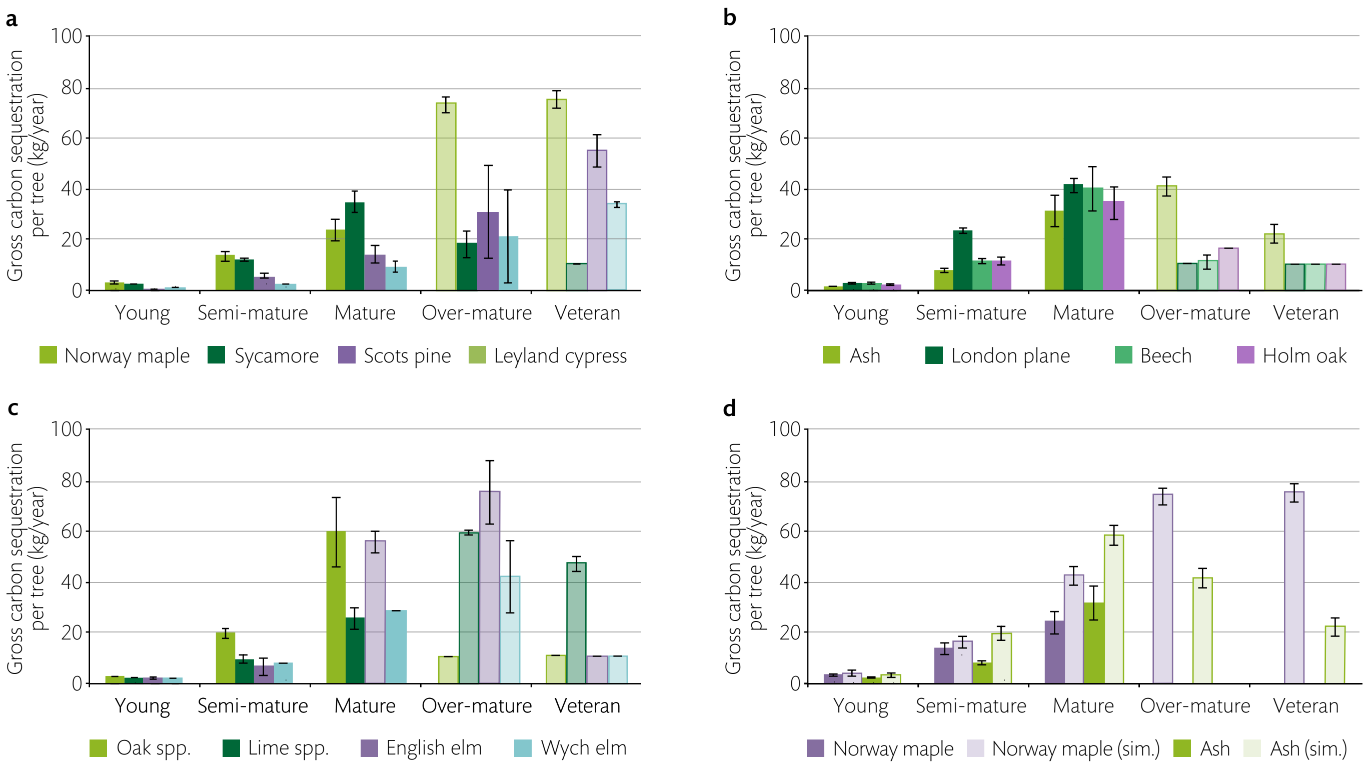
Figure 5d presents the modelled carbon storage of Scots pine and Leyland cypress across all age classifications for both field-sampled and simulated trees. The results were comparable between the field-sampled and the simulated trees in the early age classifications, but then simulated trees were estimated as higher in the mature and over-mature age categories compared with field-sampled trees. In the comparable age classification, simulated trees indicated higher estimated carbon storage than field-sampled trees. This difference may be due to the fact that the average simulated tree was around 9% larger (by DBH) in the semi-mature to over-mature age classifications in both species, and also that in some age classifications field-sampled trees were in a poorer condition than simulated trees (Table 5). For example, Scots pine field-sampled trees had higher crown dieback than simulated trees in the mature and over-mature categories, while Leyland cypress field-sampled trees had greater dieback in the mature classification.

Figure 5 Carbon storage per tree for each species. Surveyed data in solid bars and simulated (sim.) data in tinted bars; part (d) highlights species where simulated values differ slightly from the trends seen in the field data.



Note: Bars are shown ± 2 standard error of the mean. For values missing error bars, trees have reached a plateau in value with no change in stored carbon as trees age.

Figure 6 Gross carbon sequestration per tree for each species. Surveyed data in solid bars and simulated (sim.) data in tinted bars; part (d) highlights species where simulated values differ slightly from the trends seen in the actual data.



Note: Bars are shown ± 2 standard error of the mean.

Gross carbon sequestration

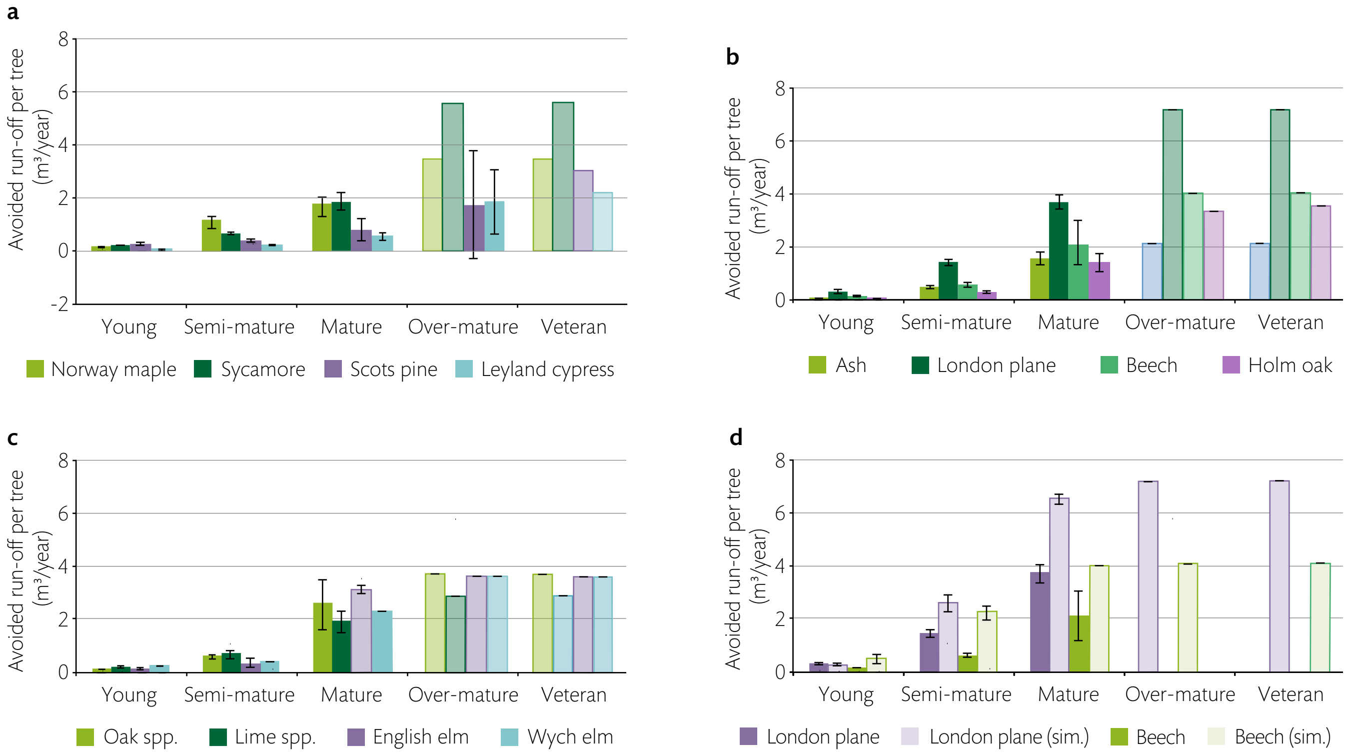
Figure 6 presents the gross annual carbon sequestration rate for the 12 species studied. Figures 6a–c show the results from the modelling of field data, including simulated tree data where field data were not available. For the field-sampled trees, gross carbon sequestration rate increased with age. The modelled ecosystem services provision for simulated trees suggests that carbon sequestration either peaked in the mature or over-mature age classification (e.g. sycamore, oak spp. and London plane) or continued to increase into the veteran age classification (Norway maple, Scots pine and Leyland cypress). The decline for some species in the older age classifications may represent the slowing of growth in older trees (White, 1998). The continued increase in carbon sequestration discovered for three of the species may indicate that the DBH boundaries for their age classification had been set too low, indicating that younger trees with a better carbon sequestration performance had been included in the older age classification. For all tree species, modelled carbon sequestration was lowest for the young age classification (<5 kg per tree per year). Most of the trees showed a small increase in modelled carbon sequestration between the young and semi-mature age classifications, followed by a larger increase between the semi-mature and mature age classifications. Oak trees sequestered the greatest amount of carbon in the mature age classification, on average 60 kg per tree per year.

Figure 6d provides a comparison between field-sampled and simulated trees for modelled sequestration rates in each of the age classifications for Norway maple and ash. For both species, the simulated trees exceeded the field data in all age classifications. This may be due to the shading reducing growth rates and consequently the carbon sequestration rates in the two species. Shading, as measured by CLE, was 2.7 for Norway maple and 1.7 for ash, whereas in simulated trees the CLE value was set to 4.

Avoided storm water run-off

By intercepting precipitation in their canopies, trees contribute to storm water flood risk mitigation in towns and cities (Xiao and McPherson, 2016). Larger trees typically had larger total leaf areas (Table 5), allowing greater quantities of rainfall to be intercepted. Figure 7 presents the change in the contribution of the 12 tree species to avoided storm water run-off as modelled in i-Tree Eco, and demonstrates an increase in their capacity to intercept precipitation with

Figure 7 Avoided storm water run-off per tree for each species. Surveyed data in solid bars and data from simulated (sim.) trees in tinted bars; part (d) shows data for field-sampled as well as values for simulated trees in each of the five age classifications.



Note: Bars are shown ± 2 standard error of the mean.

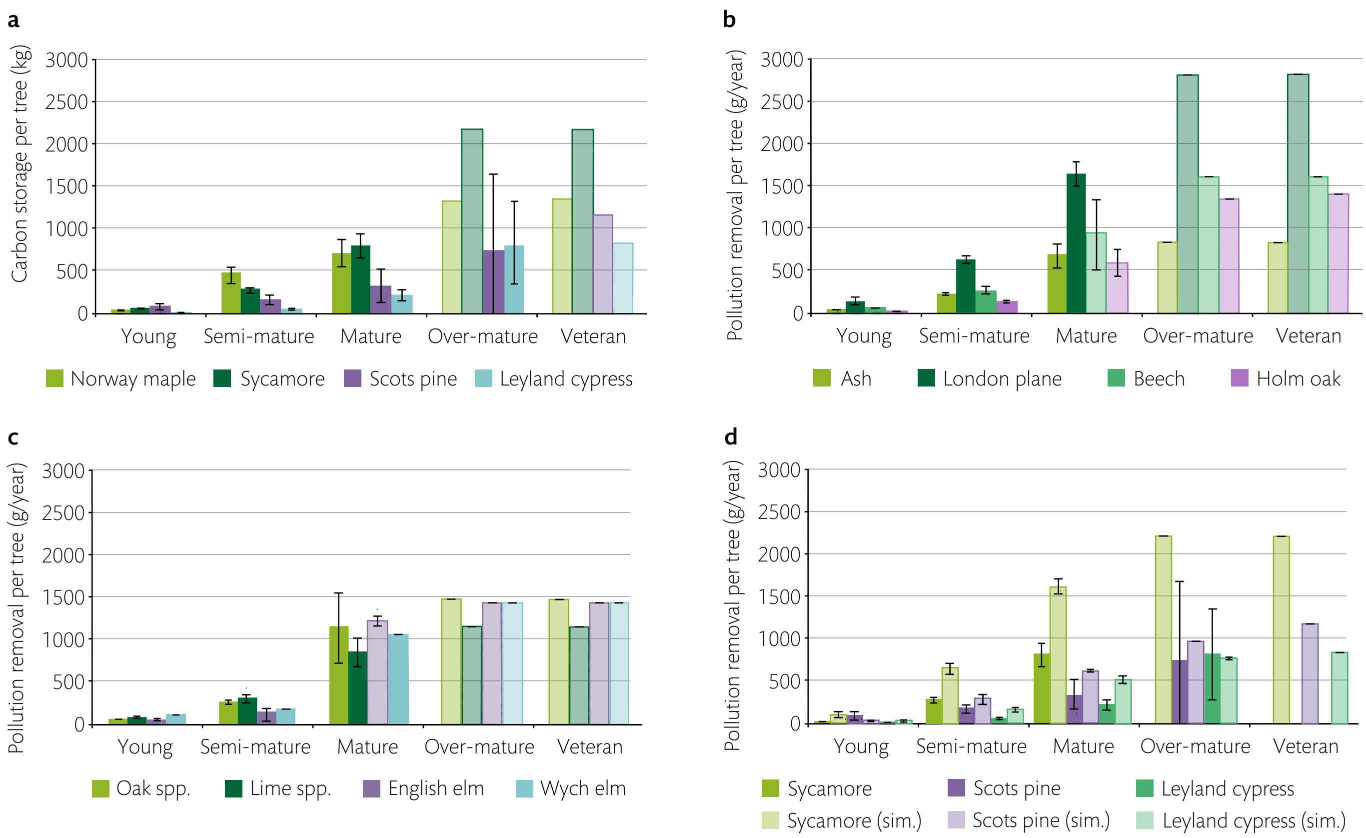
increased age classification. For example, modelled rainfall interception increased from <0.5 m^3 per tree per year for London plane, Leyland cypress, sycamore and Scots pine (Figure 7a) in the young age classification to 1.5 to 2 m^3 per tree per year in the mature age classification. The simulated data suggested that avoided run-off continued to increase into the over-mature age classification and then either plateau or show a further increase into the veteran category. Considering field-sampled data only, London plane intercepted the most precipitation on average at >3.5 m^3 per tree per year (mature category; Figure 7b). London plane, sycamore and beech were projected to intercept the greatest amounts of precipitation at >3.9 m^3 per tree per year (over-mature and veteran age classifications; model output for simulated trees, Figures 7b and 7c).

Figure 7d presents the modelled rainfall interception of London plane and beech for both field- sampled and simulated trees. The results indicate a higher level of ecosystem services provision by the simulated than the field-sampled trees and that, for instance, trees could be capable of intercepting more precipitation than shown by the survey data. For London plane the difference can be attributed to the presence of pollarded trees in the field survey dataset, a practice which can significantly reduce canopy size and is not considered in the simulated trees. Field-sampled semi-mature and mature London plane trees had approximately half the leaf area of that estimated for simulated trees. For beech, in the semi-mature and mature categories, the simulated trees were around 25% and 18% larger than the field-sampled trees, and they also had better canopy condition. Both of these factors resulted in greater modelled leaf areas and, thus, rainfall interception per tree.

Air pollution removal

Figures 8a-c show the combined field data and simulated tree modelled results for air pollution removal with increasing age. Results derived from field data indicated that most trees showed an increased capacity for pollutant removal with increasing age, a pattern that related to the change in leaf area with tree age as previously discussed. Incorporating the simulated results suggests that air pollution removal peaked in either the mature or over-

Figure 8 Air pollution removal per tree for each species. Model outputs for field-sampled trees are shown with solid bars, and simulated (sim.) trees are shown with tinted bars; part (d) shows data for field-sampled as well as values for simulated trees in each of the five age classifications.



Note: Bars are shown ± 2 standard error of the mean.

mature age classification, then remained stable into the veteran category. Four species were estimated to remove over 1 kg of air pollutants per year in the mature age classification, an average increase approximately 18 times the level of these species in the young age classification and four times that from semi-mature trees. While leaf area increases initially with age, there is a point when senescence commences, growth slows and leaf area may be reduced (Fay, 2002); this points approximately to the over-mature age classification in this study. Consequently, this trend is reflected in the stabilisation of the air pollution removal rate across the older age classifications in the simulated trees.

Figure 8d shows that the simulated pollutant removal rates for Scots pine, Leyland cypress and sycamore, and demonstrates that the values for the simulated trees exceeds those of the field- sampled trees in the young, semi-mature and mature age classifications. Field-sampled trees may have been performing more poorly than expected in comparison to the simulated trees because of various management practices that reduce crown size, or perhaps because these trees were located in areas with lower sunlight exposure than that modelled for the simulated trees. For instance, Leyland cypress is often grown as a hedge in the urban environment. In this situation, it has a CLE score of 3 in the middle of the hedge and 4 at the hedge-ends. Therefore, surveyed trees would have smaller canopies and total leaf area, and a reduced air pollutant removal capacity compared with simulated trees.

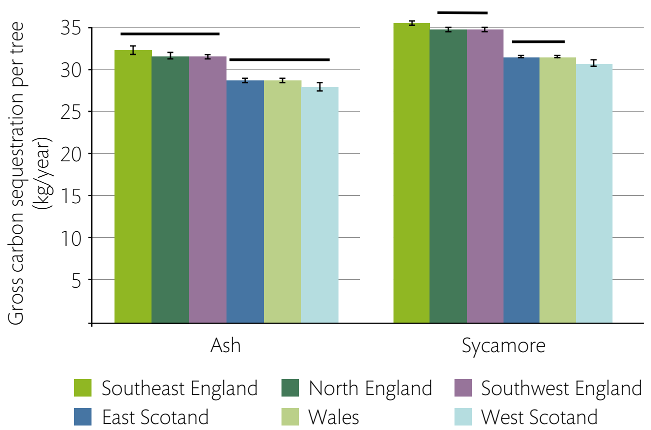
Regional variability in ecosystem services delivery

In this section, the results of modelling to assess the role of climate on ecosystem services provision are presented. Only field data were used in this comparison. The assessment compared how climate variations affected the ecosystem services carbon sequestration and avoided run-off delivered by 21 mature ash trees and 48 mature sycamore trees. Ecosystem services provision was assessed for both species in the six GB climate regions defined in the methodology. Carbon storage is not reported for clarity and because it is linked to carbon sequestration. Air pollution removal is not reported due to the complex interaction in the modelling process of regional climate and air pollution concentration, which also varies with non-regional factors such as urban area size. The difference in carbon sequestration and avoided run-off was compared.

Regional variability in gross carbon sequestration ecosystem services

The results for the gross carbon sequestration rate modelled for ash and sycamore in the six climate regions across Great Britain are presented in Figure 9. The results are shown for the mature classification, and showed minor variation across the six climate regions, with the sequestration rate approximately 10% higher in the three English regions than in Scotland or Wales. These results reflect the warmer and sunnier climates of the southwest, southeast and north England regions (Figure 2) that lead to a longer leaf-on/growing season and more time to sequester carbon (Nowak *et al.*, 2008). The statistical analysis identified significant differences between climate groups (also illustrated in Figure 9). For ash, greater carbon sequestration was identified in southerly and sunny locations in England than in locations in Scotland and Wales. For sycamore, there was a more gradual split, with southeast England sequestering the most carbon, followed by north and southwest England, then east Scotland and Wales, and finally the most northerly and wettest region, west Scotland.

Figure 9 Estimated gross carbon sequestration by ash and sycamore trees in the mature age classification in the six climate zones.

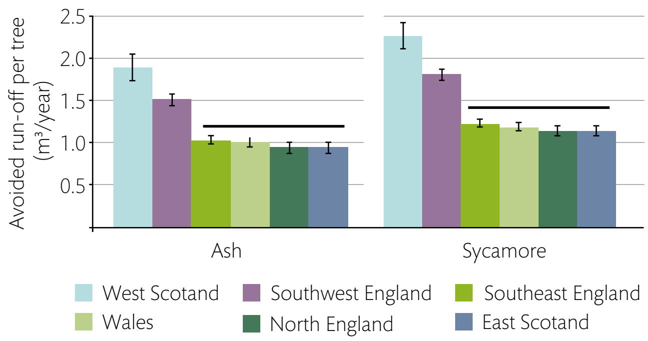


Note: The horizontal black lines indicate where regions are not significantly different ($p > 0.05$). Error bars are 95% confidence intervals calculated for within-subjects tests using the Cousineau–Morey approach (Bagueley, 2012).

Regional variability in avoided storm water run-off ecosystem services

The results of modelling the avoided storm water run-off by ash and sycamore in the six climate regions are shown in Figure 10. Precipitation is a key parameter in i-Tree Eco's calculations of storm water run-off, which helps explain the differences in the results between the different regions. The highest amounts of avoided storm water run-off per tree occurred in west Scotland and southwest England due to the greater rainfall in these regions. In comparison, avoided storm water run-off in Wales, east Scotland, southeast England and north England was lower, nearly half of that in west Scotland. Statistical analysis revealed significant differences in ecosystem services provision between the different climates for both ash and sycamore (Figure 10). For example, in west Scotland the trees provided significantly more avoided run-off ecosystem service than in other regions. For both species, no significant differences were found among southeast England, Wales, north England and east Scotland.

Figure 10 Avoided storm water run-off by ash and sycamore trees in the mature age classification in the six climate regions of Great Britain.



Note: The horizontal black lines above bars indicate where regions are not significantly different from each other ($p > 0.05$). Error bars are 95% confidence intervals calculated for within-subjects tests using the Cousineau-Morey approach (Bagueley, 2012).

Discussion

Suitability of approach

i-Tree Eco utilises the Urban Forest Effects (UFoRE) models (i-Tree, 2016). These models have been published in scientific literature and are used throughout the world to model ecosystem services provision by urban forests (www.itreetools.org); i-Tree Eco has been assessed as fit-for-use in GB (Natural England, 2013), that is, for assessing the composition of urban forests and quantifying the flow of ecosystem services from the urban trees therein. This focus on whole urban forest modelling is important with respect to the interpretation of results for single trees and small tree populations as presented in this report. When applied to a whole urban forest there is a smaller probability of bias than that which can arise from small sample numbers, given the inherent variability in urban trees. There is a smoothing (averaging) effect in the assessment of a whole urban forest population in comparison to single or small populations, and a greater probability that the modelled output is an accurate estimation of the amount of ecosystem services provision provided. In this study, the total tree dataset has been divided into age categories, of which some have a low sample size. Caution must therefore be taken when interpreting results.

The results presented in Figures 5–8 provide a modelled estimation of ecosystem services delivery by an average tree in each of the age classifications. While every effort was taken to model as large a population of trees as possible for this report, the population remains limited for some species and age classifications (Table 5). In particular, trees in older age classifications were infrequently found in i-Tree Eco field studies, as rare trees like veterans are less likely to be found using a randomly placed plot-sampling method. Because of the sample sizes involved, it is prudent not to apply the results of this study to individual trees in the urban realm that may be impacted by environmental or management factors which are different to those used within the scope of this study. To determine the ecosystem services provision of an urban tree or whole urban forest, the reader is referred to www.itreetools.org/eco/ to undertake their own analysis. The simulated tree dataset has been used to estimate ecosystem services delivery where no field trees were recorded. These results should also be considered as indicative, as these trees have been modelled under fixed values for CLE and crown condition, which can significantly affect ecosystem services provision.

The i-Tree Eco model differs in its approach to calculating carbon storage and sequestration to the carbon models used for the Woodland Carbon Code (WCC; Forestry Commission, 2018). Comparisons among estimates should be conducted with caution; i-Tree Eco requires data and models outputs at the scale of the individual tree. The WCC uses carbon models developed by Forest Research which estimate the average sequestration rate per hectare of even-aged trees. Furthermore, each is based on field data for trees growing in different environments: i-Tree Eco for urban, WCC for rural.

The assessment of data variability (see the Association between ecosystem service delivery and DBH section, page 8) revealed that there was a high level of predictability between estimated tree size and ecosystem services provision for each of the tree species investigated. This observation indicates that the results are useful for comparing ecosystem services provision by different tree species over their lifespans, and that where variations were present, because of factors including shading (CLE), canopy size and condition, these did not obscure the relationship between time and ecosystem services delivery. These relationships were strongest for carbon storage and carbon sequestration (Figure 3) but were weaker for avoided run-off and air pollution removal (Figure 4). The greater variation in avoided run-off and air pollution removal services was most likely related to variance in canopy size between trees in the same age classification. Canopy size and the health of the canopy (% canopy missing due to dieback) both affect the total leaf area of the tree and therefore the provision of these two ecosystem services. Total canopy size is also related to the total size of the tree (Vaz Monteiro, Doick and Handley, 2016), with variation also observed between species. For example, London plane had approximately double the leaf area of beech, ash and sycamore trees in the mature category, despite being of a similar height although with a slightly larger DBH (Table 5, Figure 1). Management practices can further impact total canopy size and therefore leaf area, suggesting that routine management in support of large healthy canopies can support ecosystem services provision. Trends of increasing ecosystem services provision with age were reasonable despite the intra-species variation observed, and give confidence when comparing trends and drawing conclusions on ecosystem services provision by urban trees for the 12 species being studied.

To enable comparison of ecosystem services delivery by large stature tree species which have different lifespans, two approaches were used: DBH (as a proxy for change in time) and age classification. DBH enabled the calculation of ecosystem services by different trees of the same species, to show both intra-species variability and the change in delivery with increasing tree size. Age classification allowed for the potentially very different lifespans of the 12 tree species to be taken into consideration, enabling direct comparisons among species which would otherwise not have been possible. Age class is a term used to represent distinct phases within the life-cycle of an average tree (e.g. young, semi-mature, mature or over-mature; BS5837, 2012); it is used by arborists to assess the relative condition, age and remaining lifetime of tree at that site, and different classifications may be utilised to suit the assessment method used and/or specific interest of the arborist. However, age class is not dependent solely on time, but also on location: for example, trees may be constrained from reaching maturity where conditions are not favourable. Borrowing from the age class approach, an age classification categorisation was devised for this study. This allows for trees to be apportioned into groups defined by DBH size and is specific for each of the 12 tree species. This approach means that young and mature trees of different species can be compared, even although they may be of different age or DBH. It is pragmatic to illustrate change in ecosystem services delivery over a tree's lifespan while also allowing for inter-species comparisons, including for small and medium stature trees (Hand, Doick and Moss, 2019).

The age classifications used in this report are novel: an approach applicable to the wide set of species studied has not been published previously, and it was challenging to set the DBH boundaries in order to define each category. This approach assumes that an individual healthy tree goes through a series of life stages from young through maturity to veteran. Published DBH values of champion trees were used to define a maximum attainable DBH and this was divided, as described in the Methodology, in order to set the DBH boundaries for each category. While champion trees are by definition unusually large trees for their species, comprehensive data were available for the species considered in this report (which is not the case for typical or attainable maximum DBH), and urban trees growing in parklands and cemeteries can attain similar sizes (Woodland Trust, 2019). The age classifications defined maturity based on tree size (DBH), and were based upon a rule of thirds (White, 1998), with the first and last third halved to present the rapid change from young to semi-mature in the first group and the rarity of over-mature and veteran trees, as captured in the third group. Different species may not all follow this division of age classifications; however, it was universally applied here in the absence of any precedent. The results presented for each age classification are the average of all the modelled trees within the group. This leads to an over-simplification in representing ecosystem services provision: trees of smaller DBH will deliver less of each of the ecosystem services than larger trees in the same age classification. Similarly, where an age classification was dominated by field-sampled trees of similar DBH (rather than DBHs across the full DBH range for that category), the results presented are biased towards those particular specimens.

Rating large stature trees according to ecosystem services delivery

This section discusses the results of the modelled estimations of the four ecosystem services for the 12 species common to urban environments in Great Britain and ranks them from best to worst performing for each ecosystem service (Table 6). This ranking is based on the results of modelling field-surveyed trees (unless otherwise stated) in the southwest England climate zone and is compared for each species in their mature age classification, in which ecosystem services provision peaked for most of the species investigated (according to field data results only).

Table 6 Species ranked by ecosystem provision by trees in the mature age classification.

Rank	Carbon storage	Gross carbon sequestration	Avoided run-off	Pollution removal
1	Oak spp.	Oak spp.	London plane	London plane
2	London plane	English elm#	English elm#	English elm#
3	Beech	London plane	Oak spp.	Oak spp.
4	Sycamore	Beech	Wych elm	Wych elm
5	Ash	Sycamore	Beech	Beech
6	English elm#	Holm oak	Sycamore	Sycamore
7	Holm oak	Ash	Lime spp.	Lime spp.
8	Wych elm	Wych elm	Norway maple	Norway maple
9	Norway maple	Norway maple	Ash	Ash
10	Lime spp.	Lime spp.	Holm oak	Holm oak
11	Scots pine	Scots pine	Scots pine	Scots pine
12	Leyland cypress	Leyland cypress	Leyland cypress	Leyland cypress

based on simulated trees due to the lack of mature trees in the field dataset

The top performers across all four ecosystem services were oak spp., London plane and lime spp., with English elm, beech and sycamore also performing well (Table 6). The highest ranked species for carbon storage and sequestration was oak spp., while London plane outperformed others for the ecosystem services of avoided storm water run-off and air pollution removal. London plane was found to have the greatest leaf area compared with other species (Table 5), which is the main factor determining avoided run-off and air pollution removal services. Previous studies have also found London plane to be above average for removing air pollutants (Yang, Chang and Yan, 2015). Leyland cypress and Scots pine consistently appeared at the bottom of Table 6. Oak spp. store 17 times the amount of carbon as Leyland cypress, and London plane provides seven times the amount of avoided run-off and air pollution removal than Leyland cypress. Leyland cypress and Scots pine typically had a much smaller total leaf area than other species in the same age category (Table 5). While English elm ranked highly, these values are estimated from simulated trees. The absence of field-sampled elm trees in the mature (and older) age classification is due to Dutch Elm Disease (Tomlinson and Potter, 2010) and prevents a comparison of results for field-sampled and simulated elm trees. The high ranking of English elm is therefore hypothetical and based on simulated trees, which typically overestimated ecosystem services provision compared with field trees.

The evergreen species, holm oak and Leyland cypress, were not top-ranked species; however, they provide ecosystem services delivery all year round because they retain their leaves or needles (Clapp *et al.*, 2014). In winter, the loss of deciduous tree leaves severely reduces ecosystem services delivery, particularly for air pollution removal and avoided run-off, which are closely correlated to a tree's leaf area (Baró *et al.*, 2014). However, the loss of leaves can be beneficial; for example, it allows more sunlight to reach buildings, while their canopies in summer help shade and cool (Akbari, 2002). Evergreen species also perform well in mitigating storm water run-off in winter when precipitation can be heaviest, while deciduous trees perform better in providing temperature regulation services (Davies *et al.*, 2017). Evergreen and deciduous tree species can therefore be selected to fulfil different ecosystem service requirements in urban areas.

The results are informative for tree species selection for urban planting. They should not, however, be seen as definitive, as they only consider a subset of the range of ecosystem services which trees can provide (Davies *et al.* 2017), and also because many factors must be considered in species selection including local conditions (growing space, soil type and hydrology), susceptibility to pests and diseases, and suitability under the projected changes to climate. It is vital to start by identifying a shortlist of suitable tree species. The shortlist can then be refined to take into account the potential for ecosystem services delivery to guide the final decision.

Conclusion and implications

This Research Report presents modelled data on the relative delivery of four ecosystem services by different large stature tree species to the urban realm. The report illustrates how mature trees provide the greatest amounts of ecosystem services provision, and found significant variation between tree species of a large stature, with many iconic broadleaves (London plane, oaks and elms) performing well in comparison with conifer species (Scots pine and Leyland cypress). Comparing ecosystem services provision under different climate regions across Great Britain resulted in little difference with respect to carbon storage and sequestration, but substantially higher service provision for avoided storm water run-off in western regions where precipitation levels are higher.

Evidence from England and Wales suggests that large stature and mature trees are being lost from urban environments and replaced with small stature trees (Britt and Johnson, 2008; Natural Resources Wales, 2016). Our dataset of 8881 trees from 10 i-Tree Eco surveys from around GB contained only 3259 trees of species capable of attaining large stature, and of these 86% fell into either the young or semi-mature age classification. Therefore, our dataset has some similarity with Britt and Johnson (2008) and Natural Resources Wales (2016), indicating a poor representation of mature, over-mature and veteran large stature trees in the urban realm. This represents an opportunity to increase the value of the urban forest through protection of the current stock to reach maturity, when ecosystem services provision and therefore the value of trees to society is highest. While ecosystem services provision may decline post-maturity in some species, older trees can be of significant cultural and ecological interest (Barro *et al.*, 1997; Lindenmayer and Laurance, 2017), indicating that such trees should be retained beyond maturity. Using large stature species and planning for their long-term protection can help secure a healthy and productive urban forest for the benefit of urban residents. Utilising the various strengths of the different species can help with strategic planning to meet different management objectives and plan for projected impacts under a changing climate. In all circumstances, species selection must first focus on species suitability to the location, as a tree that fails to thrive will provide lower ecosystem services than a healthy tree.

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This Research Report reviews the provision of four ecosystem services by 12 large stature tree species using the i-Tree Eco model and compares the performance of trees in different age classifications and climate regions. It is the first of two publications reviewing ecosystem service provision by trees of different stature and age in urban areas. The second Research Report reviews the ecosystem provision of small and medium trees. Collectively, these Research Reports will be useful to those engaged in urban forestry management by helping to identify which tree species may be favoured for the delivery of particular ecosystem services through selective planting.