What we know and don't know about the carbon storage and sequestration of urban trees

M. A. Rahman and A.R. Ennos

Strategic Landscape Planning and Management, Technical University of Munich
Emil-Ramann-Str. 6, D-85354 Freising, Germany

School of Biological, Biomedical and Environmental Sciences, University of Hull, Cottingham Road, Kingston-upon-Hull, HU6 7RX, UK

Tel 01482 466274
R.Ennos@hull.ac.uk

Abstract

Carbon storage and sequestration are widely regarded as one of the most important physical benefits provided by urban trees, and have been fairly widely studied, especially in the US. Both are usually determined by combining surveys of the numbers and trunk diameters of trees with allometric equations relating biomass to diameter. However, only in the US have such allometric equations been determined for urban rather than forest trees. Results show that storage of carbon in urban trees lies in the range of 10-30 t ha^{-1}, and sequestration in the range of 0.1-0.9 t ha^{-1} yr^{-1}, depending on tree cover and age, but there is considerable uncertainty in the figures. In particular more needs to be known about the storage of carbon in roots and soil beneath urban trees and the cultivation and maintenance costs of the trees themselves. Little is also known about how carbon sequestration rates vary between trees of different species and grown under different conditions. The main take-home message from the research, however, is that all of the figures are small. Carbon sequestration rates of urban trees can be two orders of magnitude smaller than emission rates due to transport and building use, and several times smaller than emission reductions due to other benefits of trees such as shading of buildings or reduction of the urban heat island. But sequestration rates would be worth knowing because of the close relationship between tree growth and physiological performance.

Introduction

The physical benefits of urban trees are well documented; they provide amongst other things cooling, carbon storage and sequestration, removal of air pollution, and reduction in rain fall runoff. However, compared with the effects of rural forests, quantifying the benefits of urban trees has proved more difficult as the trees are often isolated and make only a small fraction of the total land area. Better understanding of the benefits would help planners to conserve and also create urban areas that are more sustainable and promote human well-being (Strohbach and Haase, 2012).

Among the many ecosystem services that urban trees can offer, one that most obviously would improve urban sustainability in the light of climate change is carbon storage and sequestration. Carbon storage is due to the accumulation of woody biomass as trees grow over time; the amount of carbon stored in a tree is proportional to its biomass, which increases with its diameter, height, and canopy spread, while the amount stored in an urban area also increases with the tree density and canopy cover (McPherson, 1994). Carbon sequestration, on the other hand is the annual rate of increase of the storage of carbon in trees over the course of one growing season. The rate depends on tree growth and mortality, which in turn depends on the species composition and age structure of the urban forest (McPherson, 1998). Despite recent high profile interest in urban forests, however, relatively little data exists concerning carbon storage and sequestration by urban trees. This review investigates the methods that have been used to determine carbon storage and sequestration and the results of the studies and asks what more needs to be done in this area of research.

Research Methods Used

Of the two measurements, it is easier to estimate carbon storage because all one needs to measure is the instantaneous biomass. Sequestration is more difficult to estimate, since this involves determining growth rates. The main approach used to measure carbon sequestration by living plants is to estimate increases in accumulated biomass (IPCC, 2003) for example by using allometric techniques, destructive assays and consecutive inventories in monitoring plots (e.g. Nowak and Crane, 2002). The alternative methodologies are based on micrometeorological measurements of the flow of CO_2 and H_2O, and include the *eddy covariance* and the *Bowen-ratio energy balance* methods. These allow the continuous quantification of net ecosystem net production and the subsequent calculation of annual fluxes (Frank and Dugas, 2001 and Aubinet et al., 2012). However, though these approaches are useful in forests, they are usually impractical in urban areas; cities also house large producers of CO_2 in the form of buildings and vehicles, and water can evaporate from the many built-up areas after rain. Consequently, these last methods are usually complemented or replaced by physiological measurements of the assimilation of carbon and water vapour flow at leaf, trunk and even soil level (Munoz-Valles et al., 2013). (Grimmond et al., 2002) have used these methods to assess entire urban greenspaces but most studies, such as those of Nowak and Crane (2000, 2002), Nowak et al. (2002), Nowak (1994), Davies et al. (2011) have all used biomass and allometric equations to evaluate the system structure (tree species composition, number of trees on all land uses and their carbon storage and sequestration rate).

US Studies

The literature on the carbon storage and sequestration of urban trees has been dominated by two groups, both of whom are based in the US. The first group is the Center for Urban Forest Research (USDA Forest Service, Pacific Southwest Research Station) (McPherson, 1998; McPherson et al., 2005), which has developed the STRATUM model for resource managers to quantify the benefits and costs associated with urban trees and their management (http://www.fs.fed.us/psw/programs/cufr/). The second group is the Urban Forest, Human Health, and Environmental Quality Unit (USDA Forest Service, Northern Research Station) (Nowak et al., 2002; Nowak and Crane 2000). Their UFORE (Urban Forest Effects) model later developed as the i-Tree software suite has been used extensively to evaluate the benefits of urban trees in many cities and towns in over 60 countries throughout the world (http://www.fs.fed.us/ne/syracuse/) (McHale et al., 2009).

In the USDA technical report NE-186, Nowak (1994) described the method they used to estimate total carbon storage, and annual carbon sequestration by trees in the Chicago area. They collected data on the diameter at breast height (dbh), tree height, and species on 8,996 trees located in 652 randomly located plots throughout the study area.

The biomass of each measured tree was calculated using allometric equations (such as those of Trittton and Haombeck, 1982) which had been developed for forest grown trees. To determine the suitability of allometric equations devised for forest-grown trees to urban trees, Nowak measured the above ground fresh weight of 30 street trees using a destructive method. The study found that measured biomass from street trees in Oak Park, Illinois was significantly lower than that predicted from allometric equations from natural forest stands. Nowak later multiplied the biomass by a factor of 0.8 (a 20% reduction) to account for the discrepancy for more open-grown trees. No adjustment was made for trees found in more natural stand conditions (e.g. on vacant lands or in forest preserves). The total dry weight biomass (assuming the below ground as 22% of the total) was converted to total stored carbon by multiplying by 0.5.

Tree growth and carbon sequestration was estimated from measurements of radial growth increments. Sections cut at breast height were obtained from 543 trees of 10 different species and radial growth and tree cumulative radius to 0.05 cm were measured for each ring developed for 20 consecutive years. The average diameter growth from the appropriate genus and diameter class was added to the existing tree diameter (year x) to estimate tree diameter in year x+1. Annual carbon sequestration was the difference between x and x+1.

For better estimation of biomass and sequestration, McPherson et al. (2013) described the use of field surveys, biometric information for urban tree species and remote sensing. To calculate the biomass and C stored in each tree sampled, its species name and measured dbh were entered into the CUFR Tree Carbon Calculator (CTCC) (McPherson et al., 2008). The CTCC, a free Excel spread sheet application, was produced by US Forest Service researchers. It uses information on climate zone, species, and size to calculate C stored, sequestered and avoided emissions.

The CTCC used 26 species-specific equations for trees growing in open, urban conditions. Urban-based biomass equations were developed from street and park trees measured in cities in California (Pillsbury et al., 1998) and Colorado (Lefsky and McHale, 2008). The two types of allometric biomass equations used in the CTCC yielded above ground volume and dry weight of a tree. Green volume was converted to biomass and eventually to stored C following well established equations (Jenkins et al., 2003 a, b). This study assumed that root biomass was 28% of the total tree biomass (Cairns et al., 1997; Husch et al., 1982; Wenger, 1984).

The amount of C sequestered in year x was calculated as the amount stored in year x+1 minus the amount stored in year x. To project tree size at year x+1 the CTCC used growth curves developed from samples of about 700 street and park trees representing the 20–22 predominant species in each of the six California reference cities (Peper *et al.*, 2001a, b).

Studies in the UK and Europe

Compared to the USA, studies on the quantification of C storage and sequestration in Europe are scarce. Most studies have therefore used the US database. While developing ecological performance indicators for different cities of the UK, for instance, Whitford et al. (2001) and Tratalos et al. (2007) estimated the carbon storage and sequestration indicators by following Rowntree and Nowak (1991), and estimating carbon storage and sequestration based only on the % tree cover and assuming the same tree size, shape, and species composition found in Chicago

Other more recent studies such as that of Rodgers et al. (2014a) and Hutchings et al. (2012) have used the US-based i-Tree Eco model. They assessed the carbon storage and sequestration rates, based on measurements on actual trees, but assuming the trees had the same allometry as US trees, of the Borough of Torbay and the city of Edinburgh in the UK respectively. Davies et al. (2011) have, however, investigated the land cover characteristics of Leicester, UK using GIS and calculated above-ground dry-weight biomass for each surveyed tree using allometric equations obtained from the literature. Similarly, Strohbach and Haase (2012) estimated the above-ground carbon storage in trees in the central European city of Leipzig using both land cover and canopy cover. Once again, tree biomass was estimated using published allometric equations relating plant diameter to dry mass. Unfortunately, no similar experimental studies have been undertaken to measure the carbon sequestration rates of UK or European trees. However a study of the growth rates and allometry of five species of common urban trees is currently being studied in five UK cities (Rogers et al, 2014b).

Results of the Studies

There is now extensive information about the carbon storage and sequestration in large numbers of US cities, which considering the reasonable amount of experimental work on which it is based can be considered to be fairly reliable.

For instance, Nowak (1994) reported that the total carbon storage by trees in the Chicago area was about 5.6 million t or 85.7 t ha^{-1} of tree cover. Tree carbon stored per ha in the study area averaged 16.7 t ha^{-1}. The net sequestration rate was 0.4 t ha^{-1} yr^{-1}; of land or 2.2 t ha^{-1} yr^{-1} of tree cover. Using the same methodology in another study Nowak and Crane (2002) reported the national average of carbon storage of urban forests in USA as 25.1 t C ha^{-1} which is quite low compared to forest stands (53.5 t C ha^{-1}) due to the relatively low tree cover. An estimated urban tree gross sequestration rate (0.8 t C $ha^{-1}yr^{-1}$) is also low compared to the forest stands (1.0 t C $ha^{-1}yr^{-1}$ for a 25-year old natural regeneration spruce-fir forest). McPherson et al. (2013) reported that the overall average storage density in Sacramento, (15.40 t ha^{-1}) was about twice the amount in Los Angeles (8.15 t ha^{-1}) in USA. The overall average annual sequestration density value was also greater in Sacramento (0.90 t $ha^{-1}yr^{-1}$) than Los Angeles (0.45 t $ha^{-1}yr^{-1}$).

In recent years, large numbers of cities and other smaller areas have also had carbon storage and sequestration rates calculated using the i-Tree eco software, based on extensive tree surveys.

In Europe the results are probably less reliable due to the lack of experimental work. Whitford et al. (2001) reported the carbon density of four contrasting sites in Merseyside, UK between 1 and 17 t ha^{-1} and carbon sequestration between 0.01 and 0.13 t $ha^{-1}yr^{-1}$. Tratalos et al. (2007) estimated carbon sequestration of three contrasting sites (inner, middle and outer site) of five different cities of UK namely:

Edinburgh, Glasgow, Leicester, Oxford and Sheffield between 0.01 and 0.09 t $ha^{-1}yr^{-1}$.

Of the studies using complete surveys of individual trees, Davies et al. (2011) reported 31.6 t ha^{-1} stored in Leicester (which exceeds the average of 21.4 t ha^{-1}) for 10 cities distributed across the USA (range: 0.50–4.69; Nowak and Crane 2002), while Strohbach and Haase (2012) calculated the carbon density of Leipzig as 11 t C ha^{-1}.

Finally there is a growing number of estimates calculated using the imported i-Tree model. For instance Rodgers et al. (2014a) estimated that 15.4 t ha^{-1} of carbon is stored in Torbay, UK, while the gross sequestration of Torbay's trees is about 0.74 t $ha^{-1}yr^{-1}$. Although canopy cover in Torbay (11.8%) is higher than the UK national average and it has more trees per hectare than many US and European cities, Torbay's trees are smaller so they store less carbon compared to the US national average (15.4 compared to 25.1 t C ha^{-1}). Using the i-Tree Eco model Hutchings et al. (2012) also estimated the C storage and sequestration of Edinburgh, UK as 12.7 t ha^{-1} and 0.5 t ha^{-1} yr^{-1}.

Limitations of the Studies

The main problem with estimates of carbon storage in trees are the differences in shape between open-grown street trees and forest trees. Nowak (1994) found that street trees in Chicago had 20% lower biomass than predicted from allometric equations for forest trees. However, Jo and McPherson (1995) and McHale et al. (2009) found that existing allometric equations underestimated the biomass of some urban tree species and overestimated it for others. Only one published study (Pillsbury et al., 1998) developed volume equations for urban trees, and that was located in California. Considering this shortcoming McHale et al. (2009) implemented a newly developed method to measure total tree volume of 11 urban tree species using a terrestrial light detection and ranging system (LiDAR) (Lefsky and McHale, 2008) and compared the results with the allometric equations used by both Nowak *et al.*, (2002) and McPherson (1998). McHale et al. (2009) found that some of the allometric equations published in the literature produce similar estimates of biomass to urban-based allometric equations developed for an individual location; however, depending on scale and species or population and community characteristics, variability can be as high as 300%. Nonetheless, averaging a variety of equations and applying them to an entire urban forest community, variability can be as low as 10%. However, the study indicated that the practice of reducing biomass by 20% for open grown trees should be re-evaluated. Similarly, Escobedo et al. (2013) destructively measured the aboveground tree biomass and C storage in Southeastern US for Urban *Quercus* spp. and Russo et al. (2014) estimated urban tree C storage of Bolzano, Italy using European-specific allometric equations and compared it with both the model output from CTCC and UFORE. In both the cases the authors showed that the UFORE model consistently underestimated C storage by 15% and CTCC overestimated it by 2% on average. Moreover, in terms of C sequestration i-Tree software only provides a single estimation of net incremental value per year. Therefore using i-Tree values for future model prediction will not reflect a true value over a tree's life time. To overcome this problem, the Forestry Commission is currently working to develop growth models and leaf-area index predictive models for urban trees in the UK (Hutchings et al., 2012).

Another uncertainty about quantification of carbon storage and sequestration is the estimation of below ground biomass. Authors have used a root biomass of trees of between 22 and 28 % (Nowak, 1994; McPherson et al., 2013). However, urban root systems are likely to differ from forests due to specific urban soil conditions (Close et al., 1996; Rahman et al., 2011). The variation of root biomass can be high, ranging from anything between 16 and 41% of the biomass of urban trees (Johnson and Gerhold, 2003). Due to high uncertainty, some authors such as Davies et al.(2011); Hutyra et al. (2011) and Strohbach and Haase (2012) exclude below ground biomass while estimating carbon storage and sequestration.

A third uncertainty is that little is known about the size of soil C pools in urban forests. Authors such as Birdsey and Heath (1995) reported that almost 61% of the total carbon in non-urban forest ecosystems in the USA is stored in the soil environment. Edmondson et al. (2012) calculated city wide organic carbon budget using Leicester, UK as a case study site and reported that out of 1.2 million tonnes of organic carbon (OC) stored in Leicester, approximately 69% is stored in greenspace soil, 13% in capped soil and only 18% in vegetation. In a follow up study Edmondson et al. (2014) also showed that soil OC within urban greenspaces was significantly higher than all other land-cover classes (mean topsoil OC of 9.9 kg m^{-2} compared to 5.6 kg m^{-2} across the whole city). Therefore, more research is needed to quantify the C pool beneath urban trees.

There is also a knowledge gap regarding a systematic analysis of the carbon footprints of urban trees. Usually urban trees are C sinks, but they can also be a source of C emission due to wood decomposition, pruning, and other emissions associated with maintenance and planting. This can happen especially when a big tree is felled or decomposed and not replaced. Jo and McPherson (1995) analysed the carbon budget of two residential areas of Chicago, USA including the soil and foliage carbon density and showed that approximately 58–65% of the total carbon input was released annually back to the atmosphere due to landscape maintenance and decomposition. McPherson et al (2014) found a similar figure for Los Angeles. Therefore C footprint analysis for systematically quantifying carbon sinks and sources throughout the lifetime of urban greenspaces is very important. This has been done in the 50 year simulation study of Leipzig, Germany. Strohbach et al. (2012) calculated that the net above ground carbon footprint (sequestration minus emissions) of green space project ranges between 7.9 and 59.40 t ha^{-1} for a 2.16 ha newly planted green belt compared to the gross rate of 10 and 62 t ha^{-1}.

Finally, very little is known about the carbon storage and sequestration rates of individual urban trees in relation to their planting condition, species, tree size and planting orientation. Nowak (1994) showed that average carbon storage by individual trees in Chicago was 3 kg for a tree less than 8 cm dbh to more than 3,100 kg for a tree greater than 76 cm dbh. Average carbon sequestration by individual trees ranged from 1.0 kg yr^{-1} for a tree less than 8 cm dbh to 93 kg $yr^{-1}$for a tree greater than 76 cm dbh. On the other hand, Rahman et al. (2014) compared five different street tree species of south Manchester grown on the same growing condition for six years and showed that *Pyrus calleryana* and *Prunus* 'Umineko' had stored significantly more CO_2 than *Malus* 'Rudolph'. Further research is clearly needed incorporating tree species, size, growing conditions and geographical location to better understand the C pool in a specific city, particularly in the UK and the rest of Europe.

Putting the Results in Context

The results from all these studies show that urban trees can store and sequester large quantities of atmospheric CO_2. However, their effect is very small relative to the magnitude of emissions in urban areas. Nowak (1994) showed that the total carbon stored by trees in Chicago area (5.6 million t), which took years to sequester, equalled the amount of carbon emitted from the residential sector (including transportation use) in the study area over just a 5-month period. Net annual sequestration for all trees in the study area (140,600 t of carbon) equalled the amount of carbon emitted from transportation use in the study area in just one week. The amount of carbon sequestered annually by one tree less than 8 cm dbh is equivalent to the amount of carbon emitted by driving one car 16 km and annual sequestration by one tree greater than 77 cm dbh is equivalent to driving one car approximately 1,460 km. Similarly, while developing an Urban Tree Air Quality Score (UTAQS), using the West Midlands as a typical urban region in the UK researchers at Lancaster University calculated that the total amount of carbon stored in the West Midlands tree population is equivalent to only 6% of the CO_2 emitted to the atmosphere from the West Midlands in a single year. In other words, all the trees in the West Midlands hold the equivalent of three weeks' worth of emissions of CO_2 from the conurbation (http://www.es.lancs.ac.uk/people/cnh/UrbanTreesBrochure .pdf). The carbon sequestration rate of urban trees is therefore typically less than 1% of the carbon emissions of an urban area, sometimes far less. Therefore, though the carbon storage potential of trees is measurable and can be converted by i-Tree software into a monetary value, it is small, even in relation to other potential energy saving uses of trees.

For instance, planting trees to provide shade to buildings in the USA (Heisler, 1986) where air conditioning is a major cause of energy consumption in summer, can reduce their energy use and hence carbon emissions. In a simulation, planting 10 million trees annually in energy conserving locations over a 10-year in USA had the potential of carbon avoidance four times greater than the direct carbon sequestration rate (Nowak and Crane, 2002). McPherson et al (2014) found a lower figure for carbon avoidance by the shading of buildings in Los Angeles, but it was still 40% larger than the carbon sequestered. Similarly, evapotranspirational cooling can reduce the urban heat island directly and so indirectly reduce carbon emissions associated with air conditioning (Akbari et al, 2001).

However, despite the relatively small effect of carbon storage and sequestration, it might still be extremely useful to know the biomass and growth rates of urban trees. Because of the laws of gas exchange through the stomata of leaves, it would be expected that the evapotranspirational cooling and other physical benefits of trees should rise in direct proportion to their growth and carbon sequestration (Ennos, 2011). This emphasises the great importance of determining the size and growth rates of trees and the usefulness of tree surveys.

Conclusions: What We Do and Don't Know

A great deal is known about the carbon storage and sequestration of urban trees, especially in the USA. This is enough to produce reliable models that can be used in conjunction with field surveys to provide reliable estimates of carbon storage and sequestration by urban forests. However, a great deal is still uncertain or not known, especially for trees in the UK and Northern Europe and a good deal therefore needs to be done to investigate the growth rates and allometry of urban trees. It is clear, though, that carbon storage and sequestration are at best relatively minor benefits of urban trees.

What We Know

1) We can estimate the carbon storage of urban trees, particularly in the US, from their trunk diameters, using allometric relationships.

2) We can estimate carbon sequestration rates of urban trees in US cities using growth data.

3) We know that carbon storage and sequestration of urban trees is significant, but constitute just a tiny proportion of the carbon emissions of urban areas.

What We Don't Know

1) We have a poor understanding of the relative amount of carbon held underground in urban forests, both in tree roots and in soil carbon.

2) We have little information about the allometry of UK urban trees, so can produce only unreliable estimates of carbon storage.

3) We have very little information about the growth rates of UK urban trees, so little ability to even estimate carbon sequestration.

4) We know little about the carbon costs of maintaining urban trees in the UK

Research that We Need

Considering what we do and don't know there are three very clear needs for research.

1) To quantify the below-ground carbon storage and sequestration rates of UK trees.

2) To produce reliable allometric equations relating carbon storage of open and forest grown urban UK trees to their diameter.

3) To measure to the growth rates of urban trees in the UK in relation to their species, size, and growing conditions.

4) To carry out a life cycle analysis of the carbon budget of urban trees in the UK.

Acknowledgements

The authors thank Fund4Trees for funding MAR to carry out the work and the Trees and Design Action Group (TDAG) for coordinating the project.

References

Akbari, H., Pomerantz, M., & Taha, H., (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70, 295-310.

Aubinet, M., Vesala, T., & Papale, D. (Eds.), (2012). *Eddy Covariance. A Practical Guide to Measurement and Data Analysis.* Springer Atmospheric Sciences, Dordrecht.

Birdsey, R.A., & Heath, L.S. (1995). Carbon changes in U.S. forests. In: Joyce, L.A. (Ed.), Climate Change and the Productivity of America's Forests. USDA Forest Service General Technical Report RM-271, Fort Collins, CO, pp. 56–70.

Cairns, M.A., Brown, S., Helmer, E.H., & Baumgardner, G.A. (1997). Root biomass allocation in the world's upland forests. *Oecologia* 111, 1-11.

Close, R.E., Nguyen, P.V., & Kielbaso, J.J. (1996). Urban Vs. Natural Sugar Maple Growth: I. Stress Symptoms and Phenology in Relation to Site Characteristics. *Journal of Arboriculture* 22, 144-150.

Davies, Z.G., Edmondson, J.L., Heinemeyer, A., Leake, J.R., & Gaston, K.J. (2011). Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *Journal of Applied Ecology* 48, 1125-1134.

Edmondson, J.L., Davies, Z.G., McCormack, S.A., Gaston, K.J., & Leake, J.R. (2014). Land-cover effects on soil organic carbon stocks in a European city. *Science of the Total Environment* 472, 444-453.

Edmondson, J.L., Davies, Z.G., McHugh, N., Gaston, K.J., & Leake, J.R. (2012). Organic carbon hidden in urban ecosystems. *Scientific Report*s 2, 7.

Ennos, A.R. (2011) Quantifying the cooling benefit of urban trees. In M. Johnston and G. Percival, (Eds) *Trees, people and the built environment.* pp.113-118. Forestry Commission.

Escobedo, F., Chappelka, A., Staudhammer, C., & Mayer, H. (2013). Evaluating the use of i-Tree ECO in the Southeastern US. *Florida Arborist* 16, 1–19.

Frank, A.B., & Dugas, W.A. (2001). Carbon dioxide fluxes over a northern, semiarid, mixed-grass prairie*. Agricultural and Forest Meteorology* 108, 317-326.

Grimmond, C.S.B., King, T.S., Cropley, F.D., Nowak, D.J., & Souch, C. (2002). Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago. *Environmental Pollution* 116, S243-S254.

Heisler, G.M. (1986). Energy savings with trees. *Journal of Arboriculture* 12 (5), 113–125.

Husch, B., Miller, C.I., & Beers, T.W. (1982). *Forest mensuration*. New York, NY: John Wiley and Sons.

Hutchings, T., Lawrence, V., & Brunt, A. (2012). Estimating the Ecosystem Services Value of Edinburgh's Trees. Report by Forest Research. Forest Research, Farnham.

Hutyra, L.R., Yoon, B., & Alberti, M. (2011). Terrestrial carbon stocks across a gradient of urbanization: a study of the Seattle, WA region. *Global Change Biology* 17, 783-797.

IPCC (2003). Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF). IPCC National Greenhouse Gas Inventories Programme, Technical Support Unit, Japan.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., & Birdsey, R.A. (2003a). Comprehensive database of diameter-based biomass regressions for North American tree species (Gen. Tech. Rep/NE-319). New town Square, PA: US Department of Agriculture, Forest Service, Northeastern Research Station.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., &Birdsey, R.A. (2003b). National-scale biomass estimators for United States tree species. *Forest Science* 49, 12-35.

Jo, H.K., & McPherson, E.G. (1995). Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management* 45, 109-133.

Johnson, A.D., & Gerhold, H.D. (2003). Carbon storage by urban tree cultivars, in roots and above-ground. *Urban Forestry & Urban Greening* 2, 65-72.

Lefsky, M., McHale, M. (2008). Volume estimates of trees with complex architecture from terrestrial laser scanning. *Journal of Applied Remote Sensing* 2, 19.

McHale, M.R., Burke, I.C., Lefsky, M.A., Peper, P.J., & McPherson, E.G. (2009). Urban forest biomass estimates: is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosystems* 12, 95-113.

McPherson, E.G. (1994). Using urban forests for energy efficiency and carbon storage. *Journal of Forestry* 92, 36-41.

McPherson, E.G. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture* 24, 215-223.

McPherson, E.G., Kendall, A., & Albers, S. (2014). Million Trees Los Angeles: Carbon Dioxide Sink or Source? In M. Johnston and G. Percival (Eds), Trees, People and the Built Environment II pp 7-19. Institute of Chartered Foresters.

McPherson, G., Simpson, J., Marconett, D., Peper, P., Aguaron, E., 2008. Urban forestry and climate change. http://www.fs.fed.us/ccrc/topics/urban-forests/

McPherson, E.G., Xiao, Q.F., & Aguaron, E. (2013). A new approach to quantify and map carbon stored, sequestered and emissions avoided by urban forests. *Landscape and Urban Planning* 120, 70-84.

McPherson, G., Simpson, J.R., Peper, P.J., Maco, S.E.,& Xiao, Q.F. (2005). Municipal forest benefits and costs in five US cities. *Journal of Forestry* 103.

Munoz-Valles, S., Cambrolle, J., Figueroa-Luque, E., Luque, T., Niell, F.X., & Figueroa, M.E. (2013). An approach to the evaluation and management of natural carbon sinks: From plant species to urban green systems. *Urban Forestry & Urban Greening* 12, 450-453.

Nowak, D.J. (1994). Atmospheric carbon dioxide reduction by Chicago’s urban forest. In: McPherson, E.G., Nowak, D.J., Rowntree, R.A. (Eds.), Chicago’s Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. USDA Forest Service General Technical Report NE-186, Radnor, PA, pp. 83–94.

Nowak, D.J., & Crane, D.E. (2000). The urban forest effects (UFORE) model: quantifying urban forest structure and functions. In: Hansen, M., Burk, T. (Eds.), Proceedings: Integrated Tools for Natural Resources Inventories in the 21st Century. IUFRO Conference, 16–20 August 1998, Boise, ID. General Technical Report NC-212. US Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN, pp. 714–720.

Nowak, D.J., & Crane, D.E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution* 116, 381-389.

Nowak, D.J., Stevens, J.C., Sisinni, S.M., & Luley, C.J. (2002). Effects of urban tree management and species selection on atmospheric carbon dioxide. *Journal of Arboriculture* 28, 113-122.

Peper, P.J., McPherson, E.G., & Mori, S.M. (2001a). Equations for predicting diameter, height, crown width, and leaf area of San Joaquin Valley street trees. *Journal of Arboriculture* 27, 306-317.

Peper, P.J., McPherson, E.G., & Mori, S.M. (2001b). Predictive equations for dimensions and leaf area of coastal southern California street trees. *Journal of Arboriculture* 27, 169-180.

Pillsbury, N., Reimer, J.L., & Thompson, R. (1998). Tree volume equations for fifteen urban species in California. San Luis Obispo: Urban forest ecosystems institute. California Polytechnic State University.

Rahman, M.A., Smith, J.G., Stringer, P., & Ennos, A.R. (2011). Effect of rooting conditions on the growth and cooling ability of *Pyrus calleryana. Urban Forestry and Urban Greening* 10, 185-192.

Rahman, M.A., Armson, D., & Ennos, A.R. (2014). A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. Urban Ecosystems. *Urban Ecosystems*, 18, 371-389.

Rogers, K., Jarratt, T., & Hansford, D. (2014a). Torbay's Urban Forest: Assessing urban forest effects and values: A report on the findings from the UK i-Tree Eco pilot project. Treeconomics, Exeter. Available at: http://www.itreetools.org/resources/reports/Torbay_UF_Report.pdf

Rogers, K., Lawrence, V., & Hutchings, T.R. (2014b). Determining Tree Growth in the Urban Forest. In M. Johnston and G. Percival (Eds), Trees, People and the Built Environment II pp 71-84. Institute of Chartered Foresters.

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture* 17, 269-275.

Russo, A., Escobedo, F.J., Timilsina, N., Schmitt, A.O., Varela, S., & Zerbe, S. (2014). Assessing urban tree carbon storage and sequestration in Bolzano, Italy. International *Journal of Biodiversity Science Ecosystem Services and Management* 10, 54-70.

Strohbach, M.W., Arnold, E., & Haase, D. (2012). The carbon footprint of urban green space-A life cycle approach. *Landscape and Urban Planning* 104, 220-229.

Strohbach, M.W., & Haase, D. (2012). Above-ground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city. *Landscape and Urban Planning* 104, 95-104.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G., & Gaston, K.J. (2007). Urban form, biodiversity potential and ecosystem services. *Landscape and Urban Planning* 83, 308-317.

Tritton, L. M., & Hornbeck, J. W. (1982). Biomass equations for major tree species of the Northeast. Gen. Tech. Rep. NE-69. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 26 p.

Wenger, K. F. (1984). *Forestry handbook.* New York. NY: John Wiley and Sons.

Whitford, V., Ennos, A.R., & Handley, J.F. (2001). "City form and natural process" - indicators for the ecological performance of urban areas and their application to Merseyside, UK. *Landscape and Urban Planning* 57, 91-103.