Determining Tree Growth in the Urban Forest

Abstract

The benefits of the urban forest are likely to become increasingly important due to rising urban populations coupled with increased and intensified climatic events. Predicting the growth of tree species would enable researchers and urban foresters to predict ecosystem services over the lifetime of the urban forest whilst providing cost-benefit analysis, urban forest resilience and succession planning i.e. an improved understanding of urban tree growth would facilitate creation of valuable and sustainable urban forests. An approach to analysing tree growth in the urban forest is explored using dendrochronology. This approach allows relationships between tree growth and previous meteorological events to be investigated. Our study found that of four tree species investigated; sycamore (*Acer pseudoplatanus),* ash *(Fraxinus excelsior),* beech (*Fagus sylvatica*) and oak (*Quercus robur*), growth was greatest in ash followed by sycamore, oak and then beech. All species followed similar radial growth trends, however, sycamore cores were the most difficult to analyse due to indistinct growth rings. Sycamore cores were also the least sensitive to meteorological conditions, which indicated that this species is least affected by climate. It may also explain why sycamore is well adapted to UK urban areas. Beech showed a significant correlation between growth, annual average temperature, and sunlight hours. No significant relationship was found for growth in any of the four species when correlated with annual precipitation.

Introduction

Background

In order to develop viable strategies for conserving eco-system services, it is important to estimate the functional value of trees and woodlands so their importance can be demonstrated to stakeholders and beneficiaries (TEEB, 2009). Modeling the environmental benefits of trees is a means to ensure that the environmental benefits from urban trees are maximised. Predicting growth of tree species enables researchers and urban forest managers to model cost benefit analysis (McPherson *et al.* 2010; Sunderland *et al.,* 2012), investigate alternative management scenarios (McPherson *et al*., 1994) and select best management practices for increasing tree benefits (Adlard, 1995; Soares *et al*., 2011), thereby creating sustainable urban forests (Konijnendiijk, 2006).

Selecting, locating and managing trees to provide ecosystem services is increasingly important. Consequently the science of determining urban tree growth is fundamental to quantify these services (McPherson and Peper, 2012). However, relatively little is known regarding tree growth in UK urban forests (Britt and Johnston, 2008, UKNEA, 2011). Generally speaking, UK Local Authorities (LA's) have little information regarding plantings performed over 15 years ago (Britt and Johnston, 2008). Any information available is normally only held for public realm trees.

Consequently even less information is available on the growth rates of trees in urban areas. This lack of information is not just restricted to the UK (Darcy and Forrest, 2010; McHale *et al*., 2009; Semenzato *et al.,* 2011; Stoffberg *et al*., 2009). The US is one exception, where the USDA has developed over 1800 growth equations from measurements from 17,000 trees in 16 major US cities (McPherson and Peper, 2012).

Keywords:

dendrochronology, dendroclimatology, growth rates, urban forest

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Previous Research

In forestry disciplines, tree growth has been measured for centuries (Hasenauer, 2006) so relationships between site conditions and management are better understood. Yield tables and production forecasts are available for a variety of different species, sites and management prescriptions in many countries. The equations and empirical tables developed for plantation forestry are, however, not directly transferable to open grown urban trees because they are based on even aged, 'pure forests' (Peper and McPherson, 1998, Hasenauer, 2006, Cabanettes *et al*., 1999).

Approaches to Modeling Urban Tree Growth

Several approaches have been used to understand and develop models for urban tree growth. Nowak (1994) used allometric equations to express tree growth in estimations of carbon storage and sequestration. McPherson and Simpson (1999) developed growth curves from equations by Frelich (1992) for 3 climate zones (based on frost free days) using non linear regression as a predictive model for diameter at breast height (dbh) as a function of age. Predictions for tree height have also been modeled as a function of dbh (McPherson and Simpson 1999).

This work was further developed by Peper *et al.* (2001) into a logarithmic regression model for 16 climate zones using reference cities across the US. The models provided by Peper's work are widely adopted or used as a comparison for other studies in Europe, China, South Africa and South America (Lukaszwiewicz, 2005; Stoffberg *et al*., 2009, Jim and Chen, 2009; Escobedo *et al*., 2010; Semenzato *et al*., 2011). However, these studies have identified that it would be desirable to use growth rates which were more closely matched to the study area.

The majority of urban growth studies are based on public tree inventories (Peper *et al.,* 2001; Lukaszwiewicz, 2005, Stoffberg *et al*., 2009; Darcy and Forrest, 2010; Semenzato *et al.,* 2011). As trees used in these studies were only measured at one point in time, public records are essential to provide accurate estimations of the age of the trees studied. In the UK, however street tree records seldom go back more than 15-20 years (*Pers. Comm* Arboricultural Association, 2013). Measuring trees of different ages are required to establish relationships between age, stem diameter and other growth variables such as crown height or width. In most examples linear relationships between age and characteristics such as dbh have been established (Semenzato *et al*., 2011; Stoffberg *et al*., 2009).

Two exceptions are McPherson *et al*. (1994) who based growth rates on tree ring data from 543 trees growing in Chicago, Illinois, and Sjöman *et al*. (2011a) who analysed cores from 1159 trees from 23 species in 6 areas within an urban forest in Romania and Moldovia. In this study dbh was divided by age allowing a mean annual increment to be calculated. In a subsequent study (Sjöman *et al* (2011b), growth rates were compared to determine suitable species for urban areas through-out Northern Europe.

A review of these methods is summarised in Table 1 (below).

Table 1: Review of related urban tree growth study methodologies.

	Method Method	Notes	Author
Field Work Method	Terminal shoot growth and annual shoot extension measured		Close *et al*. (1996), Hodge and Boswell (1993).
	Diameter at breast height, height and crown spread used as relevant growth parameters	Age is normally ascertained by planting records in the urban studies.	Fleming (1988), Coombes (1994), Schwets and Brown (2000), Peper *et al*. (2001), Larsen and Kristoffersen (2002), Darcy and Forrest 2010), Semenzato *et al* (2011), Stoffberg *et al* (2009), Cabanettes *et al* (1999).
		Used in this instance to predict leaf area and leaf biomass.	Nowak (1996).

	Method Method	Notes	Author
		Targeted leaf area index relationships with diameter at breast height, tree height, bole height, crown height, crown diameter in two perpendicular directions, crown shape, crown vigour, percentage of crown dieback, and foliage discoloration.	Peper and McPherson (1998) Jim (1997a; 1997b), Achinelli *et al.* (1997).
	Tree height and crown dimensions measured	Measured tree height, maximum crown width, height of maximum crown width, diameter at maximum crown width, and height at crown break, presence of dead branches, crown dieback, hollows and fungal fruiting bodies to model urban tree growth in Canberra (Australia).	Banks *et al.* (1999).
		Looked at the DBH, Crown Diameter relationship in broadleaved trees	Hemery *et al* (2005)
		Focused on crown growth only.	Haserodt and Sydnor (1982), Kramer and Oldengram (2011).
	Increment core or tree ring widths measured		Dyer and Mader (1986), McPherson (1994), Quigley (2004), Sjoman *et al* (2011b).
	Remotely sensed data used	High-resolution spatial and aerial data used to provide dendrometric and tree health data sets. Most of this research is conducted in the forestry context (A) but it is now expanding to the study of urban forests and trees (B).	(A)Gopal and Woodcock, 1996; Leckie *et al.*, 2003; Popescu *et al.*, 2003. (B) Dwyer and Miller, 1999. Salas *et al* (2010), Kramer and Oldengram (2011).
Growth Modeling Method	Standard regression techniques and a sigmoidal growth curves used	Base growth rate used for i-tree Eco urban tree. However, McPherson and Simson (1999) found a log log model fitted urban trees better.	Frelich (1992).
		Used to model changes in dimensions of Australian urban trees.	Banks *et al.* (1999).
	Linear Regression	Models with simple linear regression or two-step least squares linear regression. Basis of model used in i-Tree Eco.	Fleming (1988), Peper *et al* (2001) Nowak (1994, 1996). Vrecenak *et al* (1989).
		Used to predict tree height based on the temperature differentials between provenance locations.	Carter (1996).

	Method Method	Notes	Author
	One-way analysis of variance and discriminant analysis		Dyer and Mader (1986).
	Analysis of variance models and regression		Hodge and Boswell (1993), Larsen and Kristoffersen (2002).
	General linear model	Estimated the growth and phenology of established Tilia cordata street trees in response to different irrigation regimes.	Bühler *et al*. (2006), Darcy and Forrest (2010), Sunderland *et al* (2012).
	Linear and non-linear regression techniques	Developed predictive model for DBH as function of age.	McPherson and Simson (1999).
		Examined trends in tree growth and stature.	Webster *et al*. (2005).
		Built up a street side Tilia cordata tree age model.	Lukaszkiewicz *et al*. (2005).
		Developed tree height and crown equations for trees in an urban South African Town.	Stoffberg *et al* (2008).
	Logarithmic regression	Built on the work of McPherson and Simson (1999).	Peper *et al* (2001).
		Developed equations to predict DBH from age and tree height, used in i-Tree Streets.	McPherson *et al* (2003).
		Growth predictions for 5 urban species in Italy.	Semenzato *et al* (2011).
	Chi-square procedure	Studied relationships between tree growth, site conditions and maintenance practices in street plantings.	Achinelli *et al*. (1997).
	Multivariate Statistics and Artificial Intelligence		Jutras (2008), Kramer and Oldengram (2011).

Dendrochronology

Dendrochronology research was pioneered by A.E. Douglass in the early part of the last century. Douglass studied conifer and hardwood trees from sites through-out North America and Europe. Douglass demonstrated that annual ring widths correlated with climatic variations and that this correlation also corresponded with patterns of narrow or wide annual rings from different tree species in the same geographical area (Douglass 1919). This is because trees respond to climatic variations such as precipitation, temperature and available sunlight (Speer 2010).

Dendrochronology was deemed to be the most suitable method for collecting growth data for this study as dendrochronology relies upon a set of principles where: 1) the rate of plant growth is regulated by the main environmental variable that is most limiting (e.g. precipitation or temperature) and 2) any individual tree-growth series can be "decomposed" into an aggregate of environmental factors that affect the patterns of tree growth over time (e.g. climate, exogenous disturbance or tree-age).

Study Area

The coastal borough of Torbay was selected as the study area because it was the site of a previous urban forest study (Rogers *et al.*, 2011) permitting further data input into already existing information previously collected from Torbay's urban forest. Furthermore, links with the local authority for the purposes of permissions and access were well established.

Torbay comprises of 3 towns; Torquay, Paignton and Brixham, with an area that covers 63.75 km^2 centered at 50° 27' N and 3° 33' W. Torbay lies in the south west of England (Figure 1) with elevations ranging from sea level to 164 m at its highest point. Torbay has a mild temperate climate due to its sheltered position and the influence of the gulf stream, with mean annual precipitation of 1,000 mm and mean average maximum and minimum temperature of 14°C and 7°C respectively (Met Office, 2013). Its population is *ca.* 134,000 (Torbay Council, 2013).

Figure 1: Torbay

Materials and Methods

Tree Coring

One hundred and four core samples (2 samples per tree) were collected from 4 different species (English oak (*Quercus robur*) ash (*Fraxinus excelsior*), sycamore (*Acer pseudoplatanus*) and comon beech (*Fagus sylvatica*) through-out the borough of Torbay, using a 30 cm manual single thread increment corer with a 5.15 mm inside tip diameter (Suunto, Vantaa, Finland).

Trees selected were less than 60 cm dbh due to core limitations, capable of only extracting a 30 cm core. Sample trees were greater than 50 years old (approximately 35 cm dbh) ensuring a reasonable meteorological record was associated with each tree. Trees selected for coring were as free as possible from exogenous variables that may have influenced tree ring growth. Trees where damage from pests, pathogens, storms etc., were observed were avoided.

Cores were removed from each tree at a height of 1 m where possible.

Orientation of the coring direction was recorded and general protocols on core collection, storage and transportation followed the methodology described by Grissino-Mayer (2003).

Core Analysis

The ten cleanest samples (those with distinct annual rings, complete from bark to pith) were selected for initial cross dating by visual methods. Skeleton plotting is the original technique developed by Douglass (1919) for dating samples. Skeleton plotting works on the principal that although 2 samples may be growing at different rates, distinct 'marker rings' that are consistently narrow or wide will appear across both samples in the same growing season. This permits identification of key marker years with which to build a master chronology from which all other samples can be cross referenced and dated to (Figure 2).

For the purposes of this study, strong marker years were identified as 2009, 1996, 1989, 1985, 1976, 1966, 1963, 1949, 1946 and 1937.

Core samples were collected from the study area during the winter of 2011/12 following protocols described in Grissino-Mayer (2003) and Speer (2010). Samples were prepared and measured using standard dendrochronological techniques (Speer, 2010; RinnTech, 2005). Rinntech produce the Time Series Analysis and Presentation (TSAP) software developed by Frank Rinn (RinnTech 2005).

Tree cores were mounted onto wooden batons and the cores sanded progressively finer using 100, 200 and finally 300 grit sandpaper to improve the visibility of the annual rings. Ring widths were viewed using a 10x-30x binocular microscope using a Lintab travelling stage connected to an IBM T41 laptop computer. Ring measurement data for each sample were recorded to 0.001 mm using the TSAP software which was then used to cross-date samples, and create average values for each tree species. Values were then compared with meteorological data present in the PractiStat statistics package.

The two cores from each tree were further compared to remove false rings and insert missing rings where appropriate. This process, known as cross dating was achieved by visual interpretation and statistically using the Gleichlaeufigkeit test (Rinntech, 2005).

Cores for each sample were then averaged to provide a mean radial growth increment for each tree for each year (also referred to as a 'sample series'). Averaging growth from two core samples also allowed for differences in tree ring growth that may be attributable to compression wood formation, damage or an ecological response to an unknown event (Speer, 2010).

The Gliechlaeufigkeit test (Glk) was used (Figure 3) to check the overall accordance of two sample series, or asks 'are two samples increasing or decreasing in growth at the same time?' (Speer 2010). Glk values over 65.0 are considered to demonstrate significant correlation between samples (Rinntech 2005, Spear 2010).

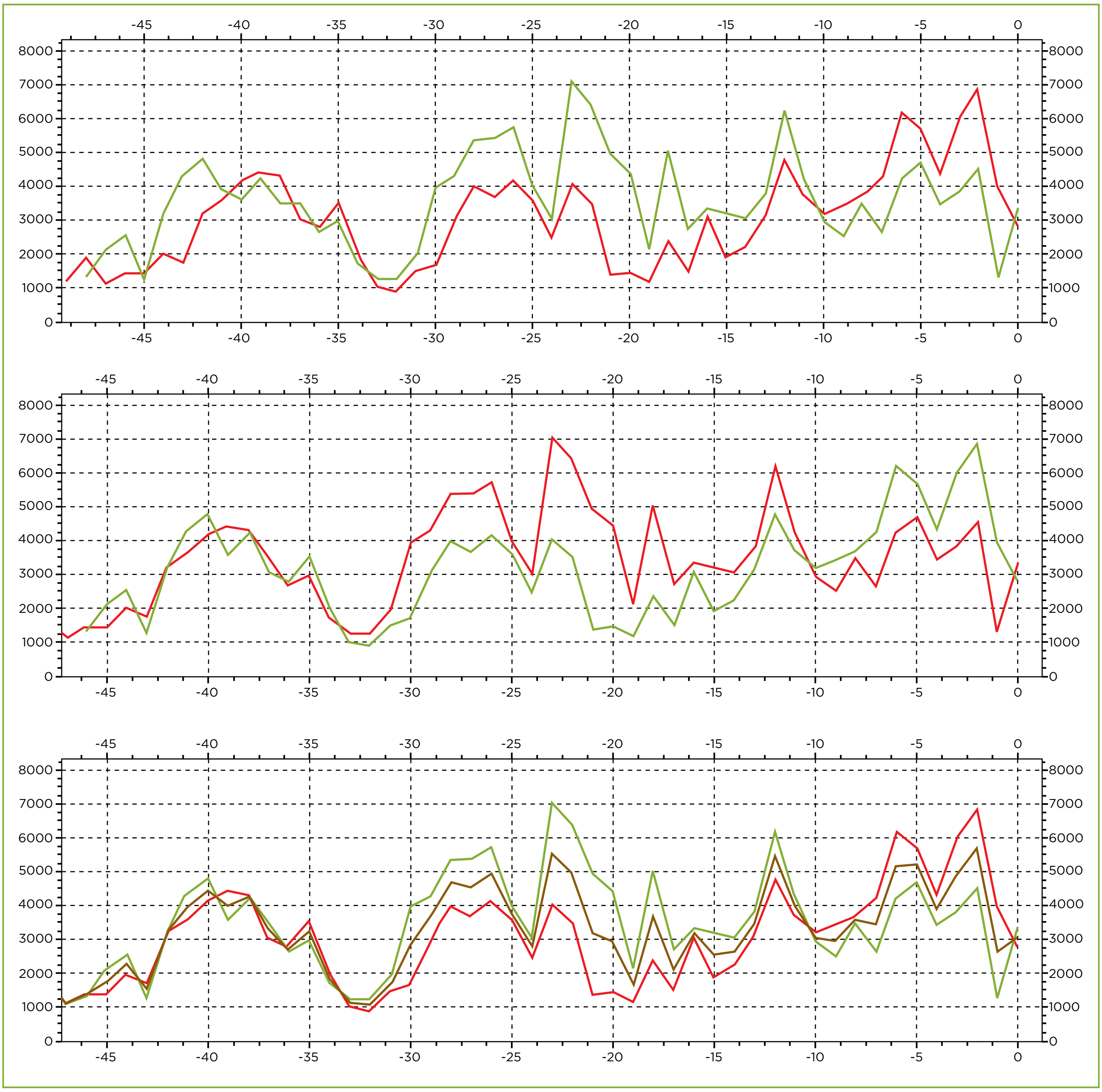

Figure 2: Example of measurements for 2 cores taken from sample 32. The top graph displays the width measurements of each annual ring from the 2 core samples. The middle graph illustrates how the two samples are cross-dated. In this instance 2 false rings were removed from years 41 and 42. The bottom graph shows the average annual increment for the 2 cores (in brown). The x axis shows each years increment from the bark to the pith (rather than from pith to the bark) and the y axis shows the measurement of ring increment to 1/1000 mm.

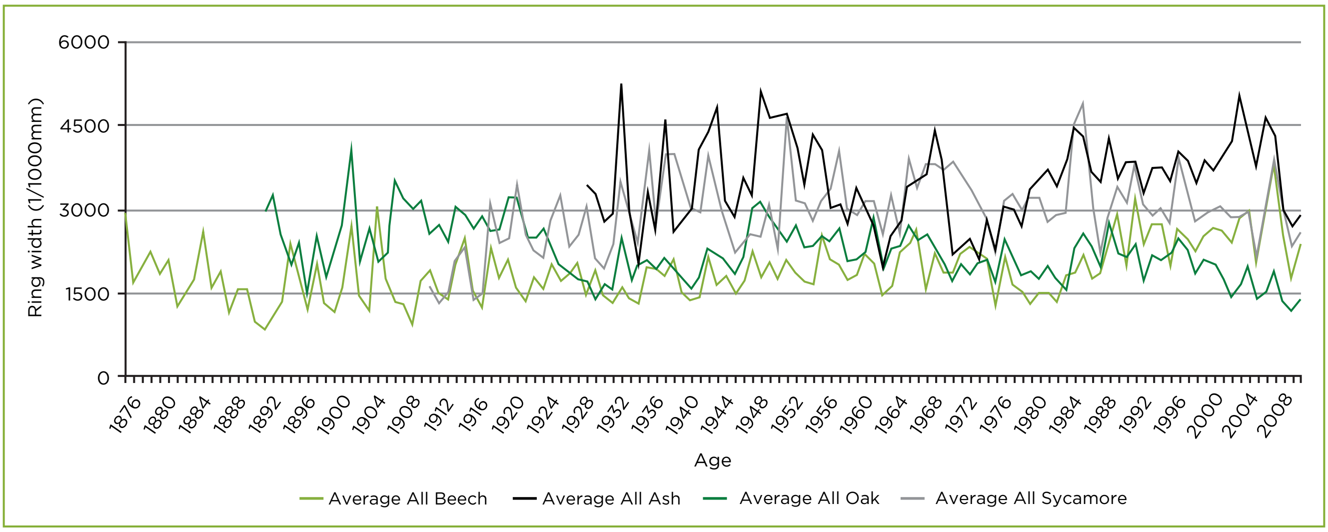

Figure 3: Correlation of annual ring width increment between species.

Samples with Glk scores under 65.0 were discarded from further analysis.

The Glk test was also used to produce an overall average for each species. Based on Glk values, two samples (T27 and T28) were rejected from analysis because they did not cross match with any other series. From the original 52 trees sampled 43 were correlated with meteorological data, representing 82% of the original sample set.

Climate Data

Climatic records were obtained from the British Atmospheric Data Centre (BADC) database using the MIDAS data set to obtain records from the Torbay study area with respect to daily precipitation (mm), sunlight hours and mean temperature (°C). Due to the length of the study period and the periodic decommissioning and replacement of weather stations, in order to provide a continuous data set over the duration of the study period, data was obtained from 3 weather stations located within the Torbay study area (Cary Green, Abbey Park and Torre Abbey).

Data was aggregated and averaged to provide annual mean averages (for temperature, precipitation and sunlight hours) and averages per growing season using phenology records, calculated as described in Rogers *et al*. (2011). Data was then compared with tree growth to establish correlations. The first year in which a complete set of data was established was 1930.

Table 2: Average growth rates plus standard deviation in brackets.

	Average Tree DBH increment (cm) per year		Average Tree Height increment (m) per year		Average Tree Canopy (m) increment per year	
MAX	0.556		1.667		3.750	
MIN	0.044		0.372		0.082	
All Average	0.300		0.750		0.840	
Open Grown Tree Average	0.394		1.455		2.541	
Others Average	0.255		0.645		0.465	
Oak	0.228	(.08)	0.601	(0.25)	0.588	(0.43)
Ash	0.400	(.08)	0.926	(0.33)	0.863	(1.15)
Syc	0.341	(.08)	0.840	(0.33)	0.931	(1.05)
Beech	0.220	(0.17)	0.643	(0.50)	0.635	(0.97)

Results and Discussion

An initial analysis compared dbh, height and canopy spread of each tree with age based on tree ring measurements (Table 2). Data could then be compared to similar studies at a later date.

Plotting the cumulative ring width increment (Figure 4) allows a measure of growth-growth between each tree species to be observed. Growth of all tree species are fairly similar for the first 15 years, thereafter rapidity of growth is in the order ash>sycamore>oak>beech. This ranking is in line with previous research (Ackers, 1938; Hamilton and Christie, 1971; Hart, 1994; Savill 1992).

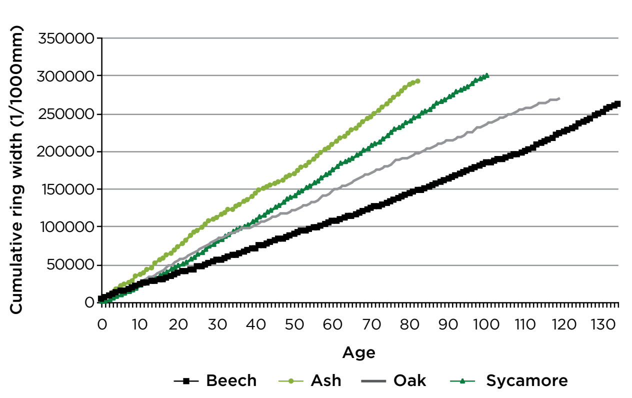

Figure 4: Culmulative ring width increment for each tree species.

According to White (1998) the growth of UK broadleaf trees for the initial 100 years was approximated to be 0.35 cm per year. Such a result equates well to average growth of ash and sycamore; 0.4 and 0.34 cm per year respectively (Table 2), where the sample series were 84 and 100 years old respectively.

With respect to oak and beech however, lower average growth was recorded, possibly because the sample series was collected from predominantly mature trees which had entered a mature phase, with reduced annual ring increment. In this instance, the sample series for oak and beech were closer to the 0.24 cm indicative radial growth rate provided by Mitchell (1979), whereby the growth of mature trees is estimated at around a 1.5 - 2.5 cm increase in circumference each year which would equate to a similar radial growth rate recorded here.

Open grown trees had increased growth over those in woodland settings which is consistent with other studies (Darcy and Forrest, 2010).Primarily this is because trees in open settings are free from competition and although competition may stimulate height growth, this is at the expense of diameter growth and crown development (Darcy and Forrest, 2010).

Specific climatic event years, determined from radial growth data are manifest as 'peaks and troughs' in Figure 3. Where these visible peaks and troughs in tree ring increment were observed across species (Figure 3) a climatic event was searched for in the literature that could explain the tree growth in that year. The results are provided in Table 3. The years of 1963 and 1976 provide examples where all sample series exhibited low radial growth (manifest as a trough in Figure 3). 1963 was a year with a severe winter in the UK and Holding (2008) also noted poor tree ring 'growth' rates in 1963 from a study on cedar trees in Taunton. The meteorological record showed that there was an extreme winter in that year, attributed to a volcanic eruption in Indonesia, whilst 1976 was a year with an exceptionally dry and hot summer.

The observation of particularly low or high tree ring increment for a given year across species and the link to various climatic events provided a very interesting exercise. Consequently, in order to determine the correlation between tree growth and climate, average tree ring increment was further correlated against the annual average meteorological variables (Table 4) using a Pearson's correlation test via the 'Practistat' software package.

Results showed that there was no significant correlations observed regarding annual rainfall and tree growth and only one significant observation with the average growth season data (beech and average temperature). Yearly averages for temperature and sunlight hours yielded results with significant correlations for beech, oak and ash. With regard to growth of sycamore no significant correlation was found with any meteorological data.

Sycamore produced the most indistinct rings in this study and these become increasingly prevalent with age. Moir and Leroy (2013), also highlighted this effect in lime (*Tilia spp*) which may limit the usefulness of these species for this type of study.

Table 3: Specific climatic event years where growth was affected across all tree species.

<table>
<tr><th>Year</th><th>Average All Beech</th><th>Average All Ash</th><th>Average All Oak</th><th>Average All Sycamore</th><th>Average Yearly Rainfall mm</th><th>Average Sun hrs/24hr Year</th><th>Average Temp Year</th></tr>
<tr><td>1933</td><td>1625</td><td>5365</td><td>2500</td><td>3511</td><td>1.94</td><td>5.30</td><td>10.95</td></tr>
<tr><td colspan="8">Event Notes: Notably WARM summer: one of the top 7 or so of the century. Regarded as extending from Jun through to September.</td></tr>
<tr><td>1937</td><td>1932</td><td>2560</td><td>1935</td><td>2656</td><td>2.88</td><td>4.53</td><td>11</td></tr>
<tr><td colspan="8">Event Notes: One of the WETTEST Februarys across England & Wales (using the England Wales Precipitation (EWP) series.</td></tr>
<tr><td>1963</td><td>1474</td><td>2036</td><td>1948</td><td>2539</td><td>2.52</td><td>4.16</td><td>9.1</td></tr>
<tr><td colspan="8">Event Notes: Mount Agung (Bali, Indonesia / East Indies) began erupting on February 18th (some references have 19th). The explosive clouds of gas and volcanic dust reached heights of more than 10km above the crater, high enough to reach the stratosphere. The atmospheric effects, including dramatically coloured sunsets & haloes around the sun, encircled the earth within a few weeks; there was a decrease in light measured from distant stars, with the decrease at a maximum between August to November 1963, lasting to some extent until mid-1964. Stratospheric TEMPERATURES rose as much as 6degC, and the average world near-surface TEMPERATURE dropped 0.4degC for 3 years after the eruptions.</td></tr>
<tr><td>1966</td><td>2380</td><td>3441</td><td>2722</td><td>3933</td><td>2.94</td><td>4.88</td><td>11.26</td></tr>
<tr><td colspan="8">Event Notes: One of the WETTEST Februarys across England & Wales (using the EWP series). RAINFALL totals were over 200% of average.</td></tr>
<tr><td>1976</td><td>1272</td><td>2301</td><td>1684</td><td>2212</td><td>2.18</td><td>5.31</td><td>11.24</td></tr>
<tr><td colspan="8">Event Notes: 1975/1976 (May to April): For the EWR series (since 1727), the 12 month period May 75 to Apr 76 was (at the time) the DRIEST in the series.
1975/1976 (two-year drought): The famous DROUGHT of 1975/76 was memorable for its severity over most of the British Isles, and also for its exceptional persistence. It produced the highest values for a drought index for south-east England in three hundred years.</td></tr>
<tr><td>1989</td><td>2367</td><td>4321</td><td>2760</td><td>2944</td><td>2.5</td><td>5.05</td><td>12.14</td></tr>
<tr><td colspan="8">Event Notes: SUNNIEST year in central London in a record which began in 1929. 1915hr recorded (against 1762hr in 1976). 2. Over a large part of the United Kingdom, one of the WARMEST & SUNNIEST in the modern (reliable) record. [see also 1959, 1995 & 2003].</td></tr>
<tr><td>1992</td><td>3210</td><td>3883</td><td>2428</td><td>3842</td><td>2.32</td><td>4.60</td><td>11.41</td></tr>
<tr><td colspan="8">Event Notes: WARMEST May of the 20th century over much of Britain, & into the ‘top-5’ warmest Mays in the entire CET record (the others were from the 18th and 19th century, so some doubt).</td></tr>
<tr><td>1996</td><td>1949</td><td>3478</td><td>2195</td><td>2744</td><td>2.54</td><td>4.95</td><td>10.71</td></tr>
<tr><td colspan="8">Event Notes: DRIEST year in the Heathrow record (started 1947). COLDEST year since the mid 1980s as well. A VERY DRY year in the EWP series: 682.2 mm/5th DRIEST in that series (as at 1999).</td></tr>
<tr><td>1997</td><td>2680</td><td>4034</td><td>2476</td><td>3985</td><td>2.38</td><td>5.11</td><td>12.01</td></tr>
<tr><td colspan="8">Event Notes: 30 month PRECIPITATION totals up to September 1997 were the LOWEST on record in England and Wales, with estimated return periods exceeding 200 years in many districts.</td></tr>
<tr><td colspan="8">Ring widths in 1/1000 mm</td></tr>
<tr><td>AVG*</td><td>2,099</td><td>3,491</td><td>2,294</td><td>3,152</td><td>2.47</td><td>4.88</td><td>11.09</td></tr>
<tr><td colspan="2" rowspan="2">Growth = 1/1000mm</td><td>Min*</td><td>1.10</td><td>2.96</td><td>8.81</td><td></td><td></td></tr>
<tr><td>Max*</td><td>3.17</td><td>6.13</td><td>12.45</td><td></td><td></td></tr>
<tr><td colspan="8">All Notes Sourced from Booty (2012)</td></tr>
</table>

*(from all series years - not just those listed)

Table 4: Results of Pearson's test for correlation with tree growth and meteorological data.

	Average Rain	r	Average Sunlight Hours	r	Average Temp	r
	Growth Season					
	Year					
Ash	NS P > 0.05	0.117	NS P > 0.05	0.166	NS P > 0.05	0.253
	NS P > 0.05	-0.069	< 0.05	0.301	< 0.05	0.282
Oak	NS P > 0.05	-0.036	NS P > 0.05	0.186	NS P > 0.05	-0.020
	NS P > 0.05	-0.082	< 0.05	0.229	NS P > 0.05	0.056
Beech	NS P > 0.05	0.052	NS P > 0.05	0.195	< 0.05	0.296
	NS P > 0.05	0.164	< 0.05	0.264	< 0.05	0.502
Sycamore	NS P > 0.05	0.114	NS P > 0.05	-0.82	NS P > 0.05	0.079
	NS P > 0.05	0.038	NS P > 0.05	-0.103	NS P > 0.05	-0.121

Results for beech yielded significant relationships in three out of six cases including the only significant correlation with growth season data. In comparison ash yielded two significant results and oak one. All significant correlations were mainly positive but severe drought years such as those which occurred in 1976 and 1996 had a negative correlation.

Conclusions

The study has demonstrated a methodology for analysing tree growth in the urban environment and a method for establishing age and growth rates from selected core samples.

Great care must be taken in the collection, preparation and interpretation of tree cores as these can present many anomalies and exhibit unusual growth patterns.

Cores need to be cross correlated within the sample (or series) and ideally should be checked against other existing chronologies where available.

The study has demonstrated that for the species observed maximum growth is achieved by ash, followed by sycamore, oak and then beech.

When comparing tree growth to meteorological variables, average temperature provided the most significant correlation with tree growth. Other variables such as average sunlight hours and average precipitation provided less meaningful results.

Similarly, comparing tree growth with meteorological averages from a growing season did not provide a strong correlation, whereas yearly averages did.

The growth response of beech to the meteorological data indicates that beech is a species which is sensitive to variations in climate than the other species studied. This concur's with other findings in the literature (Broadmeadow *et al*., 2005; Henewinkel *et al*., 2013).

Sycamore was the least sensitive to environmental conditions in Torbay with no significant correlation with meteorological data recorded. Sycamore also had the most difficult to interpret tree rings. These factors may limit its usefulness as a tree for establishing patterns in tree growth for other studies.

Ongoing Research

Building on the Torbay study, Forest Research UK are undertaking a UK wide survey to determine the growth rates of urban trees and identify how growth differs from forest stands. This research will inform us of urban growth rates for four common deciduous tree species, Sycamore (*Acer pseudoplatanus*), Common Ash (*Fraxinus excelsior*), Silver Birch (*Betula pendula*) and English Oak (*Quercus robur*). This data will feed into models, such as iTree, to calculate ecosystem service delivery of urban trees. With UK data driving the models the monetary value assigned for carbon storage and sequestration, pollution removal and avoided storm water run-off will become UK specific and, therefore, more fit-for-purpose in a UK context.

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