Chapter 3
Comparison of Methods for Estimating Carbon Dioxide Storage by Sacramento's Urban Forest

Elena Aguaron and E. Gregory McPherson

Abstract Given the increasing demand for carbon dioxide storage estimates in urban areas and the high cost for ground-based inventories, there is need for more efficient approaches. Limited open-grown urban tree species biomass equations have necessitated use of forest-derived equations with diverse conclusions on the accuracy of these equations to estimate urban biomass and carbon storage. Our goal was to determine and explain variability among estimates of CO_2 storage from four sets of allometric equations for the same ground sample of 640 trees. Also, we compare the variability found in CO_2 stored and sequestered per hectare among estimation approaches for Sacramento's urban forest with the variation found among six other cities. We found substantial variability among the four approaches. Storage estimates differed by a maximum of 29% and ranged from 38 to 49 t/ha. The two sequestration estimates differed by 55%, ranging from 1.8 to 2.8 t/ha. To put these numbers in perspective, they amounted to about one-tenth and one-quarter of the maximum differences in CO_2 storage and sequestration rates among six cities, respectively. i-Tree Eco produced the lowest storage estimates, perhaps because it relied exclusively on forest-based equations and applied a 0.80 correction factor to open-grown trees. The storage estimates produced by i-Tree Streets and CUFR Tree Carbon Calculator (CTCC) were the highest, while Urban General Equations produced relatively low estimates of CO_2 storage. Eco produced lower estimates of CO_2 sequestration rates than the CTCC across a range of species. Eco's reductions for tree condition and projected mortality may partially explain the difference. An analysis of the roles of tree growth modeling and biomass equation selection for a green ash tree illustrated how the dynamic interaction between tree growth and biomass

E. Aguaron • E.G. McPherson (✉)
Urban Ecosystems and Social Dynamics Program, USDA Forest Service, 1731 Research Park Dr, Davis, CA 95618, USA
e-mail: eaguaron@fs.fed.us; gmcpherson@fs.fed.us

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storage rate can influence the temporal stream of sequestration in complex ways. Based on these results we conclude that applying UGEs to remotely sensed data that accurately classify broadleaf, conifer and palm tree types in the Sacramento region is likely to produce conservative results compared to results from urban-based species-specific equations. The robustness of this result needs to be tested with different tree populations, and research is needed to establish relations between remotely-sensed tree crown projection area and dbh values required for biomass calculation. Of course, ground-based inventories remain necessary for more accurate estimates of CO_2 storage and for municipal forest management and health monitoring purposes.

Keywords Carbon storage • Sequestration rates • Allometric equations

List of Abbreviations

BVOCs	Biogenic volatile organic compounds
CLE	Crown light exposure
CTCC CUFR	Tree Carbon Calculator
CUFR	Center for Urban Forest Research
STRATUM	Street Tree Resource Assessment Tool for Urban forest Managers
SUFES	Sacramento Urban Forest Ecosystem study
UFORE	Urban Forest Effects Model
UGEs	Urban general equations

3.1 Introduction

Growing concern about climate change has led to research quantifying the effects of urban forests on atmospheric carbon dioxide (CO_2) (Nowak 1994; McPherson 1998; Jo 2002; Nowak and Crane 2002; Pataki et al. 2006; Escobedo et al. 2010; Stoffberg et al. 2010; Zhao et al. 2010). Most of these studies have found that urban forests can be important carbon sinks, although there is a general lack of information on urban tree biomass allometry. Similarly, relatively little is known about the release of CO_2 into the atmosphere from combustion of fuels used to power equipment and vehicles during planting and tree care activities. Once dead, trees release most of the CO_2 they accumulated through decomposition. The rate of release depends on how the wood is utilized.

A number of computer tools have been developed to calculate carbon storage and sequestration rates of urban trees, as well as emission reductions from power plants as a result of building heating and cooling energy savings. These tools produce estimates of atmospheric CO_2 reductions from urban forests that are used for policy, management, and educational purposes. To better understand the variability associated with using different tools to estimate CO_2 storage, this paper examines differences among estimates produced by three different tools and three urban general equations (one for broadleaves, one for conifers and one for palms) for the same 640 ground-sampled trees in Sacramento.

3.1.1 Carbon Storage

As part of their biophysical processes trees capture and release CO_2 to the atmosphere. During photosynthesis leaves absorb CO_2 through the stomata and, using the energy from the sun, convert it into oxygen, carbohydrates and water that are then used in the production of wood structures as well as vitamins, resins and hormones needed for growth and tree health. Trees obtain energy to grow from the carbohydrates synthesized during photosynthesis, and they respire by releasing CO_2, water, and heat energy. The combined effect of photosynthesis and respiration results in net storage of CO_2 by the tree.

The term "carbon dioxide storage" refers to the accumulation of woody biomass as trees grow over time. The amount of CO_2 stored at any one time by urban trees is proportional to their biomass and influenced by tree density and management practices (McPherson 1994).

"Carbon dioxide sequestration" refers to the annual rate of storage of CO_2 in biomass over the course of one growing season. Sequestration depends on tree growth and mortality, which in turn depends on species composition and age structure of the urban forest (McPherson 1998).

"Carbon stock" is the stored carbon in one place at a given time. Forest carbon stocks include living and standing dead vegetation, woody debris and litter, organic matter in the soil, and harvested stocks such as wood for wood products and fuel (California Climate Action Registry 2008).

3.1.2 Allometric Equations

Estimates of carbon storage are obtained from allometric equations that use several parameters to calculate tree biomass: diameter at breast height (dbh), tree height, wood density, moisture content, site index and tree condition. Parameters like wood density and moisture content vary not only among species but also among trees of the same species. Even within a single tree there can be significant differences in density and moisture content (Domec and Gartner 2002; RPBC 2003). Therefore, some error is associated with the use of average densities and moisture contents in allometric formulas.

There are two types of allometric biomass equations: volumetric and direct. Volumetric equations calculate the above ground volume of a tree using dbh and tree height for the species. Direct equations yield above ground dry weight of a tree using dbh and tree height.

The methodology to convert green volume into biomass and eventually to stored CO_2 is well established (Markwardt 1930; Markwardt and Wilson 1935; Forest Products Laboratory 1987; Hansen 1992; Simpson 1993; Jenkins et al. 2003a, b). Estimating biomass and CO_2 using volumetric equations is a process that entails calculating dryweight biomass, then carbon (C) and stored CO_2 equivalents (McPherson et al. 2008). Converting the fresh weight of green volume into dryweight requires use of density conversion factors that were published by Markwardt and Wilson (1935). The biomass stored below ground is added to above ground biomass (total biomass = 1.28 * above ground biomass) (Husch et al. 1982; Tritton and Hornbeck 1982; Wenger 1984; Cairns et al. 1997). Wood volume (dryweight) is converted to carbon by multiplying by the constant 0.50 and carbon is converted to CO_2 by multiplying by 3.67 (molecular weight of carbon dioxide) (Lieth 1963; Whittaker and Likens 1973).

3.1.3 Urban-Based Allometric Biomass Equations

There are 26 species–specific equations for trees growing in open, urban conditions. Urban-based biomass equations were developed from street and park trees measured in California (Pillsbury et al. 1998) and Colorado cities (McHale et al. 2009). Two sets of biomass equations were published, one set based only on dbh where

$$(\text{dbh}),\ \text{biomass} = a * (\text{dbh})^{b} \tag{3.1}$$

and the other set based on dbh and tree height where

$$\text{biomass} = a * (\text{dbh})^{b} * (\text{height})^{c}. \tag{3.2}$$

Very limited destructive biomass sampling has been conducted on urban trees to verify the accuracy of estimates from these equations across a range of growing conditions. In addition, limited research has quantified differences in growth and biomass accumulation between open-grown and non open-grown trees. The magnitude of error associated with the frequent practice of applying forest-based equations derived from measurements on non-open grown trees to open-grown trees is an important research question.

3.1.4 Forest-Based and Urban-Based Equations

Biomass equations for open-grown urban trees should reflect how different growing conditions, stresses and management practices influence the partitioning of biomass to bole, branches, foliage and roots compared to forest trees. Although not well documented, carbon partitioning might be different for open-grown trees than for forest trees. Carbon partitioning for a typical forest tree was reported to be about

17% in roots, 50% in trunk, 30% in branches and stems, and 3% in foliage (Birdsey 1992). Forest trees often grow in denser stands and develop smaller crowns and longer trunks than open-grown trees.

Trees in open-grown conditions do not compete as directly with other trees, and are allowed to branch into spreading crowns that support ample foliage. The growth of open-grown trees is often enhanced by periodic irrigation and care, as well as elevated levels of carbon dioxide and nitrogen deposition. Some studies indicate that urban trees grow faster than forest trees and sequester more CO_2 on a per tree basis (Jo and McPherson 1995; Nowak and Crane 2002). However, urban trees have stressors, such as constricted space, poor soils, pests, and vandalism that can restrict their growth. Little research has been published on carbon partitioning for urban trees, but there is some evidence that they partition relatively more carbon in branches and foliage, and less carbon to the bole compared to forest trees (Xiao 1998; Brack 2002).

Based on aboveground biomass weighed for 30 removed trees in Oak Park, IL, Nowak (1994) found less biomass than predicted with forest biomass equations and inferred that the biomass for open-grown trees should be multiplied by a factor of 0.8 when a forest-based allometric equation was applied. However, McHale and others (2009) found that applying the 20% reduction to carbon estimates for the Fort Collin's street tree population resulted in an estimate that was 30% less than the urban-based predictions. They concluded that standard application of the 20% reduction may lead to conservative estimates of biomass.

3.1.5 General Equations

There is a great deal of uncertainty associated with the application of biomass equations across a population of trees in a city or urban region. Although 26 species-specific allometric equations have been developed for city trees, their accuracy has not been well established, especially when applied across a range of climates, growing conditions and tree sizes.

Tree species richness is high in cities. Frequently, there are over 100 species of trees in urban populations. Because of this diversity and the limited number of urban-based allometric equations, most species are assigned a forest-based biomass equation from the same or similar species, or they are assigned an urban-based equation from a similar species. The magnitude of error associated with species assignment depends on the proportion of population assigned, as well as goodness of fit in terms of matching actual biomass to biomass predicted by the allometric equations.

The development and application of generalized equations is one approach to resolving the high variability and uncertainty associated with application of these allometric equations in both urban and forested environments (Jenkins et al. 2003a, b; McHale et al. 2009). Forest-based general equations have been developed for hardwoods, softwoods, and other types of trees, but no general equations have been developed using urban-based biomass equations.

3.1.6 Carbon Storage Estimation Approaches

i-Tree is public-domain software developed by the USDA Forest Service and cooperators for urban forestry analysis and benefits assessment. i-Tree helps communities to strengthen their urban forest management and advocacy efforts by quantifying the structure of community trees and the ecosystem services they provide. Within i-Tree, carbon storage by entire urban forest tree populations is assessed using Eco (formerly UFORE) whereas storage by discrete street tree populations is assessed using Streets (formerly STRATUM).

i-Tree Eco quantifies urban forest structure, environmental effects, and value to communities from field data and local hourly air pollution and meteorological data (Nowak et al. 2008). Setting up Eco projects for small, complete populations of trees is relatively straightforward because no sampling is involved. Eco sampling projects are typically used where the designated study area is too large to cost-effectively inventory the entire tree population. Sampling projects obtain estimates of the characteristics and benefits of a study area from a series of pre-selected sample plots. Such projects usually require project setup that can include characterization of land use and random selection of plot locations in a city using aerial photography or GIS. Field data costs $200 to $400 per 0.04 ha plot when collected by contracted professionals (Maco June 11, 2008, personal communication). A typical regional study will cost approximately $80,000 for 300 plots. Volunteers can be trained to collect field data, but there are costs associated with training, supervision, data processing, and quality control.

i-Tree Streets is a street tree specific analysis tool for urban forest managers that uses tree inventory data to quantify structure, function and value of annual benefits (Maco and McPherson 2003; McPherson et al. 2005). Users have the option of analyzing an existing street tree inventory or completing a new Streets-compatible inventory (complete or sample).

Eco and Streets produce tables and charts of information on urban forest structure, function, and value that can be exported in a variety of formats. Both models calculate the value of ecosystem services: CO_2 storage and sequestration, building energy effects and reduced CO_2 emissions, air pollution removal and release of biogenic volatile organic compounds (BVOCs). Streets includes output on rainfall interception and property value increase.

The i-Tree programs require specific types and amounts of data to accurately project the structure and benefits of urban vegetation. The validity of results depends on how closely users adhere to project setup and sampling protocols. Although the i-Tree programs are user-friendly, there is not much opportunity to adjust inputs or modify the calculations. This "black-box" design limits usefulness of the programs for customized applications.

Developed by the USDA Forest Service and first released in 2008, the Center for Urban Forestry Research (CUFR) tree carbon calculator (CTCC) is a free Microsoft Excel spreadsheet that provides carbon-related information for a single tree in one of 16 U.S. climate zones. It is the only tool approved by the Urban Forest Project Protocol for quantifying CO_2 sequestration from tree planting projects (Climate Action Reserve 2010).

Tree size data are based on growth curves developed from samples of about 1,000 street and park trees representing approximately 20 predominant species in each of the 16 reference cities (Peper et al. 2001a, b). Most of the biomass equations and calculations used to derive total CO_2 stored, total stored above ground, and annual CO_2 sequestered are from open-grown urban trees. To determine effects of tree shade on building energy performance, over 12,000 simulations were conducted for each of the 16 reference cities using different combinations of tree sizes, locations, and building vintages (Simpson and McPherson 2000).

Users enter information for a single tree, such as its climate zone, species name, size or age. The program estimates how much CO_2 the tree sequestered in the past year and over its lifetime. It calculates the biomass (dry weight) that would be obtained if it were removed. Trees planted near buildings to reduce heating and cooling costs require additional inputs because they also reduce GHGs emitted by power plants while generating electricity. These inputs include information on the tree's distance and compass bearing relative to a building, building vintage (its age, which influences energy use), and types of heating and cooling equipment. The CTCC automatically calculates annual heating and cooling energy savings, as well as associated power plant reductions using existing or user supplied emission factors for local utilities.

Another approach for calculating CO_2 storage in city trees utilizes existing imagery obtained by remote sensing with urban general equations (UGEs) for broadleaf, conifer, and palm tree types. Remotely sensed imagery is becoming increasingly available at higher resolutions and lower cost. In many cases, imagery exists for tax assessment and planning purposes. Many communities are conducting tree canopy cover assessments. It is estimated that the cost for such an assessment using available high resolution imagery (e.g., IKONOS, Quickbird) ranges from \$0.15 to \$0.25 per ha. The cost for a typical assessment for a 100,000 ha region will be approximately \$20,000.

Estimating CO_2 storage in urban forests with remote sensing and UGEs may be less expensive than ground-based sampling, but almost certainly will be less accurate. The accuracy of tree canopy cover classification typically ranges from 78% to 90% (Schreuder et al. 2003; Baller and Wilson 2008). Xiao and others (2004) reported mapping urban tree species with 94% and 70% accuracy at the tree type and species levels, respectively using high-resolution AVIRIS data.

To estimate CO_2 storage from tree cover requires converting remotely sensed tree crown projection area or diameter into dbh for use in biomass equations. The accuracy of biomass estimates using UGEs is likely to be less than obtained with species-specific biomass equations. Relations between dimensions such as tree crown projection area, crown diameter, dbh, and height have not been well established for urban species. An alternative approach is to determine CO_2 density (CO_2/m^2 tree cover) from ground sampling, perhaps by tree type, and apply these values to classified canopy cover.

3.1.7 Research Goal and Objectives

The goal of this study is to better understand how the choice of approach influences estimates of CO_2 storage in urban forests. Specifically, we compare CO_2 storage estimates obtained with different sets of biomass equations for the same sample of trees. To put our findings in perspective, we compare the variability found in CO_2 stored and sequestered per hectare among estimation approaches for Sacramento's urban forest with the variation found among six other cities.

3.2 Methods

3.2.1 Study Site

The study area consists of the urban areas in the Sacramento metropolitan region. Four counties are included in the region: Sacramento, Yolo, Placer and El Dorado (Fig. 3.1). The experimental unit of analysis involved in this research is the field plot. The total study site area is 131,742 ha.

3.2.2 Field Data

Tree measurement data used in this study were obtained from field measurements following i-Tree Eco protocols and coordinated by the Sacramento Tree Foundation (STF) (Nowak and Crane 2002). In 2007, trained volunteers from STF collected information on 300 random circular plots each 0.04 ha in size (Fig. 3.1). The total number of plots was divided and assigned to teams that had been trained to perform the inventory tasks. Each team sent out letters requesting access to the property when the plot was located on private property. If access was not rejected, the team sampled the plot, obtaining all the parameters described for the UFORE analysis, such as tree species, size (dbh and height), condition, crown light exposure (CLE), position in respect to buildings and land-use.

3.2.3 Allometric Equations

Four sets of allometric equations are described in the following sections.

3.2.3.1 i-Tree Eco

Forest-based biomass equations and the 0.80 multiplier are used to calculate carbon storage and sequestration (Nowak et al. 2002). Hahn's (1984) volumetric formulas are applied to calculate biomass for deciduous trees greater than 94 cm dbh and coniferous trees greater than 122 cm dbh (Nowak et al. 2002).

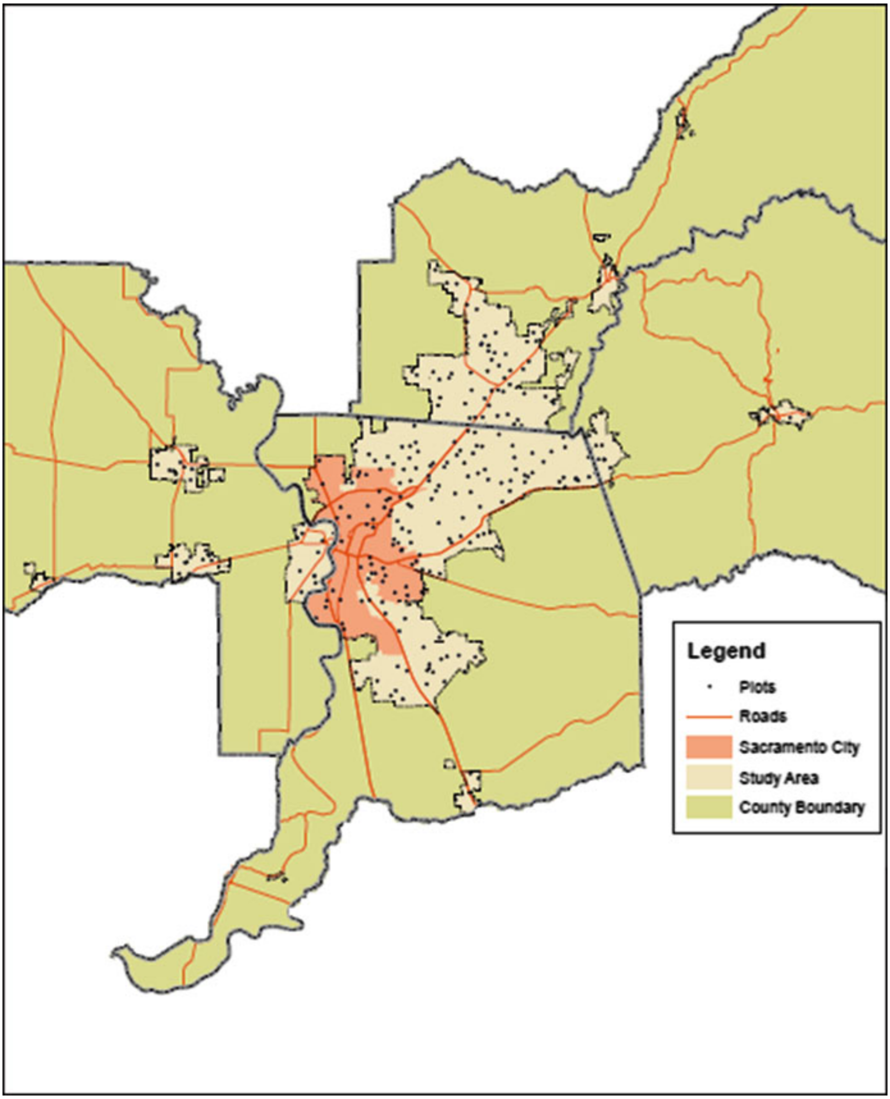

Fig. 3.1 Distribution of UFORE 300 sampling plots in study area (Source: Sacramento study UFORE Draft Report 2010 (Nowak et al. 2010))

Most equations produce dry-weight biomass, some equations compute fresh-weight biomass and are multiplied by species- or genus-specific conversion factors to convert to dry-weight biomass. When a formula is not available for a species, Eco uses the average of results from equations of the same genus. If no genus equations are found, it uses an average of results from all broadleaf or conifer equations.

Eco estimates standardized tree growth based on the number of frost free days and adjusts this base value based on tree condition and location (CLE) to calculate sequestration (Nowak 1994; Nowak et al. 2008). Frost free days are assumed to be 305 for Sacramento, and annual dbh growth ranges from 0.8 to 1.0 cm across all dbh classes. Average height growth is calculated based on formulas from Fleming (1988) and the specific dbh growth factor used for the tree. Growth rates are adjusted based on tree condition as follows: fair to excellent condition – multiplied by 1 (no adjustment), poor condition – 0.76, critical condition – 0.42, dying – 0.15, dead – 0. These growth adjustment factors are based on percent crown dieback and the assumption that less than 25% crown dieback had a limited effect on dbh growth rates (Nowak et al. 2002). Crown light exposure (CLE) provides information on the number of sides of the tree receiving sunlight and ranges from 0 (no full light) to 5 (full light from top and 4 sides).

Gross sequestration is estimated from annual tree growth. Net sequestration incorporates CO_2 emissions due to decomposition after tree death. Emissions are based on the probability of the tree dying within the next year and being removed. Annual removal rates range across dbh classes from 1.4% to 1.9% for condition good to excellent, 3.3% for fair condition, 8.9% for poor condition, 13% for critical, 50% for dying, and 100% for dead (Hoehn 2010).

3.2.3.2 i-Tree Streets

Streets uses the 26 urban-based biomass equations to estimate CO_2 storage for trees in open-grown locations (Pillsbury et al. 1998; McHale et al. 2009). When a formula is not available for a species, Streets uses the closest available urban- or forest-based equation based on taxonomic relationships and wood density characteristics. Forest-based equations are applied with the 0.8 multiplier.

For purposes of comparison, we depart slightly from the Streets protocol by adjusting storage results to account for tree condition. Results from the biomass equations are reduced by 25% for trees in poor or dying condition and 50% for dead trees.

3.2.3.3 CTCC Equations

The CTCC uses biomass equations that are derived almost exclusively from the 26 urban-based equations. Species assignation is different for CTCC because it permits the user to choose one of 16 U.S. climate zones according to the location of the study city. In this study, when a formula is not available for a species from the lists for California's climate zones, a species from the Inland Empire and Central Valley (Climate zones 3 and 4 in the CTCC, Table 3.1) is assigned based on the following criteria: 1-taxonomic, 2-expert opinion on form and growth rate, 3-native or not native. For example, of the 53 species listed for selection in the two climate zones,

Table 3.1 Tree species in Climate zones 3 (Inland Empire) and 4 (Central Valley) of the CUFR Tree Carbon Calculator (McPherson et al. 2008)

Botanic name	Model	Species assigned (Source)
Climate Zone 3-Inland empire		
Brachychiton populneus	= 0.0283168466*(0.00449*(dbhcm/2.54)^2.07041*(3.28*htm)^0.84563)	Magnolia grandiflora (1)
Cinnamomum camphora	= 0.0283168466*(0.00982*(dbhcm/2.54)^2.13480*(3.28*htm)^0.63404)	Cinnamomum camphora (1)
Eucalyptus sideroxylon	= 0.0283168466*(0.00309*(dbhcm/2.54)^2.15182*(3.28*htm)^0.83573)	Eucalyptus globulus (1)
Fraxinus uhdei	= 0.0283168466(0.00129*(dbhcm/2.54)^1.76296*(3.28*htmet)^1.42782)	Fraxinus velutina 'Modesto' (1)
Fraxinus velutina 'Modesto'	= 0.0283168466(0.00129*(dbhcm/2.54)^1.76296*(3.28*htmet)^1.42782)	Fraxinus velutina 'Modesto' (1)
Ginkgo biloba	= 0.0283168466*(0.01177*(dbhcm/2.54)^2.31582*(3.28*htmet)^0.41571)	Liquidambar styraciflua (1)
Jacaranda mimosifolia	= 0.0283168466*(0.011312*(dbhcm/2.54)^2.18578*(3.28*htm)^0.548045)	Jacaranda mimosifolia (1)
Lagerstroemia indica	= 0.0283168466*(0.011312*(dbhcm/2.54)^2.18578*(3.28*htm)^0.548045)	Jacaranda mimosifolia (1)
Liquidambar styraciflua	= 0.0283168466*(0.01177*(dbhcm/2.54)^2.31582*(3.28*htmet)^0.41571)	Liquidambar styraciflua (1)
Liriodendron tulipifera	= 0.0283168466*(0.01177*(dbhcm/2.54)^2.31582*(3.28*htmet)^0.41571)	Liquidambar styraciflua (1)
Magnolia grandiflora	= 0.0283168466*(0.00449*(dbhcm/2.54)^2.07041*(3.28*htm)^0.84563)	Magnolia grandiflora (1)
Phoenix canariensis	= (6*htm + 0.8) + (0.8*htm + 0.9)[a]	Prestoea montana (4)
Phoenix dactylifera	= (6*htm + 0.8) + (0.8*htm + 0.9)[a]	Prestoea montana (4)
Pinus brutia	= 0.0283168466*(0.008573*(dbh/2.54)^2.226808*(3.28*ht)^0.668993)	Pinus radiata (1)
Pinus canariensis	= 0.0283168466*(0.008573*(dbh/2.54)^2.226808*(3.28*ht)^0.668993)	Pinus radiata (1)
Pistacia chinensis	= 0.0283168466(0.00292*(dbhcm/2.54)^2.19157*(3.28*htmet)^0.94367)	Pistacia chinensis (1)
Pinus contorta var. bolanderi	= 0.0283168466*(0.008573*(dbh/2.54)^2.226808*(3.28*ht)^0.668993)	Pinus radiata (1)
Platanus X acerifolia	= 0.0283168466*(0.01043*(dbhcm/2.54)^2.43642*(3.28*htmet)^0.39168)	Platanus X acerifolia (1)
Platanus racemosa	= 0.0283168466*(0.01043*(dbhcm/2.54)^2.43642*(3.28*htmet)^0.39168)	Platanus X acerifolia (1)
Pyrus calleryana	= (EXP(−2.437 + 2.418*(LN(dbhcm))) + EXP(−3.188 + 2.226*(LN(dbhcm))))*0.8[a]	General hardwoods (3)
Quercus agrifolia	= 0.000169*dbhcm^1.956*htmet^0.842	Quercus macrocarpa (2)
Quercus ilex	= 0.0283168466(0.00431*(dbhcm/2.54)^1.82158*(3.28*htmet)^1.06269)	Quecus ilex (1)
Schinus molle	= 0.0283168466(0.00292*(dbhcm/2.54)^2.19157*(3.28*htmet)^0.94367)	Pistacia chinensis (1)
Schinus terebinthifolius	= 0.0283168466(0.00292*(dbhcm/2.54)^2.19157*(3.28*htmet)^0.94367)	Pistacia chinensis (1)
Washingtonia robusta	= (6*htm + 0.8) + (0.8*htm + 0.9)	Prestoea montana (4)

(continued)

Table 3.1 (continued)

Botanic name	Model	Species assigned (Source)
Climate Zone 4- Central valley		
Acer saccharinum	= 0.000238*dbhcm^1.998*htm^0.596	Acer saccharinum (2)
Betula pendula	= a^(b+c*(LOG10(dia^d)))	Betula lenta (5)
Celtis sinensis	= 0.002245*dbhcm^2.118*htm^–0.447	Celtis occidentalis (2)
Cinnamomum camphora	= 0.0283168466*(0.00982*(dbhcm/2.54)^2.13480*(3.28*htm)^0.63404)	Cinnamomum camphora (1)
Fraxinus angustifolia ‘Raywood’	= 0.0283168466(0.00129*(dbhcm/2.54)^1.76296*(3.28*htmet)^1.42782)	Fraxinus velutina ‘Modesto’ (1)
Fraxinus excelsior ‘Hessei’	= 0.0283168466(0.00129*(dbhcm/2.54)^1.76296*(3.28*htmet)^1.42782)	Fraxinus velutina ‘Modesto’ (1)
Fraxinus holotricha	= 0.0283168466(0.00129*(dbhcm/2.54)^1.76296*(3.28*htmet)^1.42782)	Fraxinus velutina ‘Modesto’ (1)
Fraxinus pennsylvanica ‘Marshall’	= 0.000414*dbhcm^1.847*htm^0.646	Fraxinus pennsylvanica (2)
Fraxinus velutina ‘Modesto’	= 0.0283168466(0.00129*(dbhcm/2.54)^1.76296*(3.28*htmet)^1.42782)	Fraxinus velutina ‘Modesto’ (1)
Ginkgo biloba	= 0.0283168466*(0.01177*(dbhcm/2.54)^2.31582*(3.28*htmet)^0.41571)	Liquidambar styraciflua (1)
Gleditsia triacanthos	= 0.000489*dbhcm^2.132*htm^0.142	Gleditsia triacanthos (2)
Koelreuteria paniculata	= 0.0283168466(0.00292*(dbhcm/2.54)^2.19157*(3.28*htmet)^0.94367)	Pistacia chinensis (1)
Lagerstroemia indica	= 0.0283168466*(0.011312*(dbhcm/2.54)^2.18578*(3.28*htm)^0.548045)	Jacaranda mimosifolia (1)
Liquidambar styraciflua	= 0.0283168466*(0.01177*(dbhcm/2.54)^2.31582*(3.28*htmet)^0.41571)	Liquidambar styraciflua (1)
Magnolia grandiflora	= 0.0283168466*(0.00449*(dbhcm/2.54)^2.07041*(3.28*htm)^0.84563)	Magnolia grandiflora (1)
Phoenix canariensis	= (6*htm+0.8)+(0.8*htm+0.9)[a]	Prestoea montana (4)
Phoenix dactylifera	= (6*htm+0.8)+(0.8*htm+0.9)[a]	Prestoea montana (4)
Pinus brutia	= 0.0283168466*(0.008573*(dbh/2.54)^2.226808*(3.28*ht)^0.668993)	Pinus radiata (1)
Pistacia chinensis	= 0.0283168466(0.00292*(dbhcm/2.54)^2.19157*(3.28*htmet)^0.94367)	Pistacia chinensis (1)
Pinus contorta var. bolanderi	= 0.0283168466*(0.008573*(dbh/2.54)^2.226808*(3.28*ht)^0.668993)	Pinus radiata (1)
Pinus radiata	= 0.0283168466*(0.005325*(dbh/2.54)^2.226808*(3.28*ht)^0.668993)	Pinus radiata (1)
Pinus thunbergiana	= 0.0283168466*(0.005325*(dbh/2.54)^2.226808*(3.28*ht)^0.668993)	Pinus radiata (1)

Platanus hybrida	= 0.0283168466*(0.01043*(dbhcm/2.54)^2.43642*(3.28*htmet)^0.39168)	Platanus hybrida (1)
Pyrus calleryana 'Bradford'	= (EXP(−2.437 + 2.418*(LN(dbhcm))) + EXP(−3.188 + 2.226*(LN(dbhcm))))*0.8[a]	General hardwoods (3)
Pyrus kawakamii	= (EXP(−2.437 + 2.418*(LN(dbhcm))) + EXP(−3.188 + 2.226*(LN(dbhcm))))*0.8[a]	General hardwoods (3)
Quercus ilex	= 0.0283168466(0.00431*(dbhcm/2.54)^1.82158*(3.28*htmet)^1.06269)	Quercus ilex (1)
Washingtonia robusta	= (6*htm + 0.8) + (0.8*htm + 0.9)	Prestoea montana (4)
Zelkova serrata	= 0.0283168466(0.00666*(dbhcm/2.54)^2.36318*(3.28*htmet)^0.55190)	Zelkova serrata (1)

Source: (1) Pillsbury et al. (1998), (2) McHale et al. (2009), (3) Harris et al. (1973), (4) Frangi and Lugo (1985), (5) Jenkins et al. (2003a, b)/Martin

[a]Equation predicts dry weight instead of volume

biomass for two pears (*Pyrus calleryana* and *kawakami*) and three palms (*Phoenix canariensisis* and *dactylifera*, *Washingtonia robusta*) is calculated with forest-based equations (general hardwoods and palms equations). Carbon dioxide storage is not adjusted for tree condition or with the 0.8 multiplier. Total dry weight biomass is calculated and converted to CO_2.

Carbon dioxide sequestration is calculated using growth curves developed from intensive measurements on a sample of about 1,000 street trees representing the 20 predominant species measured in each of the California reference cities. Sequestration is not adjusted for condition or mortality.

3.2.3.4 Urban General Equations (UGEs)

A set of UGEs equations was developed to compare with results from species-specific equation sets. Trees are classified into three types that are readily distinguished with remote sensing: broadleaves, conifers and palms. Tree volume equations are derived exclusively from the 26 urban-based formulas and converted to biomass equations (Table 3.2). Total dry weight biomass is converted to CO_2 storage. There is no tree condition adjustment and no species assignation is applied.

Development of Urban General Biomass Equations

Both sets of urban equations were converted to the International System of Units (SI units). Pillsbury's 15 equations were corrected for standard error. The publication included antilogarithmic error that had to be converted to root mean square error (RMSE). McHale's equations were corrected as well, although the publication included RMSE values for each equation. The RMSE values of the 26 equations were used in calculating new coefficients that accounted for the error. Logarithmic expressions of each of the 26 new coefficients were taken. Coefficients b and c (the later only existing in the sets of equations with height) were left unchanged.

The logarithmic expressions of all new coefficients *"a"* were sorted by tree type and the maximum and minimum values plotted to observe differences between tree types. The same procedure was repeated for coefficients b and c. The separation between broadleaf evergreen species and broadleaf deciduous species was not clear, so both groups were combined into a single tree type called broadleaf.

Differences among coefficients were evident for species belonging to broadleaf and conifer tree types. However, only two of the published equations were for conifers. More data on conifers is necessary to better identify and explain causes for coefficient differences.

The final urban general equations (UGEs) have the same format as the species-specific equations [$\text{biomass} = A^*(\text{dbh})^B$] and [$\text{biomass} = A^*(\text{dbh})^{B*}(\text{height})^C$]. Coefficient *A, B and C* were calculated by averaging the logarithmic expressions of the new *"a"* "*b*" and "*c*" coefficients.

Table 3.2 26 Available urban allometric equations from California-Colorado

Tree species	Volume equation=a*(dbh)^b	R^2	RMSE	Source	dbh min (cm)	dbh max (cm)	height min (m)	height max (m)
Fraxinus pennsylvanica	0.00059*(dbh)^2.206	0.987	0.18	McHale	1	140	Not reported	Not reported
Gleditsia triancanthos	0.00051*(dbh)^2.22	0.988	0.19	McHale	1	140	Not reported	Not reported
Tilia cordata	0.00094*(dbh)^2.042	0.953	0.26	McHale	1	140	Not reported	Not reported
Quercus macrocarpa	0.00024*(dbh)^2.425	0.938	0.37	McHale	1	140	Not reported	Not reported
Celtis occidentalis	0.0014*(dbh)^1.928	0.959	0.29	McHale	1	140	Not reported	Not reported
Ulmus americana	0.0018*(dbh)^1.869	0.924	0.27	McHale	1	140	Not reported	Not reported
Acer platanoides	0.0019*(dbh)^1.785	0.94	0.28	McHale	1	140	Not reported	Not reported
Ulmus pumila	0.0049*(dbh)^1.613	0.874	0.46	McHale	1	140	Not reported	Not reported
Populus sargentii	0.0021*(dbh)^1.873	0.991	0.18	McHale	1	140	Not reported	Not reported
Gymnocladus dioicus	0.00042*(dbh)^2.059	0.816	0.41	McHale	1	140	Not reported	Not reported
Acer saccharinum	0.00036*(dbh)^2.292	0.964	0.33	McHale	1	140	Not reported	Not reported
Acacia longifolia	0.048490*(dbh)^2.347250	0.938	0.22	Pillsbury	15	57.2	9.3	16.3
Liquidambar styraciflua	0.030684*(dbh)^2.560469	0.979	0.14	Pillsbury	14	54.4	7.3	20
Eucalyptus globulus	0.055113*(dbh)^2.436970	0.968	0.24	Pillsbury	15.5	130	14.1	43.9
Cinnamomum camphora	0.031449*(dbh)^2.534660	0.97	0.16	Pillsbury	13.2	68.8	5.2	17.1
Ceratonia siliqua	0.066256*(dbh)^2.128861	0.91	0.25	Pillsbury	15.5	71.4	4.7	10.8
Ulmus parvifolia chinensis	0.028530*(dbh)^2.639347	0.903	0.2	Pillsbury	17.3	55.9	7.6	18.9
Pistacia chinensis	0.019003*(dbh)^2.808625	0.958	0.22	Pillsbury	12.7	51.3	6.7	15.8
Quercus ilex	0.025169*(dbh)^2.607285	0.938	0.22	Pillsbury	12.7	52.1	5.2	17.1
Jacaranda mimosifolia	0.036147*(dbh)^2.486248	0.949	0.17	Pillsbury	17.3	59.7	6.9	17.5
Platanus acerifolia	0.025170*(dbh)^2.673578	0.965	0.2	Pillsbury	15.5	73.9	7.9	27.9
Fraxinus velutina 'Modesto'	0.022227*(dbh)^2.633462	0.94	0.25	Pillsbury	14.5	84.8	5.6	22.6
Cupressus macrocarpa	0.035598*(dbh)^2.495263	0.98	0.21	Pillsbury	15.7	146.6	8.1	30.8
Pinus radiate	0.019874*(dbh)^2.666079	0.969	0.24	Pillsbury	16.8	105.4	5.5	32.2
Zelkova serrata	0.021472*(dbh)^2.674757	0.969	0.19	Pillsbury	14.5	86.4	6.1	21
Magnolia grandiflora	0.022744*(dbh)^2.622015	0.958	0.22	Pillsbury	14.5	74.2	5.8	18.9

Source of equations: Pillsbury et al. (1998), McHale et al. (2009)

For the purpose of this study, dbh based equations were used for comparisons because dbh can be derived from tree crown projection area obtained from remotely sensed imagery. More research is needed to identify relations between these dimensions.

The biomass equation for palms was an equation for *Prestoea montana* based on destructive measurements for individuals of this species growing in a Puerto Rican floodplain forest (Frangi and Lugo 1985). Biomass equations for palms growing in U.S. cities are not available. Because palms trees do not have secondary growth the only parameter is tree height. The UGEs that will be used subsequently are:

$$\text{Broad leaf}_{\text{biomass}}(\text{only dbh}) = 0.16155 * (\text{dbh})\hat{}2.310647 \quad (3.3)$$

$$\text{Conifer}_{\text{biomass}}(\text{only dbh}) = 0.035702 * (\text{dbh})\ \hat{}\ 2.580671 \quad (3.4)$$

$$\text{Palm}_{\text{biomass}} = 1.282 * (7.7 * \text{ht} + 4.5) \quad (3.5)$$

These equations estimate total dry weight (kg, above and below ground) based on measured dbh (cm) and tree height (m) for palms.

3.2.4 Scale-Up

An area-based approach is used to scale-up CO_2 storage estimates from the 300 plots to the entire study area. Total storage for the 300 plots (12.1 ha) are proportionally scaled up to the entire study area (131,742 ha) using the scalar 10,851 (131,742/12.1). The total CO_2 storage density (kg/ha) for all plots is multiplied by the same scalar as well. One exception is the Eco model, which includes tree density as well as area in the scale-up calculation (Nowak 1994; Hoehn 2010).

3.3 Results

3.3.1 Comparison of UGEs with Other Biomass Equations

UGEs developed with urban-based biomass equations are compared with general forest biomass equations for hardwoods and softwoods using the same dbh or dbh-height data. The results, plotted in Fig. 3.2, reveal that at sizes larger than 35 cm dbh UGE predicted above-ground biomass is about 25% less than predicted with forest-based general equations for hardwoods and about 10% less for than for softwoods. Differences are less noticeable for smaller sized trees.

Conifers accumulate less biomass than broadleaves through their growth cycle, due in part to lower wood density. There is a small difference in biomass storage estimates between urban broadleaf tree types. However, urban broadleaf evergreens store a little less biomass than urban broadleaf deciduous trees.

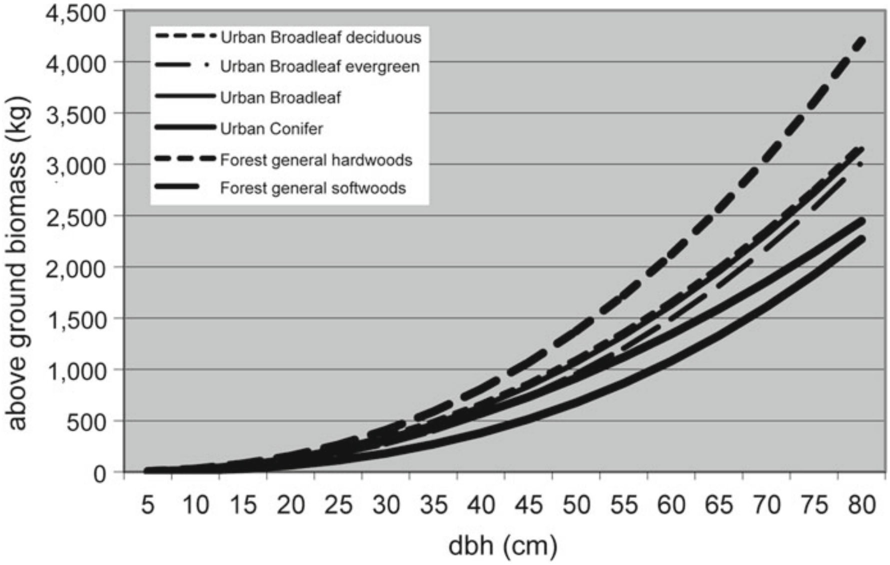

Fig. 3.2 Urban- and forest-based general equations

Table 3.3 Carbon dioxide storage (t), sequestration (t), and density (t/ha) for all plots (12.1 ha) and the study site (131,742 ha, area-based scale up)

Biomass equations	Plot storage	Plot sequestration	Study area storage	Study area sequestration	Density storage	Density sequestration
Eco	458.1	22.0	4,989,515	238,589	38.2	1.8
Streets	591.0		6,412,544		48.7	
CTCC	589.9	34.1	6,400,723	370,413	48.6	2.8
UGE	469.8		5,098,100		38.7	

3.3.2 Plot Level: Comparison of Storage Estimations

The comparison of CO_2 storage and sequestration calculations for the 640 trees in the 300 plots is presented in Table 3.3. i-Tree Streets (591 t) and CTCC (590 t) storage estimates are very similar and 26% greater than the UGE value (470 t). The i-Tree Eco CO_2 storage estimate (458 t) is about 3% less than the UGE value. The highest estimates for Streets and CTCC are 29% greater than the lowest estimate for Eco. Carbon dioxide storage density values range from 38 to 49 t/ha (Table 3.2).

Sequestration estimates are only available for the Eco and CTCC equation sets because they have associated tree growth data. The CTCC estimate (34.1 t) is 55% higher than the Eco value (22.0 t). Carbon dioxide sequestration density values range from 1.8 to 2.8 t/ha.

3.3.3 Scale Up Results

Carbon dioxide storage and sequestration differences noted at the plot level are also reflected at the regional or study area level (Table 3.2). Storage values obtained with Streets (6.41 Mt) and CTCC (6.4 Mt) equation sets are similar and substantially greater than the Eco estimate (4.9 Mt). The estimate obtained with the UGE (5.1 Mt) is about 3% greater than the Eco estimate.

3.4 Discussion

This study found a maximum 29% difference in plot-level CO_2 storage among the four sets of biomass equations. As expected, i-Tree Eco equations produced the lowest estimate (458 t), presumably because forest-based equations are used exclusively with application of the 0.8 multiplier to open-grown trees. The UGEs produced an intermediate estimate (470 t), and the CTCC and Streets equations produced substantially larger estimates that were very similar (590 and 591 t).

3.4.1 Differences by Species

To explain causes for different estimates it is useful to examine differences among species that are most important by virtue of their relative abundance and size. For example, Interior live oak (*Quercus wislizenii*) is not the most abundant species, but it stores the most CO_2 according to all four sets of equations (Fig. 3.3). Estimated CO_2 storage for the species ranged from 82 t (UGEs) to 142 t (CTCC).

According to three sets of equations (Eco, Streets, CTCC), the next most important species, Blue oak (*Quercus douglasii*) stores nearly one-half as much CO_2 as Interior live oak, but the UGE shows a small difference. Estimates from the UGE's tended to be among the lowest for the oaks, but among the highest for other important species such as Alder (*Alnus spp*.), White mulberry (*Morus alba*), London planetree (*Platanus acerifolia*) and Atlas cedar (*Cedrus deodara*). Similarly, storage estimates from the Eco equations were the lowest for oaks, but among the highest for London planetree, olive (*Olea europaea*), and several other species.

3.4.2 Effects of Different Biomass Equations

A more detailed picture of the variability among estimates of stored and sequestered CO_2 is presented in Tables 3.4 and 3.5. The values are calculated by species using

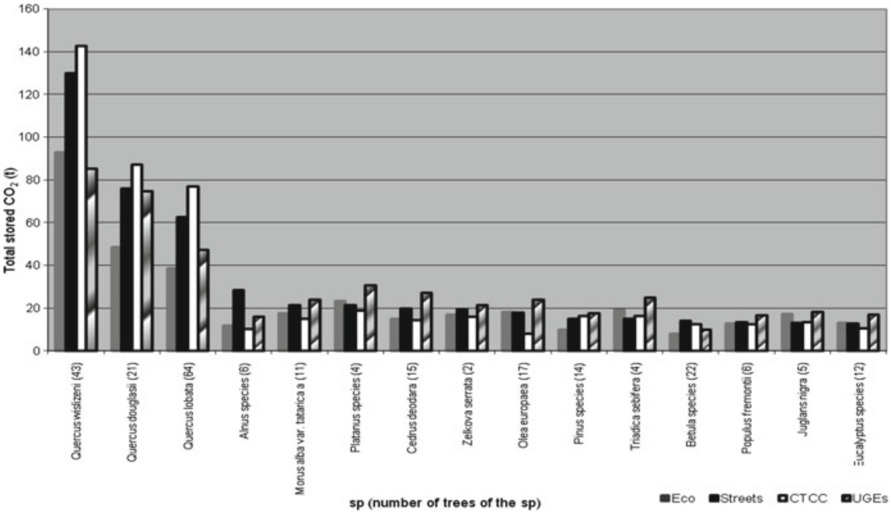

Fig. 3.3 Carbon dioxide storage estimates by species calculated with four sets of biomass equations for sampled trees (number in brackets)

the species assignments listed in Table 3.5 and the mean dbh and height for all trees sampled. They do not account for adjustments based on CLE, condition, or mortality. The maximum difference is expressed as a percentage: (High value/Low value) × 100, where 100 is no difference. The minimum difference is the difference between the two closest values.

For CO_2 storage, the minimum difference is less than 5% for five species, but greater than 10% for the remaining five species. The maximum difference is at least two-fold for all species except olive, and exceeds three-fold for five species. An eight-fold maximum difference exists for alder between the Streets (4,320 kg) and Eco (539 kg) estimates. Both minimum and maximum differences are relatively high for the three oak species, who together account for about one-half of all CO_2 stored. There are no discernable trends in terms of a set of equations always producing estimates that are the highest or lowest across all species.

In the comparison of sequestration rates among species (Table 3.4), differences exceed ten-fold for two species and are five- to six-fold for three other species. Differences are relatively high for the oaks, alder and pine (*Pinus spp*.). Here there is a clear trend, with CTCC estimates always greater than Eco estimates. Eco values are for gross sequestration, so the differences in Table 3.4 cannot be due to reductions for tree condition and projected mortality in Eco. More likely explanations are differences in tree growth rates and selection of biomass equations.

Results in Table 3.4 illustrate how selection of biomass equations influence storage estimates. Using the same tree dbh and height but different biomass equation for the same species can result in dramatically different estimates.

Table 3.4 Carbon dioxide stored and sequestered, and differences among the four sets of equations calculated on a per tree basis with mean dbh and height for the most important species

			Stored (kg)						Sequestered (kg/year)		
Common name	dbh (cm)	Height (m)	Eco	Streets	CTCC	UGE	Min diff (%)	Max diff (%)	Eco	CTCC	Diff (%)
Interior live oak	29.9	11.3	589	991	1,531	762	129	260	23.5	136.6	582
Blue oak	34.2	10.3	627	1,162	2,118	1,039	112	338	15.7	163.5	1,045
California white oak	19.3	10.5	163	395	535	277	169	327	10.8	74.4	687
Alder	44.2	15.7	539	4,320	1,454	1,879	129	801	21.5	111.1	517
White mulberry	35.6	10.8	431	1,118	680	1,140	102	265	16.6	47.3	284
London planetree	23.8	11.8	135	312	302	449	103	334	11.2	49.0	440
Atlas cedar	8.1	3.7	6	8	11	14	129	241	1.4	5.0	374
Japanese zelkova	84.1	21.1	2,280	9,705	8,114	8,307	102	426	74.1	105.3	142
Olive	24.9	8.1	288	268	265	499	101	188	12.7	33.8	267
Pine	29.7	10.7	190	401	463	414	103	244	6.6	77.7	1,171

Table 3.5 Species assignation differences among the four sets of equations

Species name	i-Tree Eco	i-Tree Streets	CTCC	UGEs
Quercus wislizeni	Q. wislizeni (Pillsbury and Kirkley 1984)	Quecus ilex (Pillsbury et al. 1998)	Quercus macrocarpa (McHale et al. 2009)	Broadleaves UGE (Eq. 3.3)
Q douglasii	Q. douglasii (Pillsbury and Kirkley 1984)	Quecus ilex (Pillsbury et al. 1998)	Quercus macrocarpa (McHale et al. 2009)	Broadleaves UGE (Eq. 3.3)
Q. lobata	Average oaks (Nowak and Crane 2002)	Quecus ilex (Pillsbury et al. 1998)	Quercus macrocarpa (McHale et al. 2009)	Broadleaves UGE (Eq. 3.3)
Alnus sp	Average broadleaves (Nowak and Crane 2002)	Populus sargentii (McHale et al. 2009)	Eucalyptus sideroxylon (Pillsbury et al. 1998)	Broadleaves UGE (Eq. 3.3)
Morus alba	Average broadleaves (Nowak and Crane 2002)	Fraxinus velutina 'Modesto' (Pillsbury et al. 1998)	Fraxinus velutina 'Modesto' (Pillsbury et al. 1998)	Broadleaves UGE (Eq. 3.3)
Platanus sp	Average broadleaves (Nowak and Crane 2002)	Platanus hybrida (Pillsbury et al. 1998)	Platanus hybrida (Pillsbury et al. 1998)	Broadleaves UGE (Eq. 3.3)
Cedrus deodara	Average cedars (Nowak and Crane 2002)	Pinus radiata (Pillsbury et al. 1998)	Pinus radiata (Pillsbury et al. 1998)	Conifers UGE (Eq. 3.4)
Zelkova serrata	Average broadleaves (Nowak and Crane 2002)	Zelkova serrata (Pillsbury et al. 1998)	Zelkova serrata (Pillsbury et al. 1998)	Broadleaves UGE (Eq. 3.3)
Olea europaea	Average broadleaves (Nowak and Crane 2002)	Fraxinus velutina 'Modesto' (Pillsbury et al. 1998)	Fraxinus velutina 'Modesto' (Pillsbury et al. 1998)	Broadleaves UGE (Eq. 3.3)
Pinus sp.	Average pines (Nowak and Crane 2002)	Pinus radiata (Pillsbury et al. 1998)	Pinus canariensis (Pillsbury et al. 1998)	Conifers UGE (Eq. 3.4)

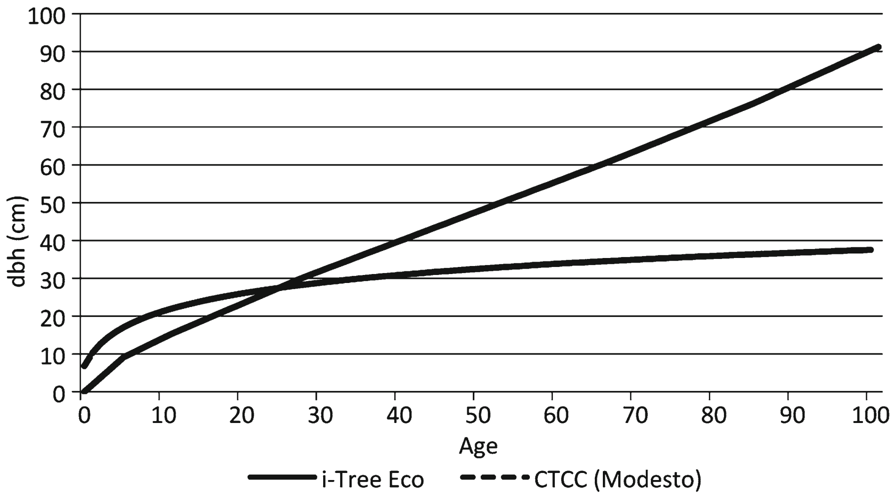

Fig. 3.4 Eco and CTCC growth curves for Green ash

3.4.3 Single Species Example

Carbon dioxide sequestration estimates produced by Eco and CTCC are influenced by tree growth and size, as well as selection of the allometric equation. The extent to which these factors influence sequestration is shown for the same species, Green ash (*Fraxinus pennsylvanica*) using unadjusted data from the i-Tree Eco and CTCC models (Fig. 3.4). The Eco growth curve shows initial rapid growth for 5 years followed by moderate growth that increases linearly until year 100. The CTCC growth model starts with a larger tree, but the growth becomes quite slow after 10 years. After 25 years the size of the tree modeled in Eco surpasses the CTCC tree, and after 80 years is twice the dbh of the CTCC tree.

The amount of CO_2 stored by the same size trees using the different biomass equations applied in Eco and CTCC shows a similar trend (Fig. 3.5). Carbon dioxide stored by the CTCC tree is greater than the Eco tree initially, but becomes less once the tree reaches 40 cm dbh and its growth ceases. In Eco, the sequestration rate gradually increases with tree size. After the tree surpasses 55 cm dbh, it begins to store more CO_2 than estimated by the CTCC tree.

The Eco growth model uses a base growth increment (0.83 cm/year) that is adjusted based on frost free days, CLE and condition. As explained by Nowak (1994) growth is also adjusted based on dbh. Growth rates are grouped by genera and dbh. Averages are used as base growth rates for specific land uses and are then altered based on length of growing season. The base tree growth rate comes from trees measured in northern latitudes, and may well underestimate growth in California. Growth rates used by CTCC are based on data measured for street and park trees in California cities.

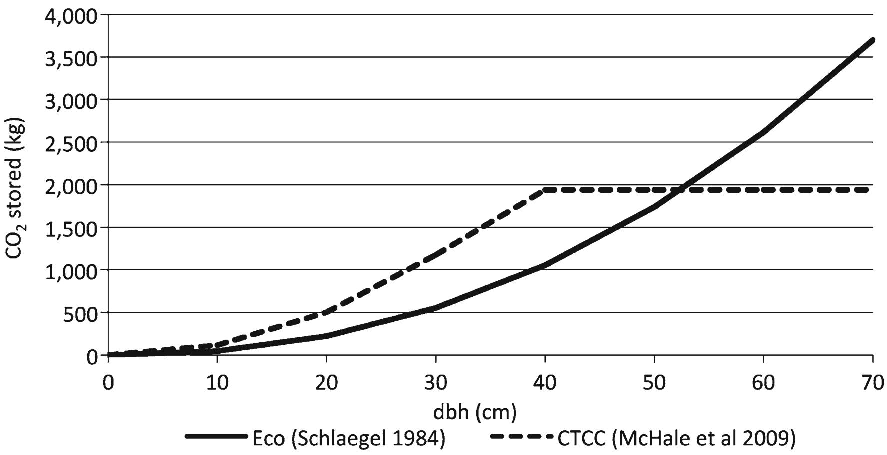

Fig. 3.5 CO_2 storage by dbh in Green ash

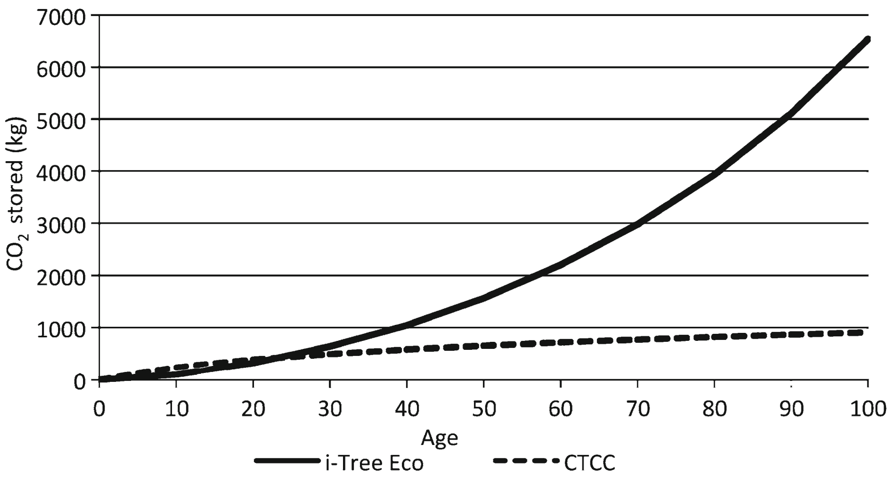

Fig. 3.6 CO_2 storage by age in Green ash

The amount of CO_2 stored as a function of tree age incorporates effects of tree growth and size with solutions produced by each allometric equation (Fig. 3.6). Differences between Eco and CTCC are small for the first 30 years, but become pronounced with tree age. At 100 years the green ash modeled with Eco has stored over six times the amount of CO_2 as the ash modeled with the CTCC.

Because the UGEs produced relatively low CO_2 storage estimates for the most important species, it is not surprising that they produced a relatively low estimate for all 640 sampled trees. UGE storage estimates could be relatively higher compared to the other approaches if the tree population had a different distribution of

Table 3.6 Tree density, stored and sequestered carbon dioxide per hectare for several cities

City	Trees/ha	Storage CO_2 t/ha	Seq. CO_2 t/ha/year	Reference
Sacramento, USA[a]	68	91.9	2.8	McPherson (1998)
Atlanta, USA	276	131.2	4.5	Nowak and Crane (2002)
New York, USA	65	56.3	1.8	Nowak and Crane (2002)
Chicago, USA[b]	69	52.0	2.4	Nowak (1994)
Miami-Dade, USA	288	43.1	3.2	Escobedo et al. (2010)
Gainesville, USA	528	117.1	4.5	Escobedo et al. (2010)
Chuncheon, Korea[b]	150	4.7	0.6	Jo (2002)

[a]City and suburban sectors only
[b]City only

importance among species and different biomass equation species assignments. It appears that the accuracy of UGE estimates relative to estimates derived from species-based equations depends on the population structure and idiosyncrasies of species and biomass equation assignments.

3.4.4 Differences Among Cities

The CO_2 storage and sequestration results from this study are difficult to compare with other studies because of differences in forest composition, age structure, and scope of the analyses. Forests with low tree density and abundant softwoods will store less CO_2 than high density, hardwood forests. Population density and the extent of urbanization influence urban forest density. Forests in old parts of the city often store more CO_2 than forests in new development because trees are mature. However, sequestration rates may be greater in younger areas where trees are growing rapidly. The scope of the study influences results because it may include CO_2 emissions from anticipated mortality and tree care activities. Some studies include reduced emissions from energy savings. Also, some studies include storage from interface forests and peri-urban natural areas, while others are limited to developed areas. To facilitate comparisons across cities mean CO_2 storage and sequestration rates are presented per hectare (Table 3.6).

Compared to the previous Sacramento study (McPherson 1998), the study area for this analysis is much larger, and includes a larger amount of undeveloped land in agricultural and other non-forest uses. Sampling intensity was greater in the previous study, with 460 plots in 61,000 ha versus 300 plots in 131,000 ha. In comparison with the previous Sacramento study (Table 3.6), the scaled-up data from this study found relatively low tree density (53/ha), CO_2 storage (38–49 t/ha) and sequestration (1.8–2.8 t/ha) rates. The mean dbh measured in the current study is 18 cm, or about one-half the size recorded in the previous Sacramento study (39 cm). Thus, the lower amount of CO_2 storage estimated in the current study may be partially explained by lower tree density and younger, smaller trees on average. To some extent, this result may be an artifact of differences in the area sampled and sampling intensity.

Sacramento tree density, stored and sequestered CO_2 rates are at the low end compared with the temperate climate cities of New York and Chicago. The range of variability reported here for different sets of equations does not exceed the ranges encompassed by the cities in Table 3.6. In this study, Sacramento's estimated CO_2 storage ranged from 38 to 49 t/ha, while it ranged from 4.7 to 131.2 t/ha for the six other cities cited (Table 3.6). Sacramento urban forest's estimated annual sequestration rate ranged from 1.8 to 2.8 t/ha, compared to 0.6 to 4.5 t/ha for the cities. Cities in the southeast USA have higher tree densities and sequestration rates. Storage rates are higher for Atlanta and Gainesville, but less for Miami-Dade, where stands of invasive punktree (*Melaleuca quinquenervia*) are the largest CO_2 sink. In contrast, storage and sequestration rates are low in Chuncheon, Korea, although tree density is relatively high compared to temperate climate cities in the USA.

3.5 Conclusion

This study found substantial variability among four approaches for calculating the amount of CO_2 stored and sequestered by Sacramento's urban forest. Storage estimates differed by a maximum of 29% and ranged from 38 to 49 t/ha. The two sequestration estimates differed by 55%, ranging from 1.8 to 2.8 t/ha. Although error associated with these storage estimates is considerable, its importance is diminished when one considers other sources of error, such as sampling, measurement, growth modeling, and biomass equation selection.

The variability associated with these four approaches is not great when compared to the variability in CO_2 storage and sequestration densities among cities. The maximum differences in CO_2 storage and sequestration rate differences among approaches are 11 and 1 t/h, respectively. These are relatively small amounts compared to the maximum differences reported for six other cities of 127 and 3.9 t/ha, respectively (Table 3.6). Differences among cities reflect differences in forest composition, age structure, and scope of the analyses, as well as differences in biomass equations, tree growth modeling, sampling, and measurement.

Explanations for differences observed among approaches are difficult to determine, although some trends are apparent. Eco produced the lowest storage estimate, perhaps because it relied exclusively on forest-based equations and applied a 0.80 correction factor to open-grown trees. The storage estimates produced by Streets and CTCC were the highest, perhaps reflecting ubiquitous application of urban-based biomass equations. The UGEs produced relatively low estimates of CO_2 storage. This result may be idiosyncratic to this sample of 640 trees because UGE estimates are more sensitive to the population's species composition and structure than do estimates derived from species-based equations.

Eco produced lower estimates of CO_2 sequestration rates than the CTCC across a range of species. Reductions for tree condition and projected mortality may partially explain the difference.

Also, selection of biomass equations to apply for each species was found to substantially influence storage estimates using the same input dimensions but different equations for the top ten species.

An examination of the roles of tree growth modeling and biomass equation selection for a green ash tree illustrated their importance. The Eco tree stored more CO_2 after 30 years than the CTCC tree, largely due to increased growth projected over the 100 year period. The analysis illustrated the how the dynamic interaction between tree growth and biomass storage rate can influence the temporal stream of sequestration in complex ways.

Based on these results we conclude that applying UGEs to remotely sensed data that accurately classify broadleaf, conifer and palm tree types in the Sacramento region is likely to produce conservative results compared to results from urban-based species-specific equations. The robustness of this result needs to be tested with different tree populations because of the large variability associated with assigning a limited number of urban-based biomass equations to diverse assemblages of species. This result suggests that there is promise of obtaining initial estimates of carbon dioxide storage by urban forests using UGEs for tree types identified with remote sensing when resources do not allow for field sampling. Further research is needed to establish relations between remotely-sensed tree crown projection area and dbh values required for biomass calculation. Of course, ground-based inventories remain necessary for more accurate estimates of CO_2 storage and for municipal forest management and health monitoring purposes.

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