Ecosystem services delivery by small and medium stature urban trees

Research Report

Forest Research

Modelling the delivery of ecosystem services for small and medium trees

Research Report

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Summary

Urban trees are increasingly being recognised for the ecosystem services they provide which support the sustainability and liveability of cities. The quantity of ecosystem services delivered varies between tree species and is influenced by tree age and health. 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) by 18 tree species of small and medium stature which are common to British towns and cities. Data from 3147 field trees, and simulated tree data where field data were not available, were modelled in i-Tree Eco to estimate ecosystem services provision. The grouping of trees into five age classifications enabled changes in ecosystem services delivery to be compared across the trees' lifespans. The results indicated that, relative to the small stature species, medium species provide greater quantities of ecosystem services both annually and over the lifetimes of the trees. Trees were also shown to provide greater ecosystem services in older age classifications, suggesting that management in support of the long-term survival of trees would contribute to ecosystem services delivery in the urban realm. Tree condition also affected the delivery of ecosystem services, with trees in poor health performing less well than healthy trees. The presence of small and medium stature species is important for adding species and structural diversity to an urban forest, as well as providing ecosystem services in areas where large trees are unsuitable.

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 Committee's 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). This Research Report concerns the delivery of four regulating ecosystem services: carbon storage, carbon sequestration, avoided storm water run-off and air pollution removal, by small and medium stature urban tree species common to the towns and cities of Great Britain.

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 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. The associations between tree species and age and the ecosystem services investigated in this report are:

Carbon storage: trees can contribute to greenhouse gas reduction targets by removing carbon dioxide from the atmosphere and storing the carbon over their lifetimes. As trees grow their biomass increases, approximately half of which is carbon (dry weight; Nowak *et al*., 2008). Carbon storage is therefore highly correlated to a tree's total volume of timber, which itself is related to trunk diameter, tree height and canopy size (Peper, McPherson and Mori, 2001).

Carbon sequestration: carbon sequestration is the annual rate at which carbon is taken out of the atmosphere and stored as tree biomass (McPherson and Simpson, 1999). It is primarily determined by a tree's growth rate (Nowak *et al*., 2008) and tends to be fastest in younger trees, slowing with age (White, 1998). In i-Tree Eco the effects of shading and condition are incorporated into the modelling of growth rates, where increased levels of shading and poorer tree condition lead to slower growth rates (Nowak *et al*., 2008). Gross carbon sequestration is calculated from the change in tree biomass each year, and does not take into account tree death or decay (Nowak and Crane, 2002).

Avoided run-off: the high cover of impervious surfaces in towns and cities causes rainfall to accumulate as storm water run-off. Trees can help reduce both the risk of flooding from this run-off and the cost of its subsequent treatment as waste water by intercepting rainfall and reducing the volume of run-off occurring. Typically, trees with a greater leaf area (concomitant with larger leaves and denser and larger crown areas) offer a greater surface area for water to gather upon (McPherson *et al*., 1997), which in turn reduces the volume of rainfall reaching the ground.

Air pollution removal: trees can contribute to air quality by removing pollutants, through uptake by leaves and deposition on their surfaces (Nowak, Crane and Stevens, 2006). As with avoided run-off, trees with greater total leaf areas tend to remove greater quantities of air pollution (McPherson *et al*., 1997; Nowak *et al*., 2008). A tree's leaf area is reduced by poor tree condition and by management practices such as pruning and pollarding (Peper, McPherson and Mori, 2001).

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. Such information can help guide the management of urban forests. Ecosystem services delivery can vary by species, stature, location and condition (Davies *et al*., 2017), and 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, will affect the ecosystem services delivery of urban forests.

This Research Report is the second of two investigating how regulating ecosystem services provision varies with tree stature and age. The first report (Hand, Doick and Moss, 2019) reviews ecosystem services provision by 12 large stature tree species. This second report focuses on small and medium stature trees and aims to model ecosystem services provision over the lifetimes of a range of small and medium stature tree species common to the urban environment of Great Britain, based on calculations incorporated within the i-Tree Eco tool. Small and medium stature tree species are defined as species in which a healthy, isolated 20-year-old specimen growing in good soil conditions typically attains a height of (small) less than 6 m or (medium) between 6 and 12 m (Stokes *et al*., 2005; RHS, 2016); note that it is the species that is defined herein as being of small or medium stature, and not the tree: it is independent of age.

Methodology: quantifying ecosystem services provision by small and medium 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.

Species selection

These 10 i-Tree Eco surveys were collated and provided a dataset of 8881 trees. From this dataset, the most common tree species were identified to generate a subset of species to explore in detail. Common species were considered to be those with a minimum of 40 trees in the dataset. The most common species were then categorised as either small, medium or large stature according to Stokes *et al*. (2005) and the Royal Horticultural Society (2016). Ten species were categorised as medium and 10 were categorised as small. Two pairs of small stature tree species (plum and apple species) were grouped together because of their similarity (Table 2), leaving eight small stature species for modelling. Prior to analysis, a quality check for incorrectly entered or missing data was carried out: five trees were removed due to insufficient data, leaving a final dataset of 3147 small and medium stature trees.

Table 2 The small and medium stature tree species commonly occurring in towns and cities of Great Britain used in this study.

Common name	Scientific name
Small stature	
Apple spp. Apple (unidentified) Common apple	 *Malus spp.* *Malus domestica*
Plum spp. Common plum Cherry (plum)	 *Prunus domestica* *Prunus cerasifera*
Common hawthorn	*Crataegus monogyna*
Common holly	*Ilex aquifolium*
Elder	*Sambucus nigra*
European bird cherry	*Prunus padus*
European hazel	*Corylus avellana*
Goat willow	*Salix caprea*
Medium stature	
Callery pear	*Pyrus calleryana*
English yew	*Taxus baccata*
European alder	*Alnus glutinosa*
English yew	*Taxus baccata*
European alder	*Alnus glutinosa*
European hornbeam	*Carpinus betulus*
Field maple	*Acer campestre*
Lawson's cypress	*Chamaecyparis lawsoniana*
Rowan	*Sorbus aucuparia*
Silver birch	*Betula pendula*
Sweet cherry	*Prunus avium*

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

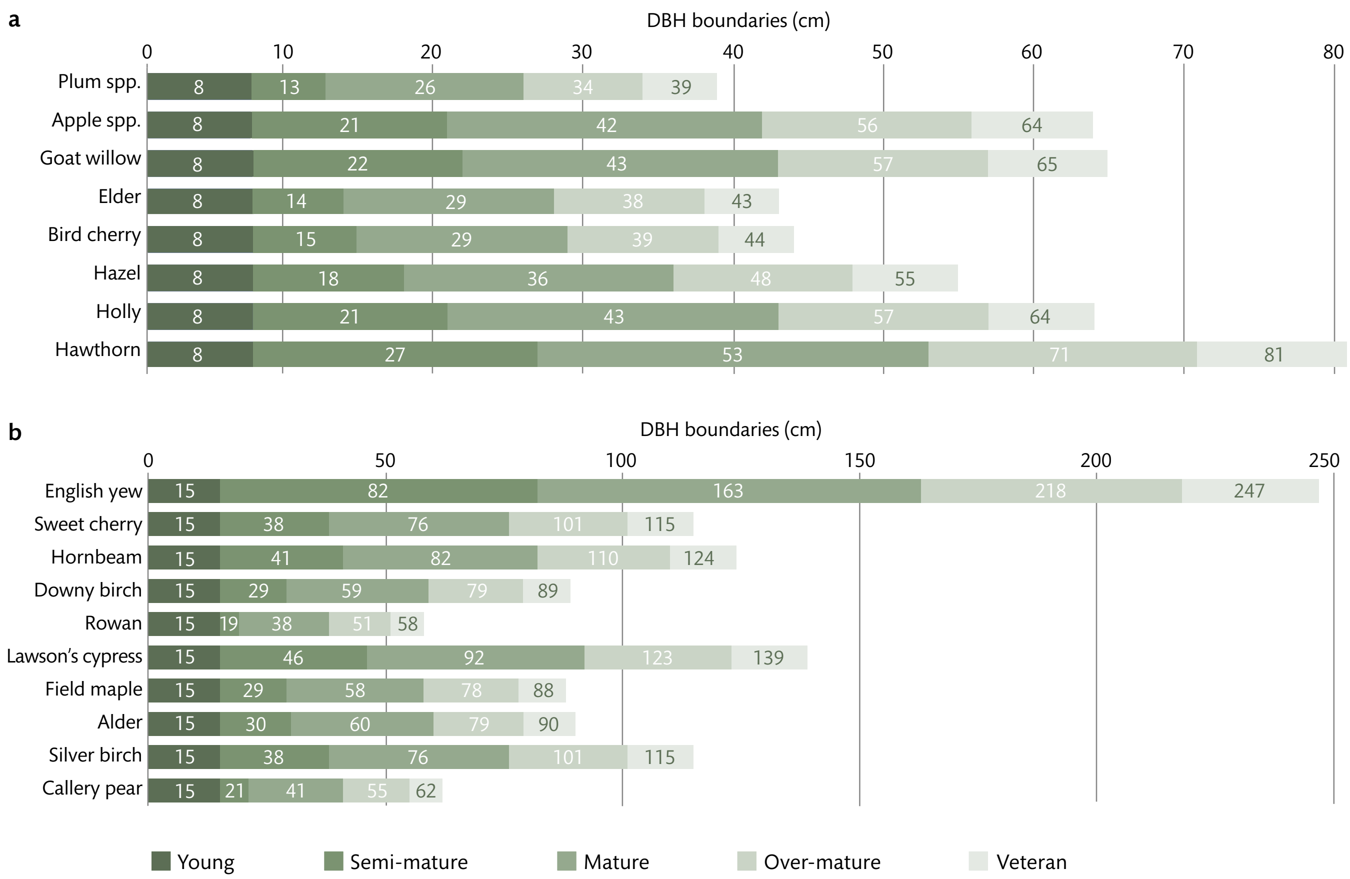
i-Tree Eco study	Reference
Bridgend	Doick *et al.*, 2016a
Area 1 Highways (Cornwall and South Devon)	Rogers and Evans 2015
Edinburgh	Hutchings, Lawrence and Brunt, 2012
Glasgow	Rumble *et al.*, 2015a
Greater London	Rogers *et al.*, 2015
Southampton	Mutch *et al.*, 2017
Tawe catchment (encompassing Swansea 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

Age classification

Ecosystem services delivery varies over the lifetime of a tree (Nowak *et al*., 2008). To illustrate these changes, two approaches were used: trunk diameter (diameter at 1.37 m) and age classification. First, measurements of trunk diameter were used as an indicator of tree age (White, 1998; Lukaszkiewicz and Kosmala, 2008), and were used here as a proxy for time to assess the robustness of trends in ecosystem services provision over the lifespan of a tree. 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 diameter at breast height (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 1a for the small stature tree species and in Figure 1b for the medium stature species. The age classifications enable the estimated ecosystem services provision of the field trees to be summarised over time. Ecosystem services provision over the lifespan of each tree species can then be assessed across the five age classifications.

Figure 1 DBH boundaries calculated by age classification for each species: (a) small stature species and (b) medium stature species. The numbers within bars represent the upper limit of that particular range.



Modelling ecosystem services delivery using i-Tree Eco

The samples of 1496 medium stature and 1651 small stature trees were entered into i-Tree Eco version 6.0.6 to estimate the ecosystem services delivery for each tree. Detailed information on how ecosystem services are calculated by i-Tree Eco are given in Nowak *et al*. (2008) and the i-Tree Eco manual (i-Tree, 2016). All trees were modelled under the same climatic conditions, based here for southwest England, with climate and pollution data used from 2013 (Hand, Doick and Moss, 2019).

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. 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, gross carbon sequestration, avoided storm water run-off, and air pollution removal. Carbon storage accounts for above-ground storage by trees only (i.e. the carbon held in the woody structure of the tree) and does not account for sequestration or storage in the soil. 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 ecosystem service for each tree. These data were grouped by species and the mean average DBH was determined for each age classification, unless otherwise stated. In addition to the database of field-sampled trees, we estimated parameters for simulated trees for each age classification for each species and also modelled those within i-Tree Eco. Simulated trees were used instead of field trees where information was missing for particular age classifications. For modelling, condition was set to 5% dieback, except for the veteran age classification, where dieback was set to 20%, as dieback is often seen as a key feature in older ages of trees (Fay, 2002; Britt and Johnson, 2008). 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 instead 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.

The estimated ecosystem services delivery was compared for different species across their lifespans. Initially, the strength of relationship between estimated age and ecosystem services provision was explored. The strength of relationship between 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. This was followed by a comparison of the four ecosystem services provided by each tree species in each age classification, where the mean value for each age classification is reported. Due to the lack of older trees in the dataset, inferences for some of the older age classifications were made from the simulated tree dataset (clearly indicated throughout). Finally, each tree species was ranked by its delivery of each ecosystem service in the mature age class, providing a ranking of the best performing trees.

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.

Results

Descriptive statistics of surveyed trees

Tree condition, height and leaf area are summarised in Table 3 for small stature trees and in Table 4 for medium stature trees. The sample size for each species and age classification is also shown. Despite the large dataset, few trees fall into the older (over-mature and veteran) age classifications. Fewer older trees were also found in the review of large stature species (Hand, Doick and Moss, 2019). This may be indicative of a paucity of older trees in urban areas (Britt and Johnson, 2008).

Small stature trees were found to attain an average mature height of 7.5 m while mature medium stature trees were on average 12.8 m tall (Tables 3 and 4). Leaf area was greater in medium compared with small stature trees, with an average of 166 m^2 for medium stature trees and 95 m^2 for small stature trees. In both small and medium stature tree species, height and leaf area tended to increase in each successive age classification. However, there were exceptions: the height and leaf area of alder, plum spp., goat willow, hazel and elder vary with age, often increasing in early age classes then declining in the over-mature or veteran age classification. These changes may reflect: (1) natural decline in older age trees; (2) management actions which reduce canopy area; or (3) small sample sizes in these age classifications, resulting in biased measures of these features.

The condition of trees varied from 0% dieback to nearly 50% dieback (Tables 3 and 4). Most trees had 0% dieback and for each species the average dieback was <10%. Twelve of the 18 tree species did not show a linear trend with dieback and age classification. Only one species showed an improvement in condition with tree age (sweet cherry) and five (downy birch, yew, hornbeam, field maple and hawthorn) showed a decline in condition with increasing age.

Table 3 Descriptive statistics of surveyed tree data for small stature tree 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
Apple spp. (146)	4 ± 4 (12)	4.1 ± 1.2 (100)	9.9 ± 2.7 (31)	18 ± 8.7 (3)	-	3.2 ± 0.5	4.5 ± 0.2	6.8 ± 0.5	7.9 ± 1.2	-	32.6 ± 23.2	33.9 ± 3.1	86.6 ± 10.9	168.3 ± 91.7	-
Bird cherry (45)	0 ± 0 (4)	0.7 ± 0.5 (19)	10.5 ± 5.2 (15)	0.6 ± 0.6 (5)	6.5 ± 6.5 (2)	7 ± 0.8	5.8 ± 0.5	7.1 ± 0.6	7.4 ± 1.2	9.4 ± 3.4	20 ± 2.4	33.8 ± 4.1	108.8 ± 25.3	±148.2 ± 50.2	207.5 ± 42.2
Plum spp. (78)	9.5 ± 8.4 (8)	5.5 ± 2.5 (29)	5.8 ± 1.4 (34)	0 (5)	6.5 ± 6.5 (2)	6.4 ± 1.5	4.9 ± 0.3	6.6 ± 0.5	8 ± 1.8	5 ± 1	11.2 ± 3.8	18.8 ± 2.4	47.8 ± 5.9	138.7 ± 42.5	31.6 ± 28.8
Elder (100)	20.5 ± 7.1 (13)	16.7 ± 3.5 (45)	12.7 ± 4.1 (30)	49.9 ± 11.1 (9)	0 (3)	4.3 ± 0.3	4.7 ± 0.7	4.7 ± 0.2	7.2 ± 1.1	5.1 ± 0.3	9.5 ± 1.3	17.8 ± 1.7	40.2 ± 5.9	40.5 ± 14.1	91.1 ± 53.8
Goat willow (253)	15.8 ± 5.7 (12)	7.4 ± 1.3 (154)	12.2 ± 2.6 (71)	17.3 ± 9.9 (11)	14.2 ± 9 (5)	7.6 ± 0.7	7.9 ± 0.2	9.6 ± 0.4	11.9 ± 0.8	10.6 ± 1.4	15.7 ± 4.3	41.3 ± 3.4	119.8 ± 11.4	268.8 ± 60	227.5 ± 13.6
Hawthorn (531)	2.6 ± 1.4 (50)	5.5 ± 0.6 (432)	13.4 ± 3 (48)	58 (1)	-	4.1 ± 0.2	5.9 ± 0.1	11	7.6 ± 0.4	-	9.9 ± 1.6	29.4 ± 1.3	91.8 ± 10.8	168.6	-
Hazel (236)	1.78 ± 1 (32)	4.7 ± 1.1 (150)	2.4 ± 1.1 (52)	28 (1)	28 (1)	5.2 ± 0.3	6.4 ± 0.2	7.3 ± 0.3	13.5	9	20.1 ± 2.8	87.4 ± 6.5	35.6 ± 2.2	104.7	60.1
Holly (262)	0.9 ± 0.5 (21)	5.72 ± 0.8 (188)	6.22 ± 1.5 (51)	0 (2)	-	4.2 ± 0.5	6.7 ± 0.2	10 ± 0.5	10.5 ± 0.5	-	17.2 ± 3.7	34.6 ± 2.8	113.8 ± 10.9	153.8 ± 73.3	-

* 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.

Table 4 Descriptive statistics of surveyed tree data for medium stature tree 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
Callery pear (84)	2.6 ± 0.9 (50)	0.2 ± 0.2 (15)	0.3 ± 0.2 (19)	-	-	5.2 ± 0.2	8.6 ± 0.3	9.9 ± 0.4	-	-	17.1 ± 1.5	63.3 ± 13.5	83.2 ± 7.9	-	-
Downy birch (77)	9.5 ± 2.4 (50)	15.3 ± 3.4 (230)	18.5 ± 12.2 (4)	-	-	8.4 ± 0.2	12.6 ± 0.6	12.8 ± 1.7	-	-	14.4 ± 2.1	69.5 ± 13.3	92.1 ±38.3	-	-
English yew (43)	0 (15)	4.3 ± 1.6 (28)	-	-	-	4.2 ± 0.3	8.8 ± 0.7	-	-	-	32.5 ± 8.3	237.7 ± 34.6	-	-	-
Alder (217)	6.2 ± 1.3 (113)	7.8 ± 2.2 (61)	10.9 ± 2.8 (38)	10.8 ± 6.1 (5)	-	8.5 ± 0.2	12.6 ± 0.5	14.8 ± 0.7	17.2 ± 2.1	-	11.9 ± 1.5	45.9 ± 7.1	213 ± 119.9	105.6 ± 12.4	-
Hornbeam (59)	1.9 ± 1 (30)	4.2 ± 1.7 (22)	19.6 ± 9.6 (7)	-	-	5.6 ± 0.7	10.9 ± 0.9	13.9 ± 1.5	-	-	21.5 ± 3.1	122.6 ± 22.4	259.4 ± 68.6	-	-
Field maple (154)	0.1 ± 0.1 (46)	2.8 ± 1.2 (83)	7.4 ± 2 (25)	-	-	7.5 ± 0.4	9.4 ± 0.3	13.4 ± 1	-	-	26.8 ± 3.1	85.9 ± 6.6	145 ± 16.9	-	-
Lawson's cypress (128)	4.6 ± 1.9 (52)	1.5 ± 0.7 (58)	4.8 ± 2 (16)	1.5 ± 1.5 (2)	-	4.2 ± 0.3	9 ± 0.6	13.9 ± 1.5	15 ± 1	-	16.5 ± 2.3	68.8 ± 9	147.5 ± 42.1	677.3 ± 146.8	-
Rowan (89)	7.9 ± 2.5 (50)	2.6 ± 1.7 (14)	4.9 ± 2.4 (22)	10.3 ± 6.7 (3)	-	6 (0.3)	6.8 (0.7)	7.6 (0.4)	10 (0.9)	-	17.9 ± 1.6	51.2 ± 8.2	108 ± 15.9	197.1 ± 61.6	-
Silver birch (419)	5.5 ± 1 (178)	5.2 ± 0.7 (213)	8 (27)	5.1 ± 1.5 (1)	-	9.9 ± 0.2	13.4 ± 0.3	17.7 ± 1.2	18.8	-	23.9 ± 1.8	90.3 ± 5.2	199.1 ± 25.7	679	-
Sweet cherry (226)	1.7 ± 0.2 (80)	1.5 ± 0.1 (120)	1.2 ± 0.1 (26)	-	-	7.2 ± 0.4	9.4 ± 0.4	10.5 ± 0.8	-	-	25 ± 2.6	106.4 ± 8.6	245.2 ± 22.4	-	-

* 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.

Association between ecosystem services delivery and estimated tree age

In this section, the results of the assessed strength of relationship between ecosystem services provision and DBH are presented. Trends between ecosystem services delivery and DBH (as a proxy for age) are used to demonstrate the suitability of this approach for modelling ecosystem services provision over the course of a tree's lifespan. The results are presented in Figures 2 and 3; a subset of three species for each stature group is shown in each graph to provide clarity. The species presented in this section provide a representative picture of the data variability observed. For a full comparison, see the Ecosystem service provision by small and medium stature tree species section (page 9). Relationships between carbon storage capacity and DBH are shown in Figure 2a for small stature trees and Figure 2b for medium stature trees. For both small and medium stature tree species, carbon storage increased with DBH. Carbon storage was revealed to be closely linked to DBH as estimated for both small and medium stature trees, with median R^2 values across species of 0.99 for both small and medium stature species (data not shown).

The rate of carbon sequestration by tree species is shown for small stature (Figure 2c) and medium stature trees (Figure 2d). Trends were observed to be more variable for the carbon sequestration ecosystem service than for carbon storage. First, there was more variation between species, most visible between sweet cherry and Lawson's cypress in

Figure 2 Estimated delivery of carbon storage (top row) and carbon sequestration (bottom row) for a subset of (a, b) small and (c, d) medium stature species. All trees are modelled based on the southwest England climate.

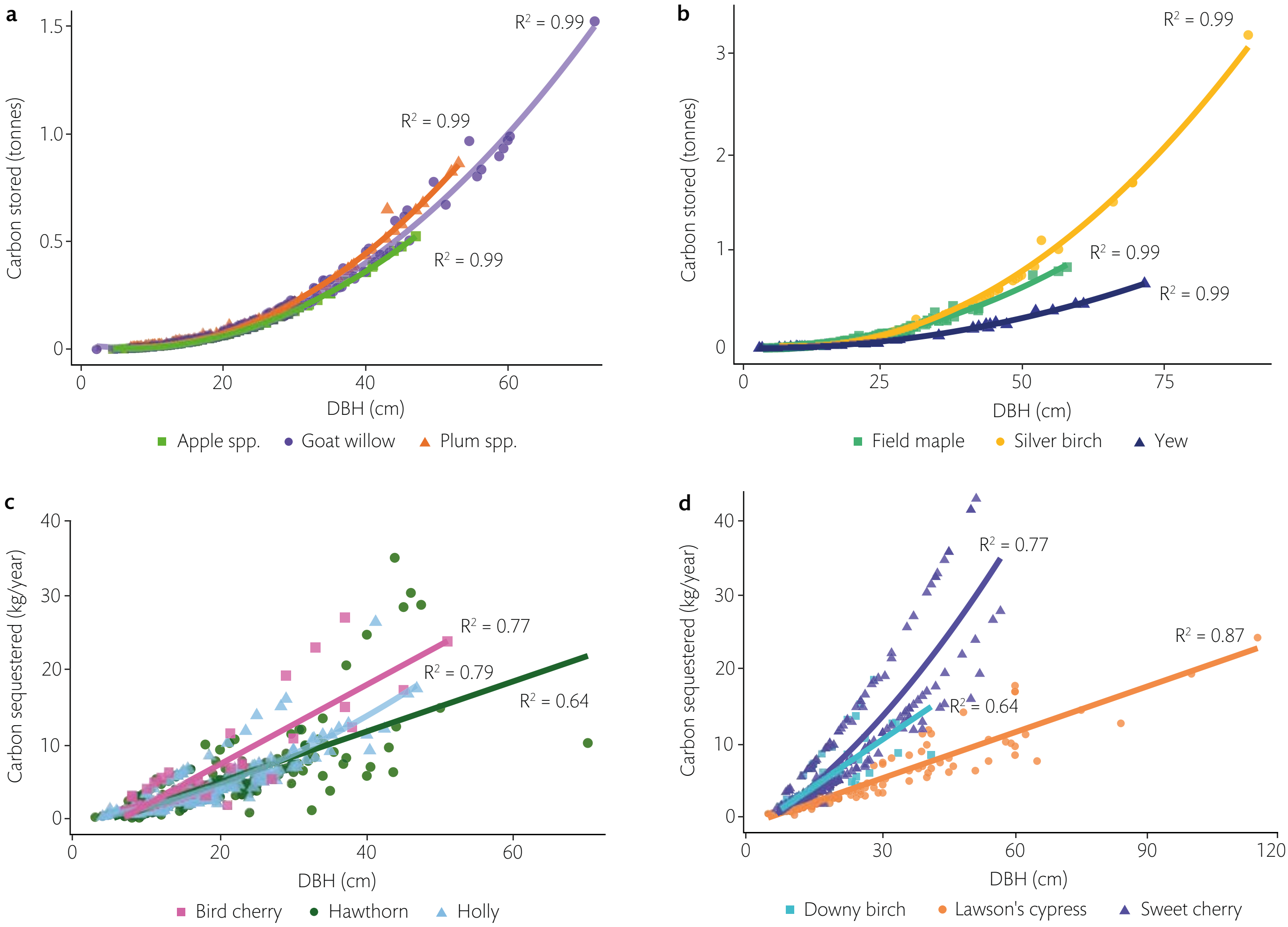


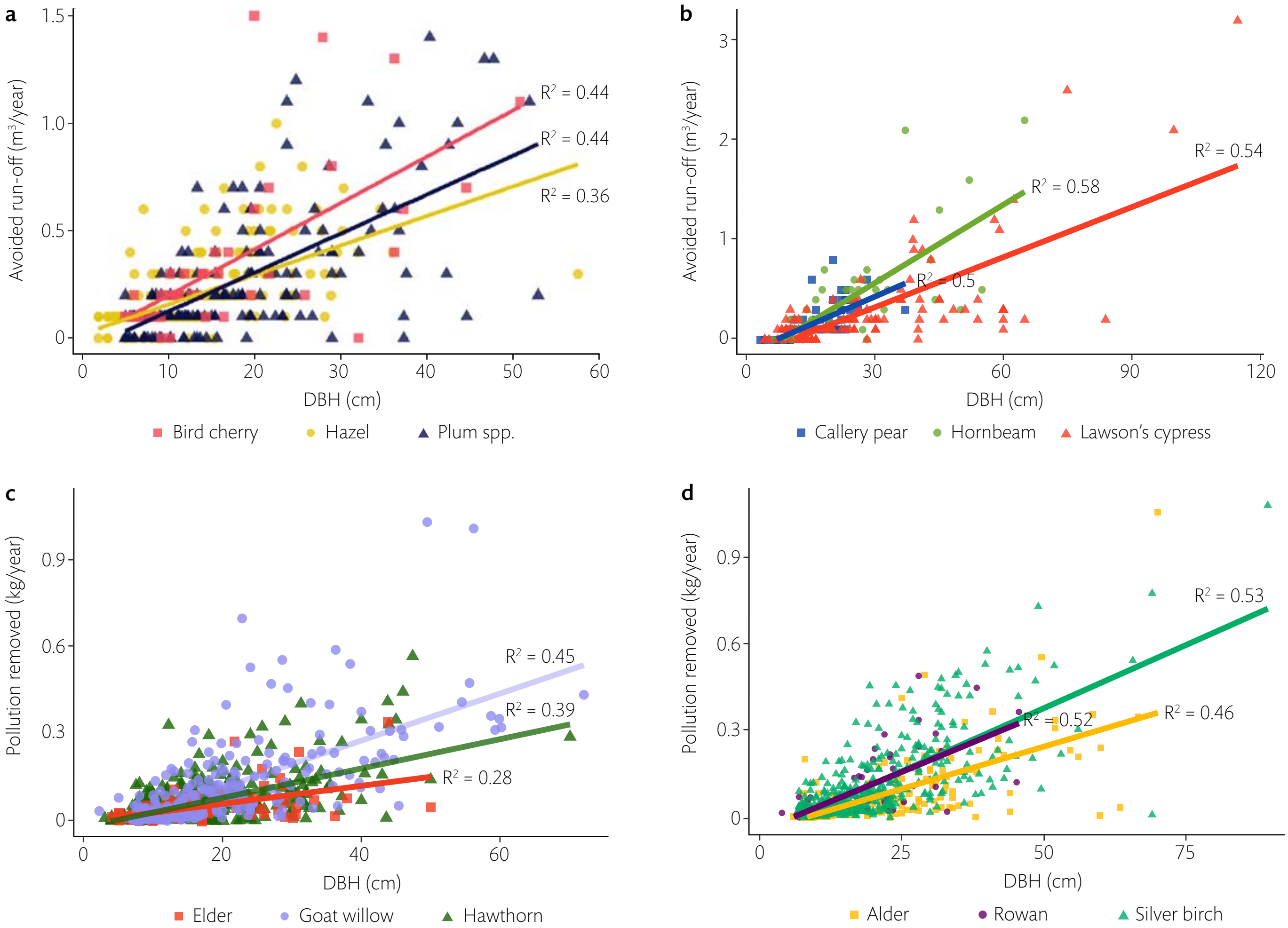
Figure 2d, due to the different growth rates of species. Second, the data varied more within each species, with hawthorn (Figure 2c) and sweet cherry (Figure 2d) showing the greatest variability in estimated carbon sequestration for similarly sized trees. This intra-species variation is probably due to local factors affecting tree growth, such as shading, surrounding land use and condition, which affect the growth rate applied within i-Tree Eco. The variability in sequestration due to these factors leads to the lower median R^2 values for this ecosystem service of 0.76 for small stature trees and 0.81 for medium stature species (data not shown).

Figure 3 shows, with subsets of small and medium stature tree species, ecosystem services delivery with DBH for avoided run-off (a: small, b: medium) and pollution removal (c: small, d: medium). Both of these ecosystem services are influenced by the tree's total leaf area. All trees showed a steady increase with DBH in avoided run-off, although the slope of this relationship varied among species and with considerable variation around the trendline. The high variation in avoided run-off among trees of the same species resulted in median R^2 values of 0.41 for small stature species and 0.53 for medium stature species (data not shown).

Trends between air pollution removal (Figures 3c,d) and DBH were similar to those for avoided run-off. Air pollution removal increased steadily with increasing tree DBH, with the rate of increase variable among species. Median R^2 values were 0.42 for small stature trees and 0.53 for medium stature trees (data not shown).

The high variability for both avoided run-off and air pollution removal services indicates that other factors beside tree DBH play an important role in determining the provision of these two ecosystem services. Other factors which probably influenced the estimated delivery of these two ecosystem services include the extent of crown dieback, particularly for small stature species, and total leaf area (Tables 3 and 4). Additionally, some trees may have had their crown sizes reduced through specific management practices such as pruning. The R^2 values for small stature trees in particular are low in comparison with large stature trees (as calculated in

Figure 3 Estimated delivery of (a, b) avoided run-off and (c, d) air pollution removal for a subset of (a, c) small and (b, d) medium stature species. All trees are modelled based on the southwest England climate.



Hand, Doick and Moss, 2019: median R^2 = 0.5 for avoided run-off and 0.54 for air pollution removal). This also suggests greater canopy area variability within species of small and medium stature than among large stature tree species.

Ecosystem services provision by small and medium stature tree species

In this section, ecosystem services provision by small and medium stature tree species common to British towns and cities is presented. The data presented are the averages of each tree species in each of the five age classifications, based upon the database of field-sampled trees. For a subset of species, values from field-sampled trees versus simulated trees are also shown to assess the comparability among ecosystem services estimates. This subset of species was selected to ensure every species was examined for at least one ecosystem service.

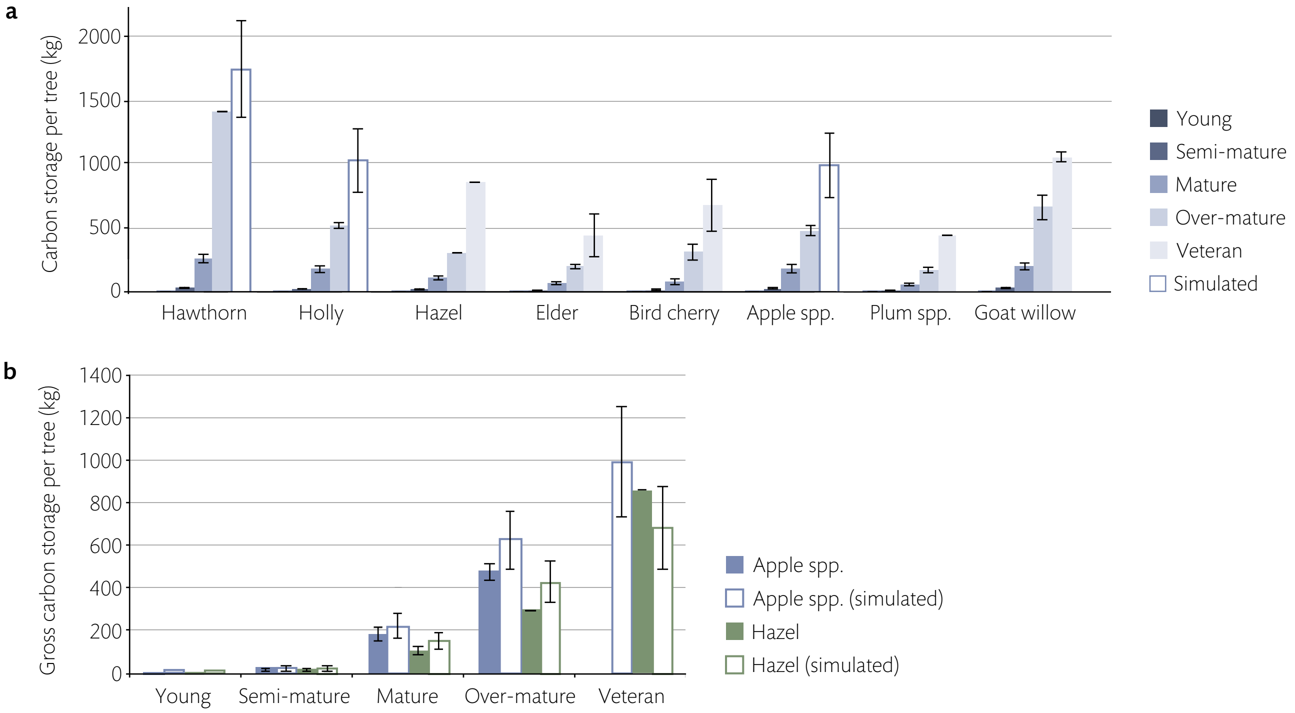
Small trees

Carbon storage

The carbon storage capacity of eight species of small stature tree is shown in Figure 4. Carbon storage was found to increase with each successive age classification. The highest amount of estimated carbon stored for a single tree of small stature was over 1500 kg for a veteran goat willow. Data from both field and simulated trees suggest that the largest increases in carbon storage are observed between the over-mature and veteran age classifications. Most of the small stature species stored over 600 kg of carbon by the veteran age classification, with the exception of elder and plum spp., which are the species with the smallest maximum DBH (Figure 1a).

Figure 4b compares the estimated carbon storage of field trees and simulated trees for hazel and apple spp. in order to consider the representativeness of the simulated trees. For these two species in most age classifications, the

Figure 4 (a) Modelled carbon storage per tree for each of the small stature species. Field-surveyed data are shown in solid bars and values estimated from simulated trees are shown in the white bars; (b) comparison between the modelled carbon storage for the field-surveyed and simulated trees for apple spp. and hazel. Error estimates are ± 2 standard errors of the mean.



estimated carbon storage was greater in simulated than for field trees. An exception was found for hazel in the veteran age classification. A single hazel tree was classified as veteran and was estimated to store 25% more carbon than the mean of the simulated trees. This greater carbon storage capacity can be attributed to this hazel field tree having a larger trunk diameter, 11% greater than the simulated tree mean. Across the other small stature species, simulated trees tended to estimate greater carbon storage than field-sampled trees in most of the age classifications. By contrast, other species including hawthorn, elder, plum spp. and goat willow showed a similar pattern to hazel, with greater estimated carbon storage in field-sampled than simulated trees in veteran classifications, which was similarly linked to greater trunk diameter. However, as sample sizes were smaller in the older age classifications, these larger trees may be atypical of trees found in urban areas. In the remaining species of apple spp., holly and hawthorn, no trees in the veteran age classification were found.

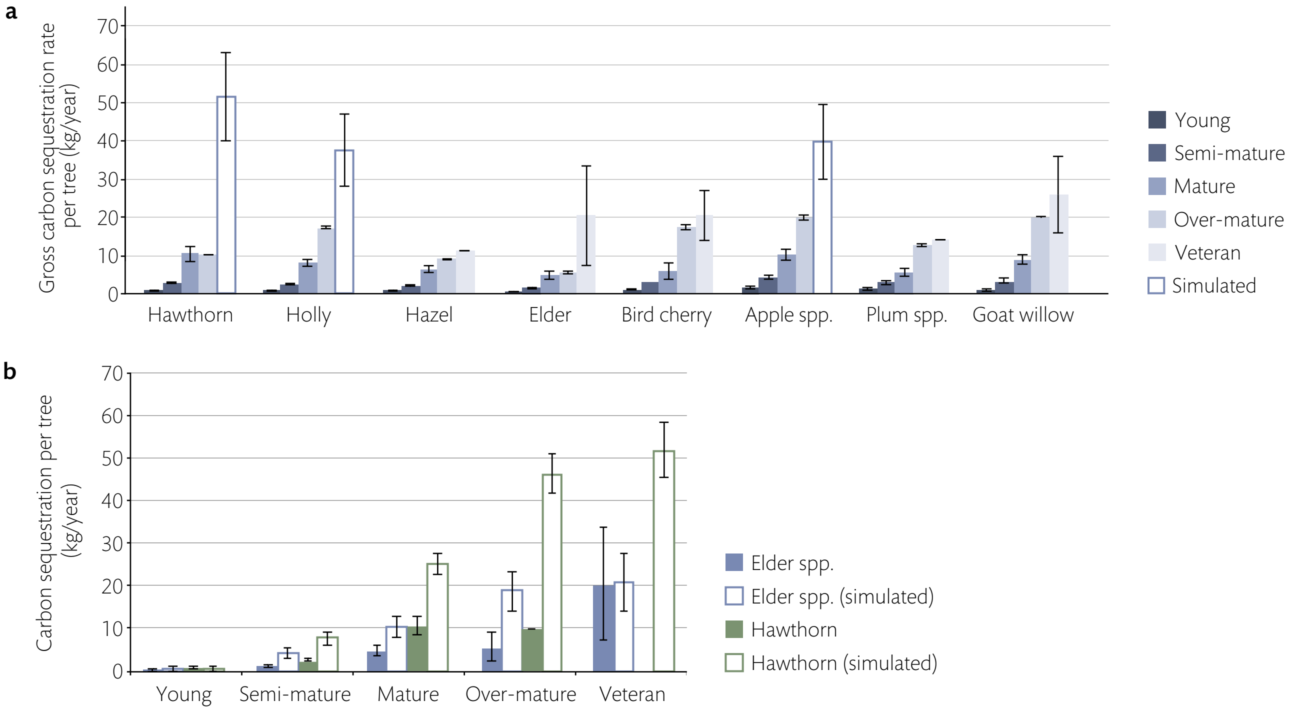
Gross carbon sequestration rate

The rate of carbon sequestration by the small stature tree species is shown in Figure 5. The rate at which small stature trees sequester carbon annually was found to continually increase with each consecutive age classification. For every species, sequestration rates were highest in the veteran age classification, according to both field and simulated trees.

Species showed different rates of change in annual carbon sequestration between age classifications. Most species showed a steady increase across all five of the age classifications with only elder showing a large increase between the over-mature and veteran age classification. All small stature species were estimated to sequester over 10 kg a year by the veteran age classification, approximately four times as much as in the young age classification. Where estimates were derived from field data, the species with the greatest annual carbon sequestration rate was goat willow, on average sequestering around 25 kg of carbon a year (field tree results, Figure 5a).

Figure 5b compares the estimated carbon sequestration rate for field and simulated trees for hawthorn and elder. Carbon sequestration rates for simulated trees were greater than that for field-sampled trees for both species in nearly all of the age classifications: the only exceptions were for elder and hawthorn in the young age classification and, in these cases, the field trees were of a greater size than the simulated trees. For trees in the older age classification, tree condition measured through crown dieback played an important role. For example, the single hawthorn tree classified as veteran was 13% larger than the mean simulated hawthorn tree, but its estimated carbon sequestration rate was lower. The lower sequestration rate appears to be due to the high crown dieback of this tree, measured at 58%, which was substantially greater than the 5% crown dieback set for

Figure 5 (a) Modelled gross carbon sequestration rate per tree per year for small stature species. Field-surveyed data are shown in solid bars and values estimated from simulated trees are shown in the white bars; (b) comparison between the modelled carbon sequestration rate for the field-surveyed and simulated trees for elder and hawthorn. Error estimates are ± 2 standard errors of the mean.



simulated trees. Higher crown dieback in elder trees can also explain the lower sequestration rates in field-sampled compared with simulated trees among the semi-mature to over-mature age classifications, while in the veteran age classification, dieback levels were similar. Across the other small stature species, higher sequestration rates tended to be estimated for simulated trees than were calculated for field-sampled trees.

Avoided storm water run-off

The change in the capacity of the eight small stature tree species to intercept rainfall and thereby contribute to storm water run-off avoided over the five age classifications is shown in Figure 6. Annual avoided run-off by the eight trees species peaked in either the over-mature or veteran age classification. For example, hawthorn, hazel, plum spp. and goat willow all peaked at over-mature and showed a decline in the veteran age classification. For hazel and goat willow, leaf area was found to decline from the over-mature to veteran age classification (Table 3). This may reflect the crown reductions associated with ageing trees (Fay, 2012), causing a decline in leaf area, or simply a factor of variation within the small sample.

High levels of variation within estimated avoided run-off were observed in seven of the tree species for at least one age classification, for example, holly trees in the over-mature grouping. This was associated with the high levels of variation found in calculated leaf area for trees (Table 3). Trees with smaller variation in leaf area, such as in hazel or elder in the young to mature age classifications, showed smaller error in estimated avoided run-off. The species which had the highest avoided run-off volumes (>0.8 m^3 per year) were goat willow, apple spp., bird cherry and holly. These species typically had leaf areas >130 m^2.

Figure 6b compares the simulated and field-surveyed data for the holly and bird cherry species. The estimated volume of avoided run-off was similar between field-surveyed and simulated trees at the younger age classes, but diverged within the older age classifications. However, the overlap in error bars shows that the difference between field-surveyed and simulated trees is not significant at these older age classifications. The trend for field-sampled holly trees to have a lower avoided run-off than simulated trees may be because holly is often pruned as part of a hedge, consequently reducing the leaf area and ability to intercept rainfall. In bird cherry there was no clear link between lower estimated run-off and the size or condition of field trees, suggesting other factors play a role.

Air pollution removal rate

The rate of air pollution removal by the small stature tree species is presented in Figure 7. Air pollution removal was

Figure 6 (a) Modelled avoided run-off per tree per year for every species of small stature. Field-surveyed data are shown in solid bars and values estimated from simulated trees are shown in the white bars; (b) comparison between the modelled avoided run-off for the field-surveyed and simulated trees for holly and bird cherry. Estimates are ± 2 standard errors of the mean.

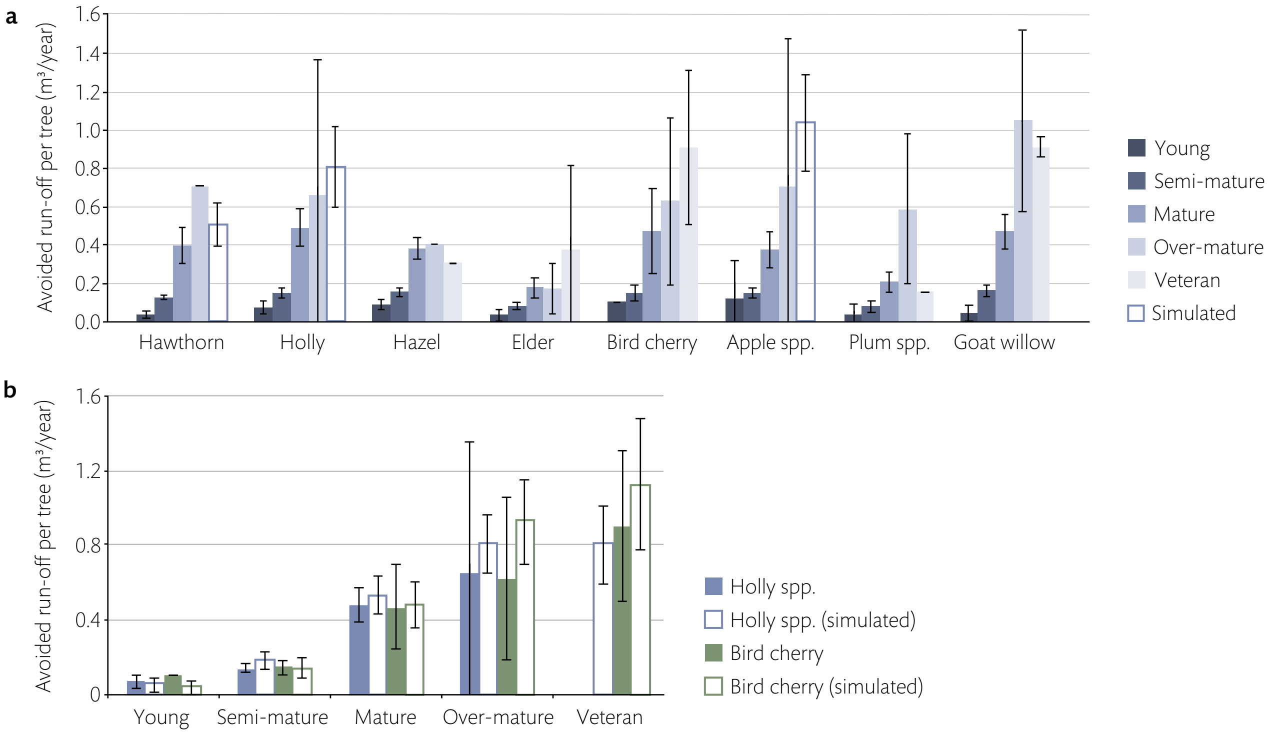
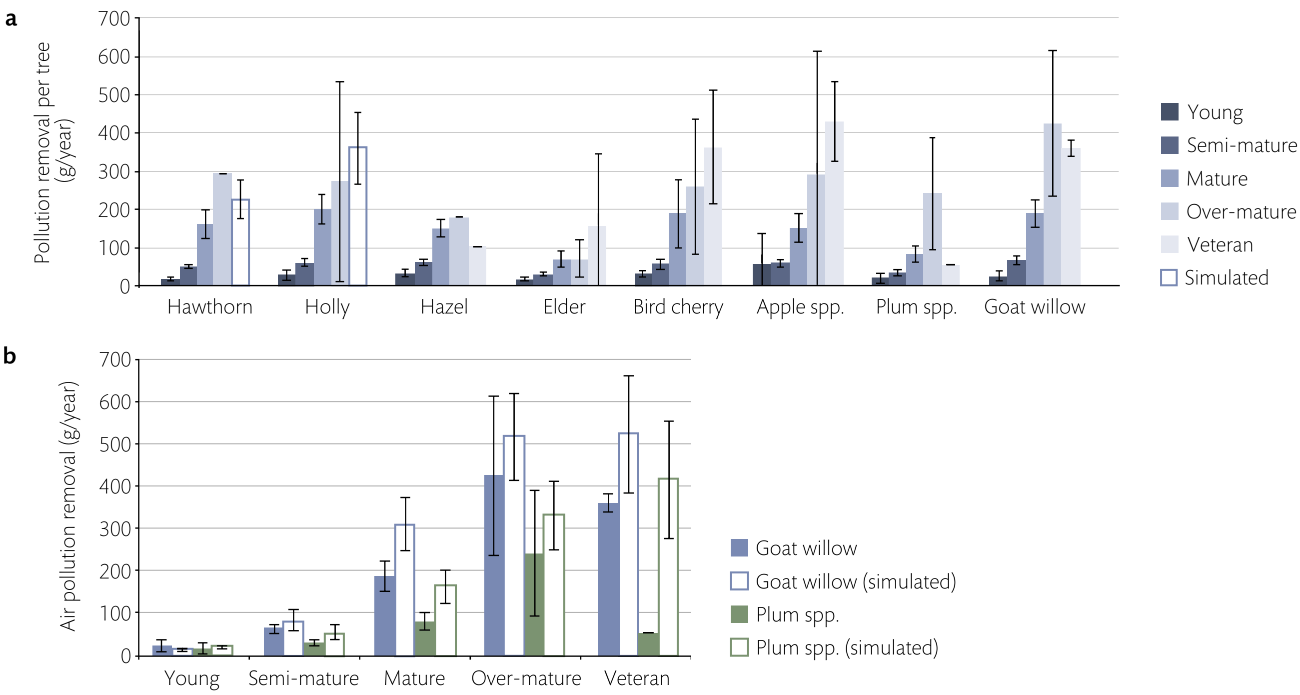


Figure 7 (a) Modelled pollution removal per tree per year for small stature tree species. Field-surveyed data are shown in solid bars and values estimated from simulated trees are shown in the white bars; (b) comparison between the modelled carbon storage for the field-surveyed and simulated trees for goat willow and plum spp. Estimates are ± 2 standard errors of the mean.



observed to peak in either the over-mature or veteran age classification. The quantity of air pollution removed by each successive age classification increased until reaching this peak. The best small stature species for air pollution removal were apple spp., goat willow and bird cherry, which were estimated to remove over 350 g of air pollutants per tree per year by the over-mature or veteran age classification. The high variation around some estimates of air pollution removal was due to the high variation present in leaf areas for certain species and age classifications, as described for avoided storm water run-off in the previous section.

Figure 7b compares the estimated air pollution removal per tree of field-sampled and simulated trees for goat willow and plum spp. The results for the field-sampled trees for both these species suggest a decline in veteran trees, following a peak in the over-mature age classification. In both of these species leaf area was found to decline from the over-mature to veteran age classifications: from 269 to 227 m² in goat willow and 139 to 32 m² in plum spp., which would explain the decline of this ecosystem service. Their height was also found be lower than in the over-mature age classification: from 11.9 to 10.6 m for goat willow and 8 to 5 m for plum spp. These declines in height and leaf area result in substantially lower air pollution removal in comparison to the simulated trees, which show either stable or an increase in values between over-mature and veteran trees. The small sample sizes of field trees in these older age classifications for both species (Table 3) raises the possibility that these declines may not represent trends in the wider population.

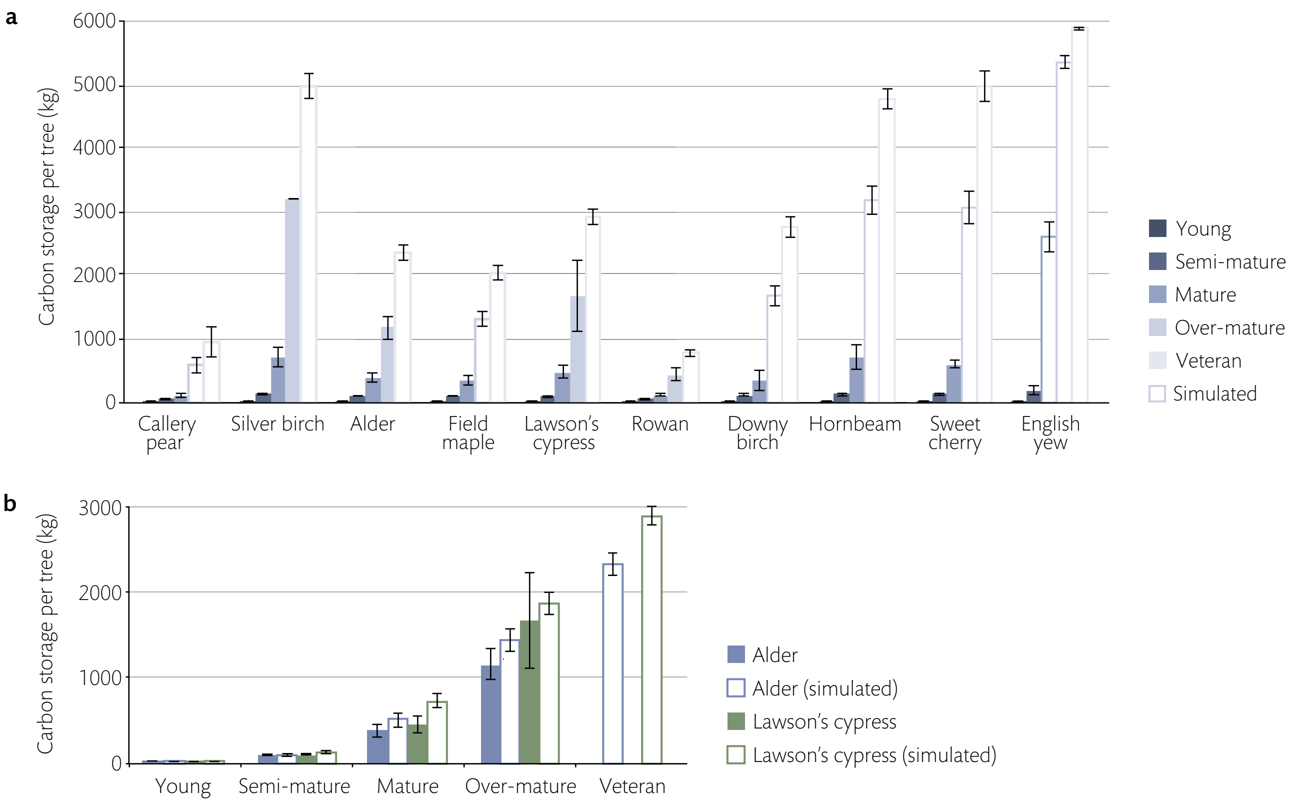
Medium trees

Carbon storage

The carbon storage capacity of the 10 medium stature tree species investigated (Figure 8) shows an increase in carbon storage in each successive age classification for every species (Figure 8a). The data from simulated trees suggests that there is a substantial increase in carbon storage from the mature to the over-mature age classification, and that there is also often a large increase between the over-mature and veteran groupings. On average across all species, trees in the mature age classification stored 50 times more carbon than young trees. Of the medium stature species, those which attained the largest DBH sizes showed the greatest capacity to store carbon; notably, yew, silver birch, sweet cherry and hornbeam were all projected to store over 4000 kg of carbon per tree in the veteran age classification (based on simulated trees). Trees with a smaller maximum attainable DBH, such as rowan or callery pear, stored less carbon, peaking at approximately 1000 kg per tree.

Figure 8b compares field-sampled and simulated trees at each age classification for alder and Lawson's cypress. For both species, carbon storage is estimated to be greater in

Figure 8 (a) Estimated carbon storage per tree for medium stature species. Field-surveyed data are shown in solid bars and values estimated from simulated trees are shown in the white bars; (b) comparison between the modelled carbon storage for the field-surveyed and simulated (sim.) trees for alder and Lawson's cypress. Error estimates are ± 2 standard errors of the mean.



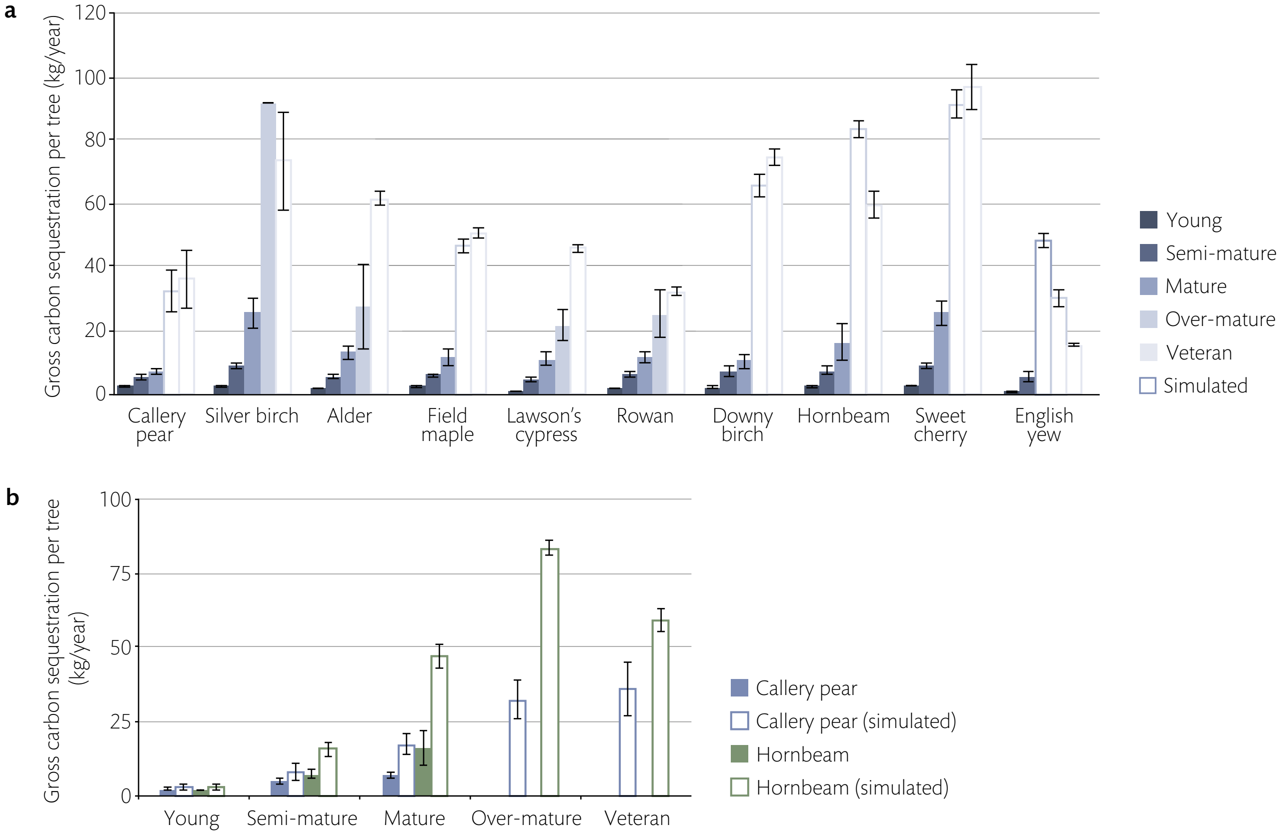
the simulated trees when compared to the field trees in each age classification. This may be in part because carbon storage for field trees was estimated as the average for that age classification, which was often composed of more trees at the younger end of that age classification. In contrast, the simulated tree dataset were developed with a full spread of trunk diameters across each classification, giving the average as the middle age of that age classification. The estimates for field-sampled trees are therefore often biased towards the younger, smaller trees in that age classification. In both alder and Lawson's cypress, field-sampled trees were on average 13% smaller than simulated trees in the semi-mature and mature age classifications, and this is reflected in the lower quantity of carbon stored (Figure 8b). The data for the simulated trees therefore reflects what would be expected to be achieved by a median tree in each age class, while the field-sampled tree data reflects the average for urban trees in each of the age classifications.

Gross carbon sequestration rate

The gross carbon sequestration rate of the medium stature trees is displayed in Figure 9a. The field-surveyed tree data suggests that carbon sequestration rate increases with tree age. The simulated tree data also shows that a slowing down of the carbon sequestration rate, sometimes followed by a decline in rate, was observed in the older age classifications. For example, hornbeam's sequestration rate declined after the over-mature age classification, while yew's rate declined earlier, reaching a peak in the mature age classification. In contrast, some species such as alder and Lawson's cypress showed an increase with each successive age classification. The species which performed best were sweet cherry and silver birch. Yew, which performed well in terms of carbon storage, had a relatively slow carbon sequestration rate, due its slow growth rate and long lifespan.

Figure 9b compares the carbon sequestration rates of field-sampled and simulated trees for hornbeam and callery pear species in each age classification. Similar to estimated carbon storage, the results for carbon sequestration rates for simulated trees exceed estimates for the field-surveyed trees. This is particularly visible in the mature age classification for hornbeam and can be attributed to the mean field trees being 20% smaller than the median size of the simulated trees. Additionally, field-sampled hornbeams in the mature age classification had a poorer condition than simulated

Figure 9 (a) Modelled gross carbon sequestration per tree per year for medium stature tree species. Field-surveyed data are shown in solid bars and values estimated from ideal trees are shown in the white bars; (b) comparison between the modelled carbon storage for the field-surveyed and simulated trees for callery pear and hornbeam. Error estimates are ± 2 standard errors of the mean.



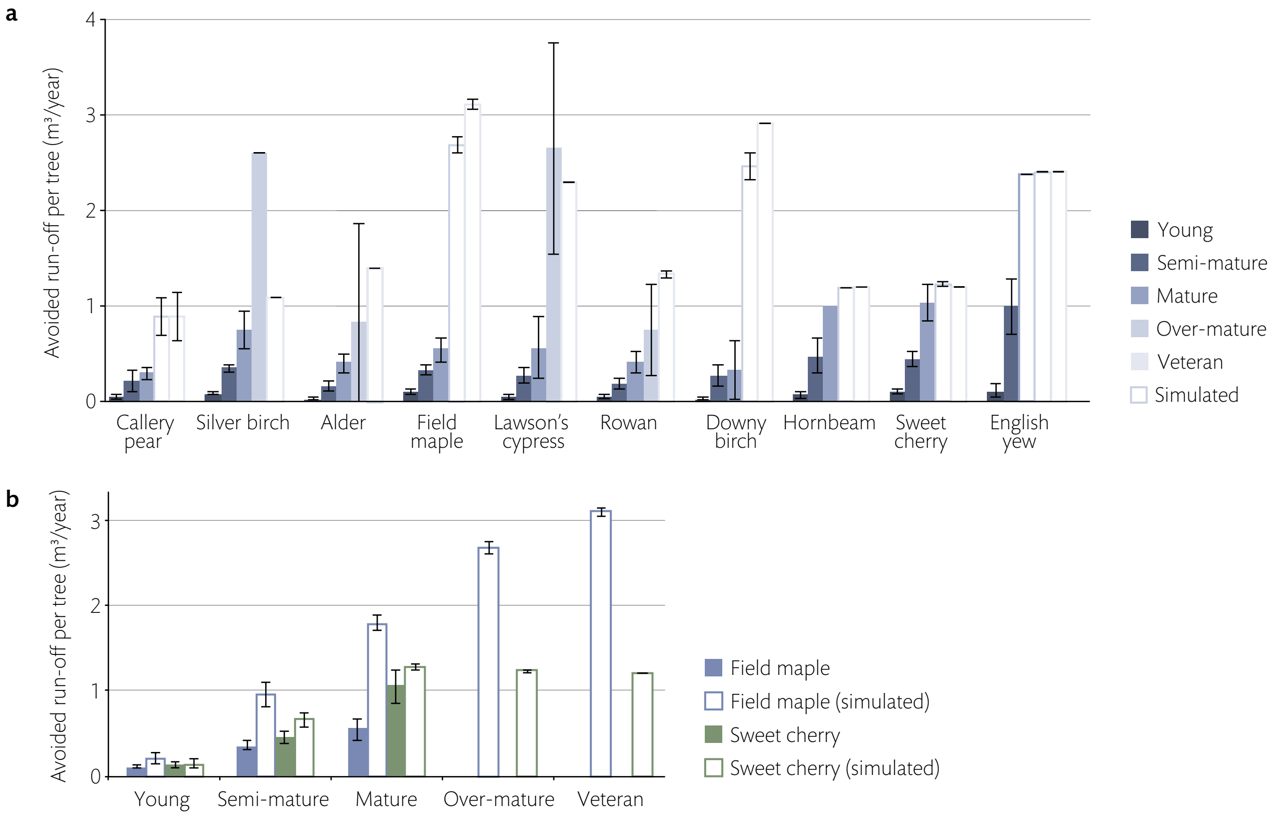
trees, which would have reduced their estimated growth rates and carbon sequestration rates. Callery pear showed a similar trend in both size and condition in the mature age classification, resulting in the high estimated carbon sequestration in simulated trees compared to field-sampled trees. The effect of shading on field trees may also have reduced sequestration rates. Field-sampled trees had, on average, a CLE value of 2, indicating that only two sides of the canopy received direct sunlight. This could be because few urban trees are open grown and are instead planted in blocks or in hedges. By comparison, simulated trees were modelled with a standard CLE value of 4, indicating that they were less overshadowed and able to grow faster, consequently sequestering more carbon.

Avoided storm water run-off

The volume of avoided storm water run-off by the medium stature tree species was found to increase with each successive age classification (Figure 10) and, when also taking into consideration the simulated data, peaked in the over-mature or veteran groupings (Figure 10a.) Substantial increases in the provision of this ecosystem service were observed from the mature to the over-mature age classification, particularly for silver birch and Lawson's cypress. This increase was also observed when considering the simulated data for field maple and downy birch. Other species displayed a more gradual increase with age classification, for instance, rowan and alder. The reaching of a peak in the older age groupings indicates that these trees have attained their maximum canopy size and density and do not expand further with increasing age. The medium stature trees which were estimated to have the highest avoided run-off values were field maple, downy birch, Lawson's cypress and silver birch. These tree species each had leaf areas >700 m^2 in the over-mature and veteran age classifications (field-sampled and simulated trees) and were each estimated to intercept 2.5 m^3 of rainfall per year.

Figure 10b compares the simulated and field-sampled data in each age classification for field maple and sweet cherry. While the simulated trees were estimated to intercept more rainfall (and thereby more avoided storm water run-off) in comparison to the field-sampled trees, this difference was much smaller for sweet cherry than for field maple. In sweet cherry, field-sampled trees were in a similar condition to simulated trees. In field maple, where a bigger divergence

Figure 10 (a) Modelled avoided run-off per tree per year for each species of medium stature trees. Field-surveyed data are shown in solid bars and values estimated from simulated trees are shown in the white bars; (b) comparison between the modelled carbon storage for the field-surveyed and simulated trees for field maple and sweet cherry. Error estimates are ± 2 standard errors of the mean.



was present, field-sampled trees were both smaller and in poorer condition than simulated trees. For sweet cherry, avoided storm water run-off peaked at 1.26 m^3 in the over-mature classification, indicating a peak leaf area had been reached. In comparison, avoided storm water run-off continued to increase for field maple through each successive age classification, peaking at 3.11 m^3.

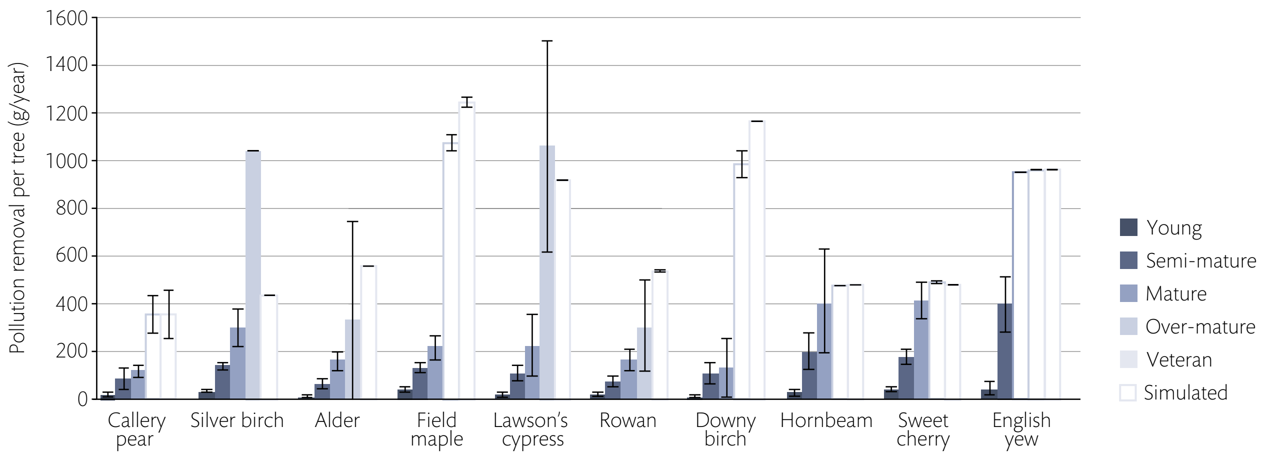
Air pollution removal rate

The air pollution removal rates across age classifications are shown in Figure 11. The amount of air pollution removed by the 10 medium stature trees studied was highest in either the over-mature or veteran age classification, based on both field-sampled and simulated data (Figure 11a). Air pollution removal peaked between the over-mature to veteran age classifications in all cases except silver birch, where a large decline was observed between the over-mature and veteran age classifications. The highest rates of air pollution removal (>1000 g per tree per year) were found in field maple, downy birch, Lawson's cypress and silver birch, based on both field-sampled and simulated data. In contrast, the other species removed just over half this quantity of air pollutants.

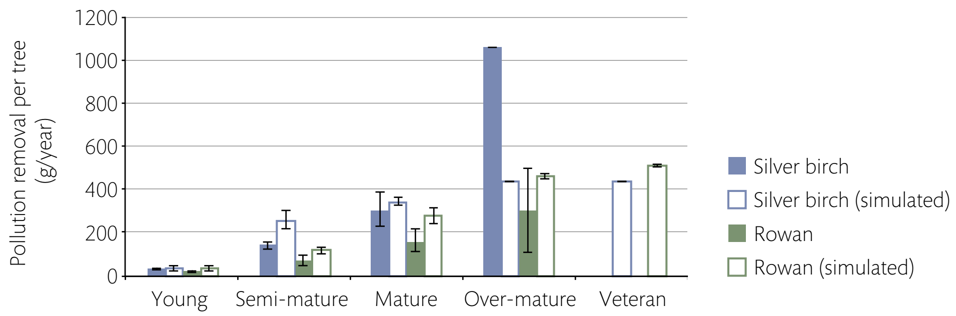
Figure 11b compares the field-sampled and simulated air pollution removal rates across all age classifications for silver birch and rowan. A greater amount of air pollution removal was estimated for the simulated trees for both species across all age classifications with the exception of silver birch in the over-mature age classification. The lower estimates reported from field-sampled trees is probably due to these trees typically being smaller than the median expected for that age classification, which was the size of tree used in modelling the simulated trees. As a consequence, field-sampled rowan trees had roughly half the total leaf area of that estimated for simulated trees in the mature and over-mature age classifications. The exception was silver birch in the over-mature age classification, which greatly exceeded estimated air pollution removal by the simulated trees. However, this may be anomalous as the field-sampled dataset consisted of a single silver birch that was tall with a wider canopy and which was in very good condition. In comparison to the over-mature simulated tree average it had nearly twice the total leaf area, which explains the significantly greater estimated air pollution removal service. This field-sampled silver birch highlights the variation that can be expected in field-sampled trees arising from constraints to growth across various different sites.

Figure 11 (a) Modelled pollution removal per tree per year for medium stature trees. Field-surveyed data are shown in solid bars and values estimated from simulated trees are shown in the white bars; (b) comparison between the modelled carbon storage for the field-surveyed and simulated trees for two species: silver birch and rowan. Error estimates are ± 2 standard errors of the mean.

a



b



Discussion

Suitability of approach

i-Tree Eco utilises the Urban Forest Effects (UFoRE) models (i-Tree, 2016). These models have been published in peer-reviewed 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.

This report reviews how ecosystem services delivery changes as trees age. An analysis of the relationship between DBH (as a proxy for time) and ecosystem services delivery was shown in Figures 2 and 3: strong trends were evident among DBH, carbon sequestration rate and carbon storage ecosystem services, but weaker trends were observed among DBH, avoided storm water run-off and air pollution removal. The greater variation in estimated avoided storm water run-off and air pollution removal ecosystem services for trees of similar size was attributed to the high variation in leaf areas estimated for field-surveyed trees. The high variation in leaf area suggests that factors which alter canopy size, such as tree health and management actions, can play an important role along with tree age in determining the capacity of trees to provide avoided storm water run-off and air pollution removal ecosystem services. Small stature trees in particular had weaker relationships for these two ecosystem services with DBH compared with medium or large stature trees (Hand, Doick and Moss, 2019). Grouping trees into age classifications (Figures 4–11), showed that older age classifications often had a high variability in estimated ecosystem services provision. In part, this may reflect natural variability in trees, or the effects of management actions, or could be a consequence of the grouping strategy, which was size-based rather than physiologically based. If a physiological definition had been adopted, the field-sampled trees may have fallen into different groupings than those used in this study. For example, an oak can be physiologically mature prior to reaching the 82–163 cm size category used for the mature age classification, and some trees with a very large trunk diameter may not have been defined as physiologically veteran ('a tree that is of interest biologically, culturally or aesthetically because of its age, size or condition' (Read, 2000)). However, a physiologically based grouping was not possible for this study as this is not routinely assessed as part of an i-Tree Eco survey. Further research to assess ecosystem services delivery in older trees and the impacts of different management actions could improve the accuracy of ecosystem services delivery estimations.

The variability in the data and error around estimates of ecosystem services delivery was partly a result of small sample sizes. While every effort was taken to model as large a population of trees as possible for this report, the population was limited for some species and age classifications (Tables 3 and 4). In particular, trees in older age classifications were infrequently found in i-Tree Eco field studies because trees of large size are comparatively rare in the urban environment (Britt and Johnson, 2008) and so are less likely to be found using a randomly placed plot-sampling method. The low sample sizes in the older tree age classifications limit the representativeness of ecosystem services estimations for these classifications to the wider urban tree population, and therefore it is prudent not to apply the results of this study to individual trees in the urban realm which may be impacted by environmental or management factors 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 either www.itreetools.org/eco/ or www.treezilla.org to undertake their own analysis. The simulated tree dataset was used to estimate ecosystem services delivery where no field trees were recorded. These results should also be considered as indicative because they represent average values within the group and also because 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.

Two approaches were used to compare ecosystem services delivery by the small and medium stature tree species with different lifespans and the maximum attainable DBHs: (i) DBH (as a proxy for change in time) and (ii) age classification. Measures of DBH enabled calculations of ecosystem services by different trees of the same species, thus showing intra-species variability and the change in delivery with increasing tree size. Age classification meant that the potentially very different lifespans of small and medium stature tree species could be considered; for example, yew may live for thousands of years whereas a rowan will be unlikely to attain an age of 60 in the urban environment. This approach enabled direct comparisons of species that would otherwise have been impossible. The term age class is used to represent distinct phases within the life-cycle of an average tree (e.g. young, semi-mature, mature and over-mature; BS5837 (2012). It is specifically used by arborists to assess the relative condition, age and remaining lifetimes of trees at that site and different classifications may be used to suit the assessment method adopted and/or interest of the arborist. However, age class is not solely dependent on time, but also on location; for example, trees may be constrained from reaching maturity where conditions are not favourable. Adapting the age class approach, an age classification categorisation was devised for this study, enabling the apportionment of trees into groups defined by DBH size, that is, specific for each tree species. This approach allows young and mature trees of different species to be compared, even although they may have a different age or DBH. It is pragmatic to illustrate change in ecosystem services delivery over a tree's lifespan while also permitting inter-species comparison, such as between small and medium or large 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 small and medium stature trees according to ecosystem services delivery

This section discusses the results of the modelled estimations of the four ecosystem services for small and medium stature species common to urban environments in Great Britain into a ranking of species from best to worst performing for each ecosystem service (Table 5). Trees are ranked based on ecosystem services delivery estimated within the mature age classification.

Yew was the best performing species across all four ecosystem services and also across all the small and medium species investigated (Table 5). A caveat to this observation is that the performance of yew is based upon simulated trees, which tended to overestimate ecosystem services provision compared with field-sampled trees. For all of the other species, results are based on field- sampled data; for medium stature trees, the top performing species were hornbeam, silver birch and sweet cherry; and, for small stature trees, the top performing species were holly, goat willow, plum spp. and hawthorn (Table 5). These species all tended to have larger DBHs and estimated leaf areas of the small and medium stature species assessed in this report, respectively

(Tables 3 and 4). However, this was not always the case; for example, alder had a larger leaf area than silver birch but was ranked lower.

The role of tree size in supplying greater ecosystem services delivery is evident from the top six species (Table 5) all being medium stature. Nevertheless, some small stature species supplied high levels of ecosystem services and outperformed a small number of medium stature species. Furthermore, species varied in their relative rankings across the different ecosystem services. For example, Downy birch performs poorly in terms of avoided run-off and pollution removal, but has much higher rankings for carbon storage and sequestration. This is attributable to the difference in tree structures: downy birch has a leaf area which is much closer to that of small stature species, while it tends to have a larger DBH, which is more in line with medium stature species. For holly, the opposite is true, in that it has a much greater leaf area compared with other small stature species. Evergreen species, including yew, Lawson's cypress and holly, provide ecosystem services throughout the year, while the deciduous species deliver these ecosystem services (except for carbon storage and some minor interception of rainfall) only in the leaf-on period, and therefore evergreens tended to be ranked mid-range or higher within their stature groupings.

Table 5 Small stature and medium stature tree species ranked from highest to lowest provision of ecosystem service.

Rank	Carbon storage	Gross carbon sequestration	Avoided run-off	Pollution removal
1	Yew #	Yew #	Yew #	Yew #
2	Hornbeam	Silver birch	Sweet cherry	Sweet cherry
3	Silver birch	Sweet cherry	Hornbeam	Hornbeam
4	Sweet cherry	Hornbeam	Silver birch	Silver birch
5	Lawson's cypress	Alder	Lawson's cypress	Lawson's cypress
6	European alder	Field maple	Field maple	Field maple
7	Downy birch	Rowan	Holly	Holly
8	Field maple	Lawson's cypress	Bird cherry	Bird cherry
9	Hawthorn	Plum spp.	Goat willow	Goat willow
10	Goat willow	Hawthorn	Rowan	Rowan
11	Apple spp.	Apple spp.	Plum spp.	Plum spp.
12	Plum spp.	Downy birch	Alder	Alder
13	Holly	Goat willow	Hawthorn	Hawthorn
14	Rowan	Holly	Hazel	Hazel
15	Hazel	Callery pear	Apple spp.	Apple spp.
16	Callery pear	Hazel	Downy birch	Downy birch
17	Bird cherry	Bird cherry	Callery pear	Callery pear
18	Elder	Elder	Elder	Elder

based on simulated trees due to the lack of mature trees in the field dataset
Note: Rankings are based upon the mature age classification and field-sampled trees, with the exception of yew, for which no trees were found within the mature age category and so its values are estimated from simulated trees. Medium stature tree species are indicated by a purple background.

The lowest ranked species for every ecosystem service was elder. Other small stature species (bird cherry, hazel and apple spp.) each performed poorly in at least one ecosystem service. Callery pear and downy birch, both medium stature species, provided less ecosystem services than the other medium stature species, and also most of the small stature species as well. There was a substantial difference in the quantity of ecosystem services provided by the top and lowest ranked species. Elder stored less than 3% of the carbon stored in yew (2594 kg) and just 10% of that stored in hornbeam (715 kg). Yew was estimated to prevent 2.4 m^3/year of storm water run-off, which was 12 times the amount of elder, and sweet cherry was estimated to remove 426 g/year of air pollutants, which was six times more than elder.

Conclusion and implications

The results reported here provide a guide for relative ecosystem services provision for trees of different species and ages. Individual field trees can vary greatly in their ecosystem services provision, and local factors play a major role in the ecosystem services delivery of individual trees. Overall, tree age was found to be strongly associated with ecosystem services provision, as older trees had greater trunk and canopy sizes, which supported greater capacity for ecosystem services provision. In comparison to the review of large stature trees (Hand, Doick and Moss, 2019), small and medium stature trees deliver less ecosystem services provision for the same age classification, with this difference being more pronounced in the mature and older age classifications. To optimise ecosystem services delivery by urban forests, the data suggest that management should focus on planting the largest stature of tree appropriate to each planting location. Many urban locations are unsuitable for large stature trees, for instance because of space limitations or risk to buildings. In these locations, planting small and medium stature trees can contribute to the overall canopy cover and ecosystem services provision objectives. In all circumstances, species selection must initially focus on species suitability to the location, as a tree which fails to thrive will not provide as much ecosystem services provision as a healthy tree.

The results reported here suggest that to enhance ecosystem services delivery for all trees, regardless of stature, management should aim to support the survival and long-term health of trees to enable more of them to reach older ages, when ecosystem services provision peaks. The evidence suggests that only a few urban trees attain maturity in urban areas. In a review in England, Britt and Johnson (2008) found that only 17% of trees were classed as mature and 0.2% as over-mature. In this study, out of the 3147 small and medium stature trees assessed, 16% were classed as mature and 2% as over-mature or veteran, which was similar to Britt and Johnson's findings. As well as providing greater regulatory ecosystem services provision as discussed here, mature and older trees also provide high amenity, cultural and biodiversity values (Barro *et al*., 1997; Lindenmayer and Laurance, 2017).

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This Research Report reviews the provision of four ecosystem services by 18 small and medium stature tree species using the i-Tree Eco model and compares the performance of these trees in different age groups. It is the second of two publications reviewing ecosystem service provision by trees of different stature and age in urban areas. The first Research Report reviews the ecosystem provision of large stature 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.

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