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An inventory of trees in Dublin city centre

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While urban areas are often considered to be comprised chiefly of artificial surfaces, they can contain a substantial portion of green space and a great diversity of natural habitats. These spaces include public parks, private gardens and street trees, all of which can provide valuable environmental services, such as improved air quality. Trees play a particular role in cities as they are often placed along roadsides and in the median strip of busy streets. As such they regulate access to sunshine, restrict airflow, provide shelter, scavenge air pollutants and manage noise at the street level. A tree planting policy can be an important part of a broader environmental strategy aimed at improving the quality of life in urban areas but this requires up-to-date knowledge of the current tree stock, which does not exist for Dublin. This article presents an inventory of trees in Dublin's city centre, defined as the area between the Grand and Royal canals. The results show that there are over 10,000 trees in the study area representing a density of 684 trees km^{-2} or one tree to approximately every 50 residents of the city centre. The tree canopy extent when in full foliage was nearly 1 km^2 in extent or 6% of the study area. A more detailed analysis of those trees planted along streets shows little species variation but clear distinction in the sizes of trees, which is indicative of the age of planting. These data are used to estimate the carbon stored in Dublin's trees.

Keywords: urban forest; environmental services; carbon storage; Dublin

Introduction

In 2008, the world's population crossed an important threshold when half of the world's 6.7 billion people were reported as living in urban areas. In most of the developed industrialised nations, more than 70% of their inhabitants are living in cities while the urban population in developing countries surpassed 40% and is rising sharply. With rapid urbanisation, it is expected that by the year 2050, two-thirds of the global population will live in cities (United Nations 2008). Cities are human constructs imposed on the natural landscape which, by their very nature, are concentrations of humans, materials and activities (Fenger 2009). While urbanisation is generally associated with economic development it is also associated with environmental problems such as noise, loss of green space, congestion, air pollution and lack of ventilation. Urban areas significantly alter climate at the micro-scale as a result of their physical form and functions. However, many of the undesirable aspects of the urban effect can be addressed by vegetation.

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Urban form refers here to the three-dimensional structure of the city and its material composition. In meteorological terms, buildings represent roughness elements (as do trees) that modify airflow patterns and generate areas of shadow and sunshine. The airspace below the rooftops of buildings forms an urban 'canopy' (by analogy with a forest canopy) where energy exchanges are governed by micro-scale interactions such as, for example, the exchange of radiation among the walls of buildings and the intervening street surface. The materials used for building and paving are generally impervious so that rainwater is quickly removed from the urban surface, with implications for urban runoff. More specifically it means that the soils below city streets (in which trees are rooted) are sealed from the overlying atmosphere. *Urban function* refers here to the gamut of human activities that occur within the city that generate waste heat and materials. This includes the heating of buildings, much of which is lost through the envelope and contributes to the warming of the urban atmosphere. In addition, motor vehicles generate a host of waste by-products including carbon monoxide, nitrous oxides, sulphur and particulate matter that is injected directly into the urban canopy layer. Together, form and function produce distinctive micro-scale urban climates that differ significantly in nearly every respect from the 'natural' non-urban climate. A measure of the impact of urban areas globally is that, while they occupy less than 3% of the Earth's land area (Miller and Small 2003), they are responsible for 80% of all anthropogenic emissions, including greenhouse gases such as carbon dioxide (Fenger 2009).

Vegetation can be used to manage urban-scale climate changes while contributing global-scale climate change adaptation and mitigation strategies. For example, trees may be used to shade and shelter buildings, thus reducing the need for energy to heat and cool the indoor environment (e.g. Gartland 2008). More broadly, trees play a role in pollution control (e.g. Brack 2002), carbon sequestration (e.g. Nowak 2006) and noise abatement (e.g. Fang and Ling 2003). In addition to the environmental services they provide, trees also bring important social benefits, especially in urban environments where open green spaces may be limited (Nilsson 2006). This research is focused on Dublin's urban form and function and the role of vegetation in a city-based climate management strategy. This article presents the results of a survey of trees in Dublin's city centre based on remote sensing analyses and fieldwork examination of street trees. This will provide a current inventory of Dublin's urban trees that will provide the basis for a more comprehensive environmental analysis, which will be presented in a subsequent article.

Trees in the urban environment

A tree is a perennial woody plant of substantial height and size with a single main stem (trunk) that branches to form a canopy. Small woody plants are categorised as shrubs. Trees may be classified into evergreen, which keep their leaves throughout the year, and deciduous species. Although they take on many different forms and sizes, tree morphology consists of three basic parts; crown, trunk and roots (Figure 1), each of which has specific functions. The trunk provides support to the canopy and is a conduit linking atmospheric exchanges at the leafy canopy to the exchanges at roots. The root system anchors the tree and provides water and nutrients. The canopy consists of branches that grow from the stem and support the leaf system. The main atmospheric exchanges occur at leaf surfaces, where energy, mass and momentum

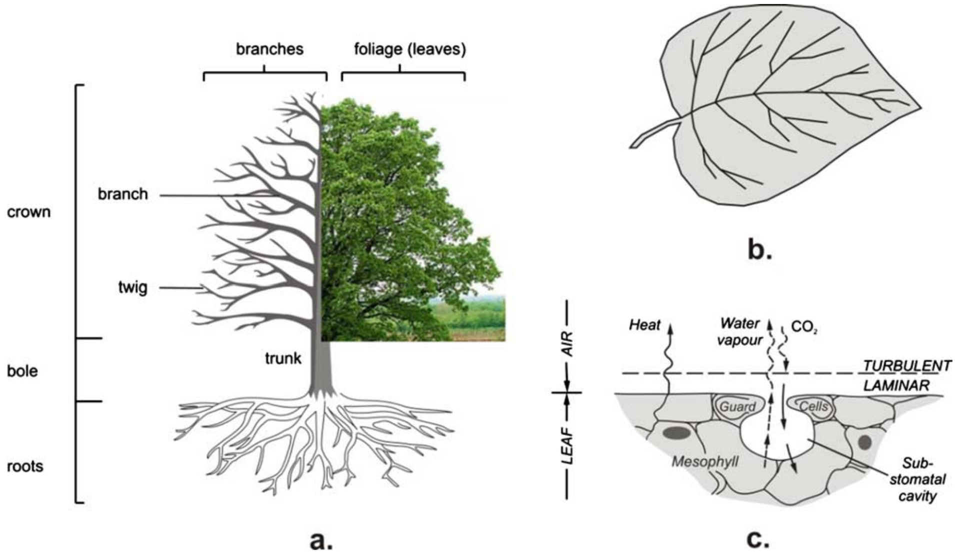


Figure 1. The structure of a tree (a) consisting of the roots, the main (trunk) stem and its branches and twigs. The bole is the commercially valuable part of the trunk. The crown consists of the leafy canopy and the supporting branches. The canopy is comprised of individual leaves (b) that represent the gaseous exchange surfaces of the tree. Each leaf will have a great number of stomata (c) that allow regulated interactions between the atmosphere and the leaf interior.

fluxes are concentrated. At each leaf surface gaseous and material exchanges between the leaf interior and the ambient atmosphere occur via stomata (Figure 1c), the density of which ranges from 50-500 per mm^2 of leaf surface (Oke 1987). Exchanges between the ambient atmosphere and the leaf interior are regulated by guard cells that control the size of these apertures. When open, they can account for between 0.3 and 1% of total leaf area (Oke 1987). It is at leaf surfaces that the exchanges required for photosynthesis (P) and respiration (R) occur,

P: (Carbon Dioxide + Water Vapour + Light energy) → (Carbohydrates + Oxygen)

R: (Carbohydrates + Oxygen) → (Carbon Dioxide + Water Vapour + Combustion energy)

It is the difference between P and R that results in the sequestration of CO_2. The rate of sequestration depends on the species of tree, its age and environmental conditions. Generally, this rate will increase with time as the tree grows in size. A large healthy tree will sequester over 90kg C/yr, while a small tree will capture 1 kg C/yr (Nowak 2006). The annual growth results in the cumulative storage of carbon by the body of the tree, much of it stored in the trunk. Approximately 50% of the dry weight of a tree represents carbon (Nowak and Crane 2002).

Most trees within the cities are planted, although in a few cases, urban forests have evolved and have been preserved, especially those that had grown naturally before the city came into existence. Due to the nature of the urban environment, city trees are exposed to a high level of environmental stress owing to excessively compacted soils, interferences with rooting systems, restricted access to light and to nutrients, impermeable surfaces, poor air quality including particulate matter that accumulates on leaves, and so on. Trees that are young are particularly vulnerable to these conditions and have high mortality rates (Quigley 2004). As a consequence, managing urban tree stocks can be quite challenging. Pauleit *et al*. (2002) examined tree establishment practices in 17 towns and cities across Europe. They found a wide variation in practices: while the trees selected for planting reflected the local climate, there was little guidance for tree managers on selection and establishment practices. The cost to establish trees in urban settings was found to range from €200 to over €1500 per tree. In addition to environmental stresses, however, part of this cost was linked to vandalism, which was found to affect up to 30% of the newly planted street trees.

There has been little work published on Dublin's trees. The Parks and Landscape Services Division of Dublin City Council reports that there are 60,000 street and roadside trees within the city and that an average of 5000 trees are planted each year.[1] However, there is no inventory of Dublin's trees that records their location, species, age or health. Pauleit *et al*. (2002) reported that varieties of Maple (*Acer*, 23%), Ash (*Sorbus,* 17%), Birch (*Betula*, 14%), Hornbeam (*Carpinus*, 14%) and Lime (*Tilia*, 11%) were the most commonly planted tree species in Dublin and found that, while climatic conditions were favourable for establishment, air pollution and vandalism represented the major threats. In addition, Kingston *et al.* (2003), while examining biodiversity in Dublin, advocated a planting scheme that included species diversity as a means of enhancing biodiversity in the city. However, in the absence of a database on the existing trees, it is difficult to devise a strategy for future tree planting in Dublin. It is hope that this study will provide a valuable contribution to the international literature on urban trees and a useful database to inform environmental policy.

Data and methods

The study area comprises the city centre of Dublin, defined as the area that lies between the Grand and Royal canals, an area of 14.4 km^2 (Figure 2). The city centre comprises about 12% of the administrative area of the Dublin City Council and contains a population of approximately 500,000 (or 4300 persons per km^2), according to the 2006 Census (www.cso.ie). For this area a digital base map was created from available sources. This map included the road network, building footprints and the Moland land-use database, which assigns land parcels (with a minimum map unit of 1 hectare) to one of 11 classes based on the activity at the ground floor level (European Environment Agency 2002). A geographic inventory on trees in the study area was obtained from digital satellite and aerial images, which provided an overview of the location of trees and of canopy coverage. This information was complemented by a fieldwork programme which gathered detailed data on those trees located along streets. Each methodology is discussed in turn.

Remote sensing

Two main sources of imagery were used to compile an inventory of trees in the study area. GoogleEarth (earth.google.com), which employs imagery from the QuickBird

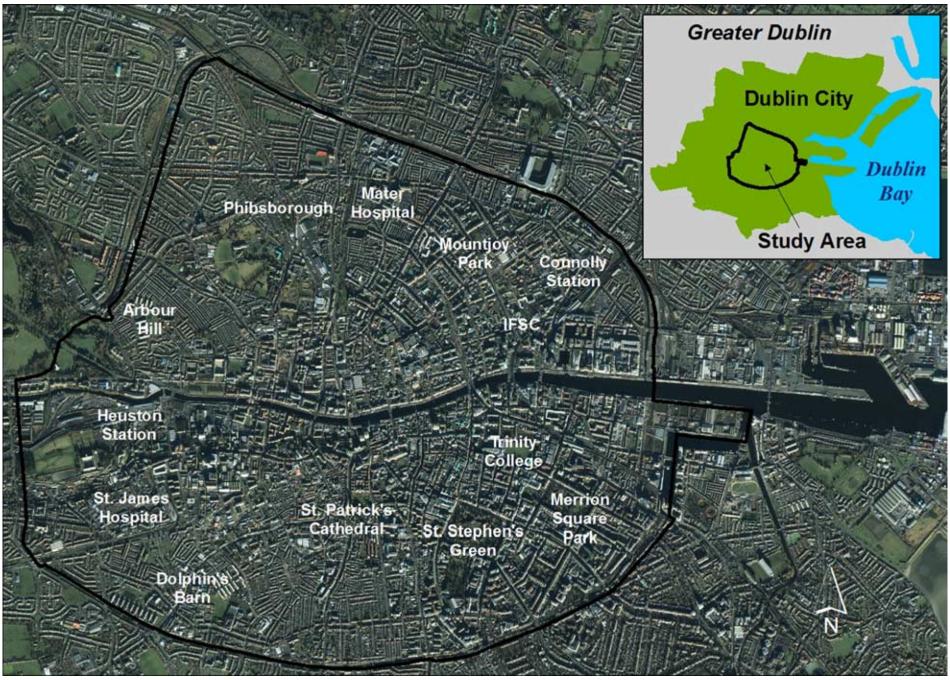


Figure 2. The location map of study area (14.4 km^2), the inset shows the study area in relation to Dublin City area (115 km^2).

satellite, was the main source of images. These record reflected radiation from the surface in four spectral bands corresponding to blue, green, red and near-infrared. The spatial resolution of each image is 61 centimetres on a side (or an area of about 3600 cm^2), which allows one to easily identify features like cars and trees. This information was complemented with oblique aerial images from Bing Maps (www.bing.com/maps). BingMaps allows the user to view the landscape at an equivalent resolution. Its advantage is that it provides oblique views (to 45° off vertical), which provides views of building facades, city streets and side views of trees (Figure 3). Together, these resources provide a comprehensive and up-to-date coverage of the study area. Moreover, using a web-based resource called DualMaps,[2] the images of both GoogleEarth (GE) and BingMaps (BM) can be viewed together for any location. This ability proved invaluable in the data acquisition phase of this study.

The images available on GE are updated at regular intervals so that the tree crown in leaf can be captured for the entire study area. However, each image covers a limited area and needs to be registered to a geographic co-ordinate system. To generate a single image (or mosaic) of the study area, a software utility called StitchMaps[3] was employed. The mosaic was imported into ArcGIS and geo-referenced to the Irish coordinate system. Individual trees and their canopies were subsequently digitised using a process termed 'heads-up' digitising. If the tree was clearly distinct and individual, the outline of the canopy was digitised and the location of the trunk was placed at its centre. Where many canopies merged, the DualMap facility was used to refine the location of tree canopies and their trunks.

Figure 3. The image on the left is taken from GoogleEarth and shows a view of St. Stephen's Green from above. The image on the right is taken from BingMaps and shows the same area from an oblique angle.

At the end of the procedure, each tree has a unique identification code that is linked to its location and canopy area. Other information on species type, relative size and health estimates, for example, could be obtained from these sources.

Fieldwork

Detailed information on some of Dublin's trees was obtained through fieldwork. We can crudely divide the tree population into those located in private and those in public spaces. Of the latter, trees are located in green park spaces and along streets. It was decided at the outset of the study to focus attention on public trees located along streets for both pragmatic and policy-relevant reasons. In contrast to trees in private spaces, street trees are accessible so that acquiring information is relatively easy. Moreover, these trees provide specific urban functions because they are positioned along transport corridors and their placement affects the adjacent buildings and outdoor environment experienced by road-users and pedestrians.

The fieldwork took place between April and November 2009. Using the digitised inventory obtained via remote sensing as a base-map, each of the streets in the city that had trees was visited to gather information on the nature of the tree stock. At each site, trees were photographed, their species identified and the circumference of the trunk at breast height recorded. Other information on the height of the tree and the shape and dimensions of the tree canopy were extracted from digital photographs taken at the site. The fieldwork spanned a period of nine months and revisits made it possible to take photographs of trees both during on-leaf and off-leaf seasons. One of the authors stood in each photograph to provide a scale. Various dimensions of the tree, such as height and crown width, can be abstracted from these images using software such as Photoshop. In addition, these photographs provided a record of the structural composition and variations between different species present in the study area. The information gathered during fieldwork was entered into the GIS database at the end of each session. Tree specimens such as leaves, barks, fruits and nuts of species that were not identified in the field were collected for identification later. In addition, the photographs were linked (via the tree identification code) to the elements in the GIS database.

Results

The presentation of results is divided into two sections associated with the overall character of Dublin's urban trees (derived chiefly from remote sensing images) and specifically with the data gathered from public street trees using images and fieldwork.

Dublin's trees

Over 10,000 trees (or 684 trees per km^2) were identified in the study area from the remote sensing images. The total tree canopy coverage is about 800,497 m^2 or 6% of the study area. Tree density shows significant variations across the city centre, with distinct clustering in some areas and lines of trees in others (Figure 4). To obtain estimates of tree density, a grid of cells (100m on a side) was placed over the study area and the trees within each grid cell were enumerated, resulting in units of trees per 10,000 m^2 (or hectare). When compared with an average of almost 7 trees per hectare (7 trees ha^{-1}) for the study area, areas in the south-east (e.g. St. Stephen's Green) and north-west have high values (>40 trees ha^{-1}). These areas are typically associated with green parks that are densely planted. Higher than average values also occur in the areas around parks and along the canals, which bound the study area. By comparison low values are found in the city centre, particularly on the north side, and along the quays in the eastern part of the city.

Initially, GIS functions were used to divide the tree population into those located in private and public spaces (using the Moland database) and those located within

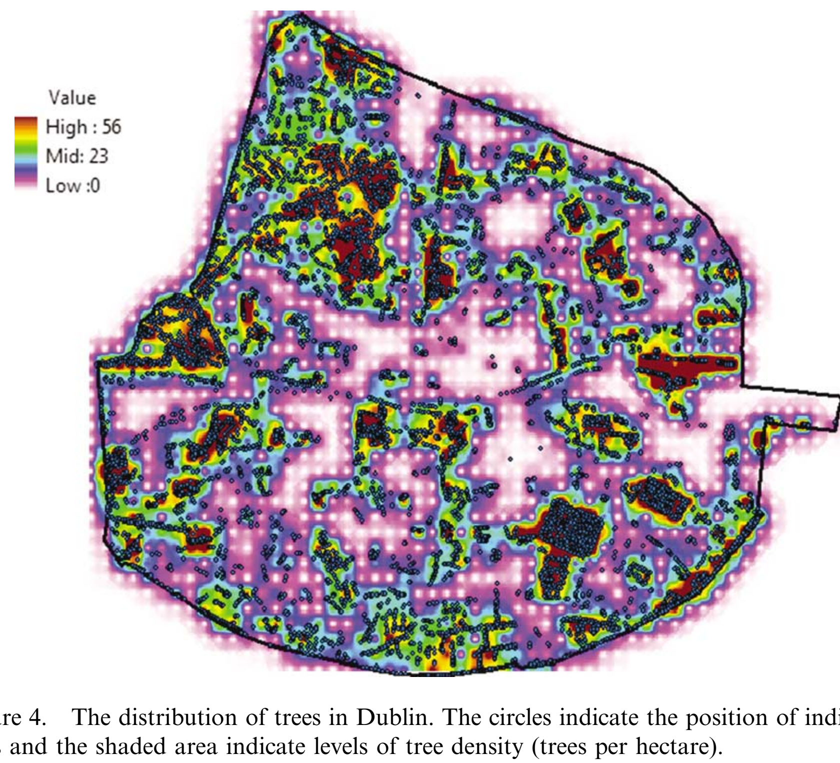


Figure 4. The distribution of trees in Dublin. The circles indicate the position of individual trees and the shaded area indicate levels of tree density (trees per hectare).

road corridors (defined as within 3m distance of the curbside). Approximately 63% of trees are located in private spaces (such as gardens) and 37% in public spaces (such as urban parks). However, when canopy size is considered, the smaller number of 'public' trees comprises 56% of the total canopy area in the study area. Trees located within the road corridor make up 27% of all trees, yet comprise just 17% of the total canopy area. It is not possible to categorise the road corridor trees into public and private using the base map information. However, these results suggest that the trees in public parks, which are outside the road corridor, are generally larger (based on canopy size). This indicates distinct sub-populations of trees associated in the study area associated with differences in species type and/or age (Table 1).

The relationship between trees and land-use/land-cover (LULC) was explored by assigning each tree to a Moland category (Table 2). The two largest LULC classes in the study area were 'Commercial' and 'Residential', which together comprise 65% of the land area. While the 'Residential' proportion of trees (40.5%) is comparable to the proportion of land (39.6%) it occupies, this is not the case for 'Commercial' area, which has just 16.7% of trees, although it occupies 25.1% of the land area. This difference is clearer when canopy coverage is considered; just 10.2% of the total canopy is based in 'Commercial' areas. Not surprisingly, it is the category 'Green Space' that stands out. Although it occupies just 6.3% of the study area, nearly 20% of the trees and 35% of the canopy area is in these areas. These results help to explain the pattern shown in Figure 4. Generally, trees are concentrated in public parks ('Green Areas') and these trees tend to be larger, which indicates that they are more mature. There are relatively few trees in 'Commercial' areas and those present are smaller in size. There are more trees by comparison in 'Residential' areas both in gardens and along streets but these trees are small by comparison with those in parks.

Street trees

Fieldwork was confined to those trees located along streets and are referred to as 'street trees' in the text that follows. A total of 2552 trees fell into this category and these were located primarily (85%) in 'Commercial' or 'Residential' areas (Table 2). Although fieldwork identified 41 different trees, most belong to just four deciduous species (Table 3): Lime (38%); London Plane (27%); Maple (14%) and; Hornbeam (5%). The 'Other' category in this table includes a wide variety of species such as Alder, Alder, Beech, Cherry, Chestnut, Copper Beech, Elm and Willow. Many of the trees in the 'Other' category tend to be concentrated along one street. For example,

Table 1. GIS assessment of the location of trees. Those located in public space include those located in public parks and along roads. Those not assigned to public space are considered to be in private space, mostly the gardens of residences. The numbers in parenthesis are percentages. Note that those trees located within the road corridor includes both private and public spaces.

Area	Number	Canopy (m^2)
Public space	3937 (37)	449769 (56)
Private space	6632 (63)	350728 (44)
Road corridor	2899 (27)	139371 (17)
Total	10569	800497

Table 2. Land-use/land-cover (LULC) in the study area. Each of the columns represents area, number of trees, area of canopy and number of street trees, respectively associated with each LULC category. The values in parentheses are percentages of the totals presented in the last row. The LULC categories are taken from the Moland database.

Land-use	Area (km^2)	Trees	Canopy (m^2)	Street trees
Commercial	3.612 (25.1)	1765 (16.7)	81295 (10.2)	917 (35.9)
Green Space	0.907 (6.3)	2038 (19.3)	282612 (35.3)	53 (2.1)
Health	0.716 (5.0)	645 (6.1)	60228 (7.5)	11 (0.4)
Industrial	1.049 (7.3)	391 (3.7)	27376 (3.4)	122 (4.8)
Recreational	0.237 (1.7)	166 (1.6)	12309 (1.5)	20 (0.8)
Religious	0.106 (0.7)	154 (1.5)	9268 (1.2)	24 (0.9)
Residential	5.706 (39.6)	4284 (40.5)	220646 (27.6)	1241 (48.6)
Restricted	0.184 (1.3)	70 (0.7)	6711 (0.8)	2 (0.1)
Services	1.146 (8.0)	979 (9.3)	85351 (10.7)	138 (5.4)
Transport	0.436 (3.0)	77 (0.7)	2684 (0.3)	24 (0.9)
Water	0.292 (2.0)	0 (0.0)	2015 (1.5)	0 (0.0)
	14.4	10569	790495	2552

along Mountjoy Street, in the north inner city, young Maidenhair trees were planted, elsewhere lines of Cherry Plum or Silver Birch dominate. In residential streets, it is Lime and Hornbeam that dominate, but fruiting and flowering trees like Rowan, Japanese Crab Apple and varieties of the Cherry species are also found. As 84% of the street trees belong to just four species, we focus on these in what follows.

In Table 4 a summary of the general characteristics of each of the four main street tree species is presented. The measured attributes for each street tree include tree height, trunk dimensions (height, diameter at breast height (DBH) and volume) and crown dimensions (height, depth and width). DBH was estimated from measurements of circumference. While the overall summary statistics for these attributes are presented in Table 5, Figure 5 shows the distribution of trees for two of the most important measures, tree height (H) and DBH. Both of these are indicators of the maturity of a tree. (See also Figure 6.)

There are several Lime sub-species but the hybrid or Common Lime is the most common of Dublin's street trees and, combined with the other Lime variants,

Table 3. A breakdown of surveyed street trees by species. The number in parentheses represents the percentage. There were 41 species identified through fieldwork of which just four species account for 84% of trees – the 'Other' category includes a large variety of species including familiar species such as Alder, Beech, Cherry, Chestnut, Copper Beech, Elm and Willow.

Tree Species	Count
Hornbeam	116 (5)
Lime	970 (38)
London Plane	697 (27)
Maple	354 (14)
Other	415 (16)
Total	2552

Table 4. Characteristics and images of the four most common street trees in Dublin. There are several sub-species of Maple and the characteristics of Sycamore are presented here. The description of tree characteristics is obtained from Aas and Riedmiller (1994).

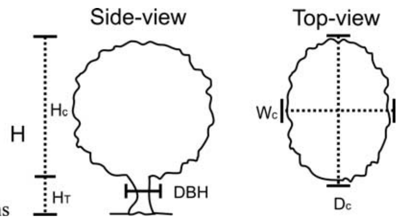
Tree Species	Example	Leaf
Lime Deciduous tree that grows to 40m tall. Has a relatively short trunk and wide, low, dense evenly domed crown. Flowers between June and July. Prefers moist open, base-rich loamy soils. Deeply-rooting shade species. (Photo: Memorial Rd./ Amiens St.)		
London Plane Deciduous tree growing to about 35m tall, with heavily branched crown. Flowers in May. Grows best on moist, deep soils. A deeply-rooting, hardy, light-loving species. (Photo: Cook St.)		
Maple (Sycamore) Deciduous tree growing to 35m tall with a strongly branched domed crown. Flowers in May and prefers deep moist, fertile, base-rich soils in cool humid sites. Fairly deep-rooted semi-shade species. (Photo: Quarry Rd./ Fassaugh Ave.)		

Table 4 (*Continued*)

Tree Species	Example	Leaf
Hornbeam A deciduous tree growing to 25m tall, with dense, rounded crown. It flowers between May and June and prefers moist, base-rich, loamy soils. Deep rooting semi-shade species. (Photo: Bloomfield Ave./ Ave Rd)		

Table 5. The statistics associated with the sampled trees, broken down by species. The mean (μ), standard deviation (σ) and skewness (Sk) are presented for the tree (height in m) and for properties of the trunk and crown. For the trunk, height (m), circumference (cm) and diameter (cm) at breast height, and estimated volume (m^3) are shown. For the crown, height (m), width (m) and depth (m) are listed.

Tree observations



		Tree	Trunk			Crown		
	Statistic	H	H_T	DBH	V_T	H_C	D_C	W_C
Lime	μ	6.640	2.422	17.144	2.393	4.221	4.485	3.591
N = 970	σ	2.431	0.712	11.569	2.567	1.790	3.959	3.071
	Sk	2.015	1.349	2.526	3.128	2.444	1.595	1.377
Hornbeam	μ	6.729	1.731	15.097	1.335	4.998	2.481	2.066
N = 116	σ	0.964	0.216	7.333	0.709	0.823	2.388	1.952
	Sk	−1.048	0.298	0.027	0.148	−1.373	0.368	0.217
London Plane	μ	12.902	3.865	55.771	11145	9.043	12.373	10.053
N = 697	σ	2.282	0.683	16.558	4.306	1.604	4.655	3.777
	Sk	−0.741	−0.725	−0.823	−0.380	−0.739	0.050	−0.294
Maple	μ	7.100	2.485	20.305	2.714	4.616	5.576	4.007
N = 354	σ	1.689	0.591	8.157	1.694	1.098	4.723	2.943
	Sk	0.741	0.741	0.801	1.442	0.741	1.951	0.123
Other	μ	6.630	1.754	16.823	1.769	5.049	4.113	2.727
N = 415	σ	2.361	1.076	11.607	2.285	3.170	6.776	3.502
	Sk	1.268	11.084	1.543	5.586	11.821	3.711	1.319

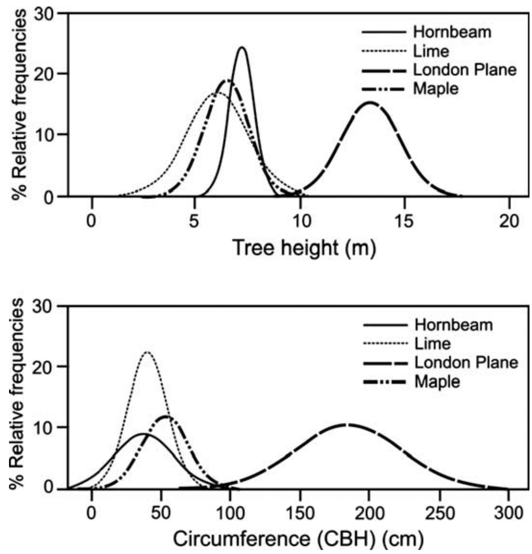


Figure 5. The distribution of height and circumference at breast height (CBH) for four tree species in inner city Dublin.

comprises almost 40% of the surveyed trees. A mature Lime tree has a columnar appearance and can reach a height of 40m and a spread of 20m. It flowers in early spring, grows quickly and is tolerant of urban conditions (Coombes 2004). There were 970 Lime trees surveyed with a mean height of 6.6 m, of which 2.4m is visible as a trunk with a DBH of 17cm. London Plane is a large tree that can extend to 35m in height and 25m in spread. It is highly tolerant and adapts well to urban environment.

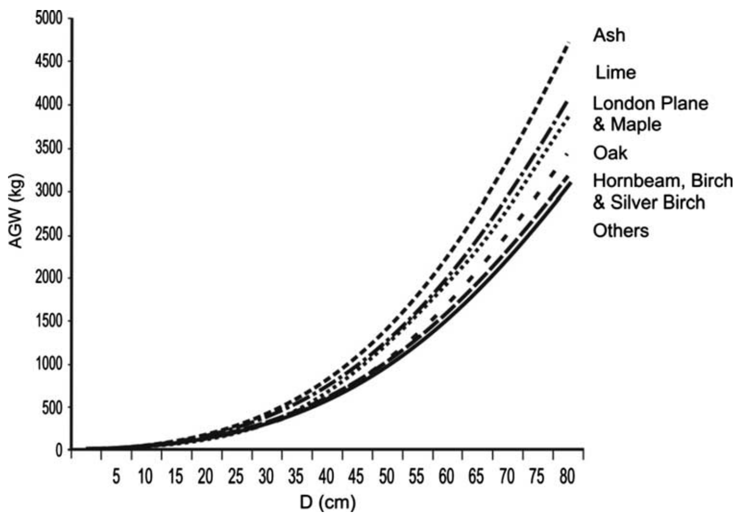


Figure 6. The relationship between the diameter of a tree trunk measured at breast height (D) and the above ground weight of a tree (AGW). The six curves shown are selected for the corresponding tree species listed and are based on relationships in Zianis *et al.* (2005).

There were 697 surveyed with a mean height of 13m and a DBH of 56cm. These dimensions are reflected in the size of the average crown, which is twice that of most species. Maple also features prominently in the survey (354 trees) and has many sub-species. The species in Dublin can be 25–30m in height, with a spread that increases with age to 15–20m when mature. In the survey these trees had an average height of 7.1m, a DBH of 20cm and crown dimensions similar to that of the Lime tree. There were 116 European Hornbeams in the survey. These trees are conical in shape when young but can develop rounder crowns as they mature. They can grow to a height of 30m and with a spread of 25m. In Dublin, their average height is just 6.7m with a DBH of 15cm. The statistics for the remaining trees (415) have comparable mean values to the other species except for London Plane, but possess a large skewness coefficient compared to the four main species, indicating the variety of species it includes. Overall, the London Plane trees are clearly identifiable as a separate sub-group of large street trees. This observation is reflected in Figure 5, which presents relative frequency distributions. Note that the distributions of Hornbeam, Lime and Maple overlap each other indicating that these species are approximately the same age. By comparison the London Planes are significantly larger.

Discussion

The pattern of Dublin's trees shows distinctive clusters of trees associated primarily with green areas (both public and private) and some streets. The street trees examined (which comprise almost 25% of the estimated total tree population) show little variation in terms of species however this sub-population is unlikely to be representative of all the trees in Dublin city. The larger canopy size associated with those trees in public parks suggests that these trees are either older or healthier or different species from street trees. One must bear in mind however that street trees are often pruned to ensure access to light so that canopy areas are not necessarily indicative of age. Nevertheless, the sizes of the street trees indicate distinct periods of planting. Of the four dominant species, London Plane has the largest average diameter (DBH) of 56cm, which corresponds to their average age of 80–100 years.[4] By comparison, the mean DBH for Lime trees (the most common species) is just 17cm, which is broadly similar to the average for both the Maple and Hornbeam species. As each of these species has approximately the same growth pattern, they are all of a similar age. Using the Lime trees as an example, Lukaszkiewicz *et al.* (2005) proposed a relationship between age and DBH based on a sample of street trees ($r^2 = 0.926$),

$$Age = -a + e^{b+c(DBH)},$$

where a = -444.106, b = 6.10556 and c = 0.2543367. Applying this equation to the Dublin data indicates that the Lime trees are, on average, just 24 (± 15) years old. This result shows that there is a 'gap' in the ages of street trees with few aged between 40 and 80 years.

Urban trees perform a great number of environmental services, many of which are difficult to estimate. This is particularly the case when one attempts to evaluate their net impact on an issue such as air quality, which depends on the nature of emissions, the ability of vegetation to remove airborne pollutants and meteorology.

Table 6. Average carbon stored and sequestered by DBH class based on Table 3 in Nowak (1994).

DBH Category	C storage (kg/tree)	C seq. (kg/tree/yr)	N	C storage (kg)	C seq. (kg/yr)
0–7	3	1.0	192	576	192
8–15	24	4.4	876	21024	3854
16–30	105	9.4	678	71190	6373
31–46	399	19.1	229	91371	4374
47–61	962	34.6	247	237614	8546
62–76	1808	55.3	291	526128	16092
≥77	3186	92.7	39	124254	3615
				1072157	42047

On the other hand, evaluating the role of vegetation in carbon sequestration and storage is relatively easy. Carbon (C) stored in the tree is evident in its woody biomass, which can be estimated from the measurements of DBH presented here. Nowak (1994) presented a simple relationship between categories of DBH and both total C stored (kg per tree) and the annual rate at which C is sequestered (kg per tree per year) (Table 6). Note that both the carbon stored and the carbon sequestration rates increases exponentially with size of tree – a large healthy tree (DBH > 77 cm) stores 1000 times more carbon, at rate 90 times that of a small healthy tree (DBH < 8cm).

The total amount of C stored in Dublin's street trees is 1,072,157 kg (or nearly 745 kg ha^{-1}) and 42,047 kg of C is sequestered per year (29.2 kg ha^{-1} yr^{-1}). The majority of the stored carbon (82%) is held by just 22% of the tree stock comprising trees that have DBH values over 46 cm (Table 6). As most of these large trees are London Plane it is not surprising that this tree species is responsible for 81% of stored C (Table 7). If we were to assume that the characteristics of street trees were representative of the tree population generally within the canals then the C storage values and sequestration rates become 3084 kg ha^{-1} and 88 kg ha^{-1} yr^{-1}, respectively. This is almost certainly an underestimate as the trees located outside the street corridor tend have larger canopies that would imply a larger stock of C (Table 2). Of course, street trees are often pruned so the difference in C storage may not be as large as the canopy differences imply.

A rudimentary comparison can be made with published data for other cities, of which there are few. For the Boston metropolitan area (an area of over 10,000 km^2 which incorporates significant green areas) the tree density is over 80 trees per hectare, that is, twelve times the density for the study area. These trees are estimated

Table 7. Average carbon stored and sequestered by species of street tree.

Species	N	C storage (kg)	C seq. (kg/yr)
Hornbeam	116	6891	696
Lime	970	114468	7644
London Plane	697	866901	28536
Maple	354	38675	3050
Others	415	45222	3120
Total	2552	1072157	43047

to store 20,300 kg of C per hectare and sequester 670kg of C per hectare annually (Nowak and Crane 2002). Although these values are substantially larger than those for Dublin, this is almost certainly a result of the delimitation of the study area which is confined to the inner city. Expanding the current study to include the built-up area of Dublin would increase the tree density, carbon storage and sequestration rates as it would include large tracts of mature suburbs and extensive green areas.

Conclusion

The research presented here is the first attempt to gather detailed information on trees in Dublin, specifically those within the area bound by the Royal and Grand canals, which delineates the city centre. Through a remote sensing survey, we estimate that there are more than 10,000 trees located in the study area and of these, more than 2500 were surveyed. The result is a database on the locations of Dublin's trees generally, and on the dimensions and species of street trees in particular. The sampled trees display distinctive properties both in terms of dimensions and locations – these are associated with species type and age. These data provide a valuable resource for examining the environmental services that urban trees can provide and provide a basis for a tree planting strategy.

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Notes

1. Source: www.dublincity.ie/RecreationandCulture/DublinCityParks/Pages/TreesintheCity.aspx
2. http://www.mapchannels.com/DualMaps.aspx.
3. http://www.stitchmaps.com.
4. Based on a conversation with the Parks and Landscapes Services Division of Dublin City Council.

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