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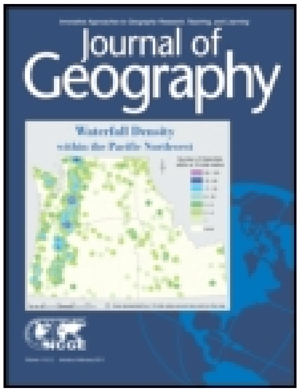

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A Sustainability Initiative to Quantify Carbon Sequestration by Campus Trees

Helen M. Cox

Abstract

Over 3,900 trees on a university campus were inventoried by an instructor-led team of geography undergraduates in order to quantify the carbon sequestration associated with biomass growth. The setting of the project is described, together with its logistics, methodology, outcomes, and benefits. This hands-on project provided a team of students with several learning opportunities including an introduction to carbon sequestration, basic arboriculture, field-based measurements, mapping, geographic information systems, and biogeography concepts. A GIS geodatabase was produced containing information on tree location, species, size, biomass, carbon content, and annual CO_2 sequestration, which was later customized for integration into campus facilities management.

Key Words: *tree, GIS, carbon sequestration, sustainability, environmental education*

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Introduction

California is the twelfth largest emitter of carbon dioxide in the world (among all states and nations). Recognizing the effects of global warming, on September 27, 2006, Governor Arnold Schwarzenegger signed AB 32, the Global Warming Solutions Act, into law. This law sets the road map for California to reduce its greenhouse gas (GHG) emissions over the next fifty years with targets of a reduction to 1990 levels by 2020 (a 25% reduction in current levels) and to 80 percent below 1990 levels by 2050. Significant GHG sources are mandated to reduce emissions in accordance with this law, and even nonmandated entities can realize benefits by conducting a GHG inventory. These include tracking, verifying, and achieving organizational social responsibility goals, identifying opportunities to reduce waste and costs, and participating in GHG reporting programs and emission markets. In 2008 the Institute for Sustainability was formed at California State University, Northridge (CSUN), and embarked on a campuswide effort to conduct a GHG inventory.

A GHG inventory typically includes direct (Scope 1) emissions from mobile and stationary sources as a result of the combustion of fuels, and indirect (Scope 2) emissions incurred by utility companies as a result of the electricity consumed. So-called Scope 3 emissions incurred from business travel and commuting are sometimes included, but seldom is carbon sequestration from vegetation a component. However, in California, the Urban Forest Protocol established by the California Climate Action Registry (CCAR 2008) permits municipalities and educational campuses to offset carbon dioxide emissions by participating in forestry projects in which tree planting beyond normal replacement is planned and undertaken for the purpose of sequestering carbon dioxide from the atmosphere. In the interests of assessing the feasibility of such a plan, and to answer other interesting research questions—such as whether differences in CO_2 uptake by different species are significant enough to consider in making planting choices—an inventory of trees was initiated on the CSUN campus in spring 2009. The inventory data were utilized in carbon sequestration calculations to compute the carbon offset afforded by the trees and to analyze their relative contributions.

The trees that sequester the most carbon dioxide from the atmosphere are those that grow the most rapidly. Trees grow through the process of photosynthesis, whereby they take in carbon dioxide and water from their environment and use sunlight to process these into glucose, releasing oxygen as a byproduct. Cellulose is formed by the tree when it links up chains of the glucose molecules. The carbon stored in their woody mass is released back to the atmosphere when the tree dies unless it becomes buried underground. The amount of carbon stored by a tree depends on its species (since all trees have slightly different chemical compositions), but roughly 50 percent of the tree's dry weight, or 25 percent of its fresh (wet) weight is carbon (Lieth 1963). Since each carbon molecule combines with two oxygen molecules to form carbon dioxide, the mass of carbon dioxide sequestered during growth or produced during decay is 3.6 times that of carbon alone. Thus the amount of carbon dioxide consumed by a tree during growth, or produced upon decay, is roughly 1.8 times its dry weight or 0.9 times its fresh (wet) weight. Most trees sequester carbon at the highest rate during the mid to later phase of their life. At a very young age, even though they are growing rapidly, their size is too small to account for much mass growth. At maturity, the rate of growth slows and thus the carbon sequestration rate diminishes. Eventually the tree reaches its maximum size, and carbon sequestration ceases.

Benefits of Study

Although the tree inventory was originally conceived as part of the carbon footprinting process, it is also closely aligned with the other goals of the Institute for Sustainability and the university, namely education and research. The project, undertaken by a professor (the author) and team of students in the geography department, afforded a unique educational opportunity for students to learn about research methods, field measurements, mapping, and biogeography. In addition students gained valuable experience in geographic information systems (GIS), carbon calculations, and project management. This project covered three types of environmental education—education *about* the environment (tree types and benefits, carbon sequestration), education *in* the environment (field-based measurements and mapping), and education *for* the environment (to select and place appropriate trees) (Vowless 2002).

In educating *about* the environment, students were introduced to the many benefits of trees, including social ones (Gold 1976; Akbari 2002). TreePeople (2010) provided instructional material and data on other benefits including shade, energy reductions for cooling in summer, reduction of stormwater runoff, erosion control, pollutant removal, and habitat provision for many insects, birds, and animals. Students were challenged to think about the role of nature in their lives, and encouraged to engage in further biogeographical research. This research has included one thesis project to look at the native distributions of the tree species found on campus and another in which the role of trees in mitigating the urban heat island effect is being examined.

Educating *in* the environment includes the use of field methods. In addition to fieldwork, students were involved in the GIS mapping of tree locations and beginning students learned new skills such as the joining of tabular data to locational data using unique keys, database management in a shared environment, and the use of metadata for documentation. GIS is well known to meet many educational goals including supporting the inquiry process, facilitating learning across a range of subjects, and increasing motivation (Audet and Abegg 1996; National Research Council 2006; Hagevik 2008).

Educating *for* the environment includes an analysis of the carbon sequestration benefits of trees, and the exploration of what-if analyses through the creation of a database and tool, which allows students to study the carbon benefits of alternative scenarios. Students were challenged to think about the factors that should be considered in the selection of tree species for planting, including their water consumption, native climate, the habitat they provide, their ability to provide shade, their rate of growth, maintenance requirements, and practicality in a campus setting. In one project they were asked to recommend tree selections for the campus based on their findings.

The campus community in general also benefitted from one end product, an interactive tree atlas, that provides a botanical guide to all the trees on campus and information on carbon sequestration. The guide describes the process by which CO_2 is removed from the atmosphere and stored by trees, together with specific amounts of carbon sequestered by each tree annually and how this is computed.

The tree inventory served other purposes—it produced a database for physical plant management use in tree maintenance; provided data for facilities management to utilize in campus planning; has been incorporated into self-guided and educational tour maps; and has been used by university advancement to locate memorial trees. The GIS database was expanded to facilitate tree management and maintenance by the addition of data fields for storing dates, tree condition, and comments.

Study Area

The CSUN campus is located in the San Fernando Valley northwest of Los Angeles. Fifty years ago the Valley was a rich farming region producing fruit and vegetables for Los Angeles and the surrounding districts. Today one of last vestiges of this agricultural history is a small orange grove preserved on the southeast corner of the CSUN campus. The San Fernando Valley has become a vast (260-square-mile) area of urban sprawl supporting multiple industrial, manufacturing, and service activities. Although there are suburban neighborhoods around the campus providing pockets of greenery, urban land cover dominates the proximate area. The campus itself is relatively green, containing large expanses of lawn, shrubbery, and over 3,900 trees on its 353 acres.

The campus enjoys a Mediterranean climate characterized by hot, dry summers and mild, wet winters with an average summer maximum temperature of 32°C, and average winter minimum temperature of 6°C. The average annual precipitation is 14.5 inches, with 90 percent falling between November and April. Vegetation native to the region includes chaparral, sagebrush, and oak woodland. Although native trees supported in Southern California include maple (*Acer*), alder (*Alnus*), fir (*Abies*) and pine (*Pinus*), at the elevation of the university campus native tree species are restricted primarily to ash (*Fraxinus*), sycamore (*Platanus*), cottonwood (*Populus*), cherry (*Prunus*), oak (*Quercus*), and willow (*Salix*). Although the campus includes some native trees, the majority are ornamental.

Project Description

A plant atlas was produced by the CSUN geography department (Gohstand 1989) in 1989 after almost a decade of mapping by students and faculty. The atlas included locations and identification of all vegetation on campus including shrubbery. However, the 1994 Northridge earthquake rendered this outdated only a few years after its publication. Since then the easy accessibility of digital data including high resolution imagery and CAD (computer-aided design) building data, together with the massive expansion in GIS technology, prompted the production of a new atlas in an electronic format.

Between March and September 2009 an instructor-led group of geography students, tagged, mapped, measured, and identified over 3,900 trees on the CSUN south campus. They recorded data in a spreadsheet and mapped tree locations on an aerial image in the field. Tree identification (genus and species) was carried out with the aid of botanical guides, books, staff, faculty, and alumni. Carbon sequestration calculations employed an algorithm from the CUFR (Center for Urban Forest Research), a branch of the U.S. Forest Service (CUFR 2008), and were subsequently incorporated in the tree geodatabase, together with data fields for recording maintenance information. Interactive and printed versions of the atlas were produced, and the GIS geodatabase was handed over to campus facilities staff for management and updates. The carbon sequestration computations were incorporated in the university's GHG inventory.

Methodology

Fieldwork and Mapping

To facilitate mapping, the campus was divided into twenty-five quads, each containing roughly one to two hundred trees. Twelve students from the geography department were recruited to participate in the mapping, and divided into groups of two or three for fieldwork. Each group was supplied with a dbh (diameter at breast height) calibrated measurement tape, numbered aluminum tree tags, nails, wire, a hammer, an aerial photo of the quad, and a data entry sheet. The tree tags, lightweight aluminum nails (minimally damaging to trees), and dbh tape were obtained from a forestry supplier, and used to tag, number, and measure the diameter of the trees. For trees less than six inches in diameter, tags were wired rather than nailed. Measurements of tree diameter were made at a height of 4.5 ft., and each individual stem of multistemmed trees was recorded. The method for measurement follows that of the U.S. Forest Service (2005). While one team member conducted the size measurement, other members of the team identified tree species (when able), marked the tree's precise location and tag number on an aerial photo, and recorded dbh and species on a spreadsheet.

In carrying out the fieldwork, the primary challenges that the students encountered were carrying everything they needed while keeping it all accessible; handling multistemmed trees in an efficient manner; gaining access to trees when overgrown shrubbery was present or trees had sharp or prickly foliage; and identifying species. The first problem was addressed by using tool belts and/or using student groups of three rather than two. To address the second problem, which was particularly common in the campus's orange grove of almost six hundred multistemmed trees, a compromise was made in the measurement method and students were instructed to measure the tree below the point at which it became forked, rather than measuring each stem individually. Although this does not strictly follow the U.S. Forest Service guidelines, computations indicated that the differences in equivalent diameter were very minor. Boots and gloves were used to access areas within prickly foliage. The problem of identifying species was one that was postponed for the most part to a second round of surveying by students with botanical knowledge, and experts on and off campus who volunteered their time.

Another implementation decision made was the utilization of a high resolution aerial photograph of the campus to map tree locations rather than the use of a global positioning satellite (GPS) unit. Accurate mapping (within a meter or better) by GPS requires a high caliber unit, the reception of signals from multiple satellites, and postprocessing capability using differential correction data. On-campus buildings make reception difficult, but an even more significant problem in tree mapping is the blockage of the GPS signal by the tree canopy. Even if a high-precision unit is used, a separate antenna must be mounted on a rod long enough to penetrate through the tree canopy in order to receive the GPS signal. Campus surveyors found it necessary to install a roof-mounted base station for precise mapping on campus and so this method was rejected in favor of marking locations on printed maps generated from a high resolution georeferenced aerial image. Although free downloadable one-meter National Agriculture Imagery Program imagery (NAIP 2005) provided an adequate base map, the project benefitted from an eight-inch resolution aerial image of the campus taken by a contracted flight in summer 2009, which aided in the precise positioning of trees because of its high resolution and accuracy (recentness).

Field data were recorded electronically on spreadsheets in the lab and tree location data from the marked-up aerial image were recorded in a GIS. Spreadsheet data from all quads were "joined" to the point location data within a GIS, using the tag number as the "join" (common) field. The GIS geodatabase was then used to generate a series of printed maps, highlighting those trees that lacked species identification. With the aid of a reference book (Hatch 2007), species identification was undertaken by four students and an alumnus over the following two-month period. Where students were unable to identify species in the field they took photographs and collected leaves that were brought back to the lab. Reference books, online databases (Hickman 1993; USDA 2010), and knowledgeable staff, alumni, and faculty helped in identification. A complete quality check was carried out in fall 2009 to address tree location misplacements, misidentifications, and missing tags. After completion, the tree geodatabase was corrected and exported back into an Excel spreadsheet format in order to execute the carbon calculations.

Carbon Sequestration Calculations

The Center for Urban Forestry Research Carbon Tree Calculator (CCTC) software available from the U.S. Forest Service (CUFR 2008) facilitated the carbon sequestration calculations. This is a free, downloadable application programmed in an Excel spreadsheet that provides a menu-driven interface to determine carbon uptake and storage for a variety of trees in different climate zones, and is the only tool approved by CCAR for quantifying carbon dioxide sequestration from tree planting projects.

Computations of carbon dioxide sequestration rates can vary greatly depending on assumptions made about tree growth rates, which depend significantly on climate and irrigation. The CCTC software used in this analysis bases growth rates on species, age (or size) of tree, and climate.

In these computations tree volume is first estimated from dbh using empirical species-specific volumetric equations from Pillsbury, Reimer, and Thompson (1998) and Lefsky and McHale (2008), e.g., for *Quercus ilex*:

$$V = 0.0283168466\left(0.025169\left(\frac{\text{dbh}}{2}\cdot 54\right)^2\cdot 607285\right)$$

where V is in m^3 and dbh is in cm. Volume is then converted to dry weight or fresh weight biomass through multiplication by density and by a factor of 1.28 to account for below ground biomass (Husch, Miller, and Beers 1982; Tritton and Hornbeck 1982; Wenger 1984). Once the total biomass is estimated, carbon storage can be computed assuming 50 percent of dry weight, or 25 percent of fresh weight, is carbon. The CCTC volumetric equations were based on trees grown in a forest setting, but adjusted by a factor of 0.80 because open-grown urban trees tend to be less massive (Nowak 1994).

To compute tree growth rates, the CCTC software uses regression to fit empirical data on 650–1,000 street trees from six different reference cities. For each city, samples of 30–60 trees from each of the most abundant species in the city were employed. Linear and nonlinear regression equations were fitted to dbh as a function of age for each species in each city, and then employed in predictive models (Peper and McPherson 2003). These models form the basis of the growth and sequestration rate estimates.

The embedded models do not cover the full spectrum of species found on campus, thus it was necessary to construct a look-up table in which each species found in the field was modeled by one available in the software. Using reference material, students classified campus trees into leaf/species types (broadleaf, conifer, or palm and deciduous or evergreen) and size (small, medium, or large at maturity) and selected a representative species for each type and size among those available.

The menu-driven interface of the CCTC software provides ease of use for single tree entry but is cumbersome for application to some 3,900 trees. Unfortunately the CCTC software is also protected, preventing edits to the embedded source code. To work around this limitation, a macro was programmed in Visual Basic within a separate Excel workbook, which iterated through the hundreds of tree records one at a time, each time calling the CCTC application that was running in a separate instance of Excel. After each call to the CCTC spreadsheet, the output was captured and moved into a location in a separate worksheet where it would not be overwritten by the subsequent iteration through the tree records. The computation for all 3,900 trees took several hours to complete on a desktop PC.

Data Output

Once the carbon sequestration calculations were completed, the tree records were exported to the geodatabase and rejoined to tree location data in a GIS. A flow chart detailing the general steps in the project is shown in Figure 1.

In order to provide online access for users without GIS software, the tree dataset was exported to a .kml format for display in free downloadable applications like Google Earth (2010). The .kml file is posted on the university's Web site for download or can be viewed on the Web site directly within the browser (CSUN 2011). Clicking the mouse on a tree symbol immediately displays a pop-up window showing its attributes, including size, species, carbon content, and CO_2 sequestration rate (Fig. 2).

Findings

The project took approximately 1,000 hours of student labor to tag, measure, map, identify, and carry out the GIS work for the 3,900 trees. The fieldwork accounted for roughly 750 hours of this, or five trees per student-hour. This rate is misleadingly slow because trees were surveyed by teams of students, so the actual rate was about three times this (approximately four minutes per tree). The other 250 hours were spent on GIS tasks, quality control, and species identification. Approximately 200 hours of additional time was spent in project management and carbon calculations. Initial miscommunication between project staff and the ground staff led to a number of tree tags being removed, which necessitated additional inspections and tagging. A small amount of vandalism of tags has also occurred. The following provides a summary of the data.

The CSUN campus is home to over two hundred different species of trees in the southern (academic buildings) portion of campus, an area of some 250 acres. The north campus, which houses the student dormitories, was not included. Some 3,900 trees were tagged, mapped, and measured, and of these, only twelve (all exotic species within the botanic garden) are currently unidentified.

The most common species on campus is the Valencia orange (*Citrus sinensis 'Valencia'*) of which there are almost six hundred examples, a remnant of the Valley's agricultural past. The second and third most common species on the campus are the Canary Island pine (*Pinus canariensis*) and the Mexican fan palm (*Washingtonia robusta*), with approximately two hundred examples of each, followed by coast live oak (*Quercus agrifolia*), Deodar cedar (*Cedrus deodara*), crape myrtle (*Lagerstroemia indica*), and bottle tree (*Brachychiton populneum*), each with over a hundred examples.

The most common native trees on campus are the coast live oak (*Quercus agrifolia*) and California sycamore (*Platanus racemosa*). Other Southern California natives can be found on the campus but in smaller numbers, primarily

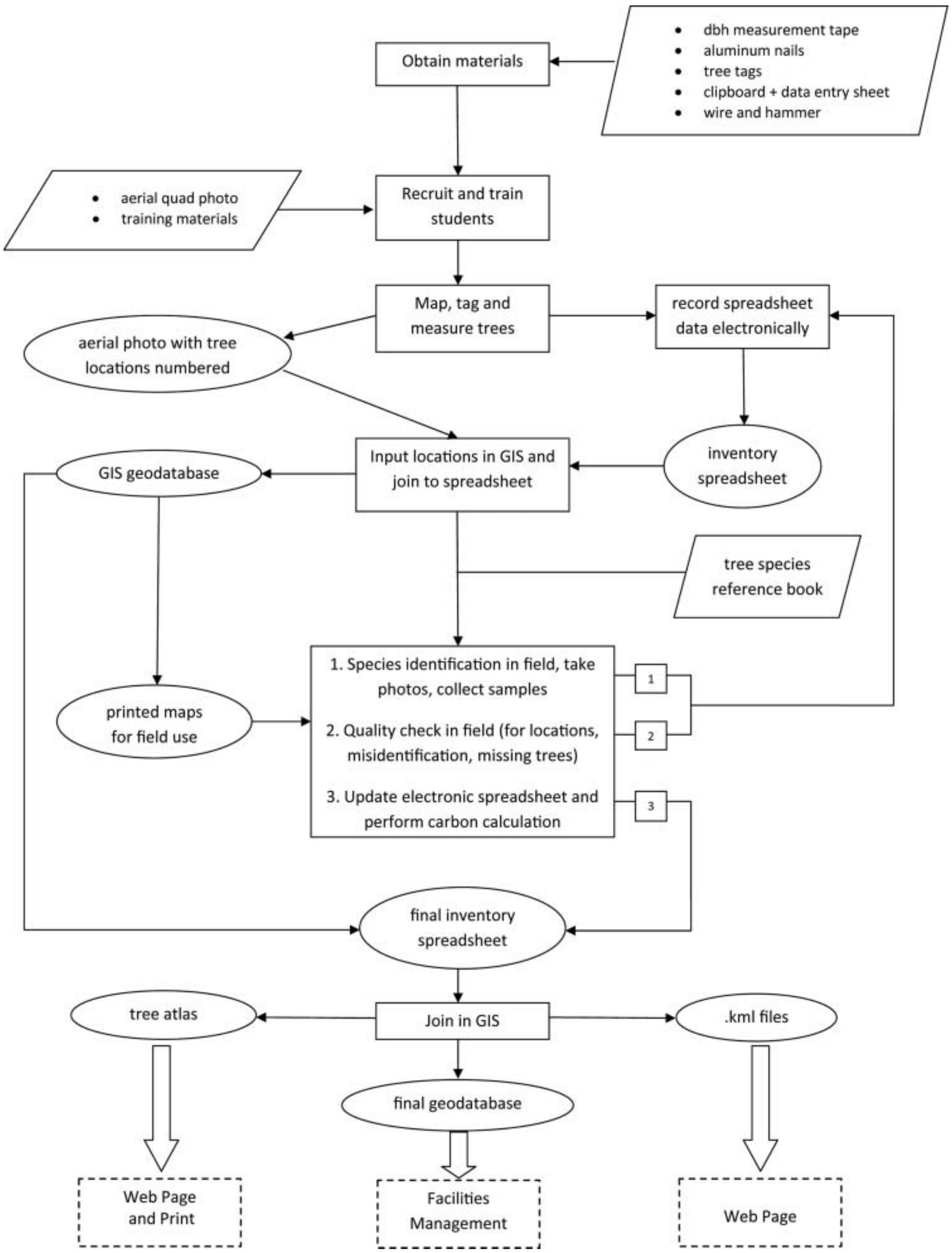

Figure 1. Flow chart showing the tree inventory process using a GIS and spreadsheet-driven CCTC carbon calculator.

other species of oak (*Q. engelmannii, Q. ilex, Q. kelloggi, Q. laurifolia, Q. lobata, Q. suber*), white alder (*Alnus rhombifolia*), hollyleaf cherry (*Prunus ilicifolia*), ash (*Fraxinus velutina, F. uhdei),* and walnut (*Juglans californica*). Native trees were cleared when the area was developed for agriculture and for the planting of the first citrus orchards in the mid-to-late nineteenth century. These orchards were later cleared when the campus was developed in 1958, and ornamental trees typical of those from the Mediterranean and Australia, which do well in the southern Californian climate, were planted.

The largest (by diameter) trees on the CSUN campus are two chinaberries (*Melia azedarach*) with dbhs of 54 and 62 inches, and an aleppo pine (*Pinus halepensis*) with a dbh of 58 inches. Most trees have dbhs between 5 and 15 inches, with a mean overall value of 11.4 inches and a median of 9.2 inches. A histogram of tree dbhs is shown in Figure 3.

From a carbon sequestration standpoint, those trees that sequester the most carbon dioxide from the atmosphere are those that grow (by volume) the most rapidly. Large trees such as eucalyptus (*Eucalyptus)*, cedar (*Cedrus*), plane, or sycamore (*Platanus*) can sequester carbon dioxide at a rate of between 300 and 550 kg/yr each. For the first few years of life, trees less than ten inches in diameter sequester only up to about a tenth of this. Many smaller trees (e.g., jacaranda (*Jacaranda*), yew pine (*Podocarpus macrophyllus*), carrotwood (*Cupaniopsis anacardioides*)) sequester carbon dioxide at a maximum rate of about 25 kg/yr, whereas medium-sized trees (e.g., camphor (*Cinnamomum camphora)*, carob (*Ceratonia siliqua)*, magnolia (*Magnolia*)) sequester at a maximum rate of 70–150 kg/yr. There is significant variation from species to species. Figures 4 and 5 show the computed carbon sequestration amounts in kg CO_2 per year, and a map of the distribution of these over part of campus.

The typical (median) campus tree sequesters about 10 kg CO_2 per year, has an estimated height of 24 feet and an aboveground dry weight of about 100 kg. It stores roughly 65 kg of carbon including its biomass, and upon decay or combustion will release 235 kg of carbon dioxide into the atmosphere. The total carbon dioxide sequestration for all the trees on campus is computed to be 154 tonnes per year, an average of 40 kg per tree.

It is useful to consider this number in the context of carbon dioxide emissions. Annual U.S. per capita emissions (for 2006) were 19.3 tonnes (CAIT (Climate Analysis Indicators Tool) 2010). Thus campus trees offset the emissions of eight typical U.S. residents. In 2006 CSUN reported total CO_2 Scope 1 and 2 emissions of 22,640 tonnes. Thus

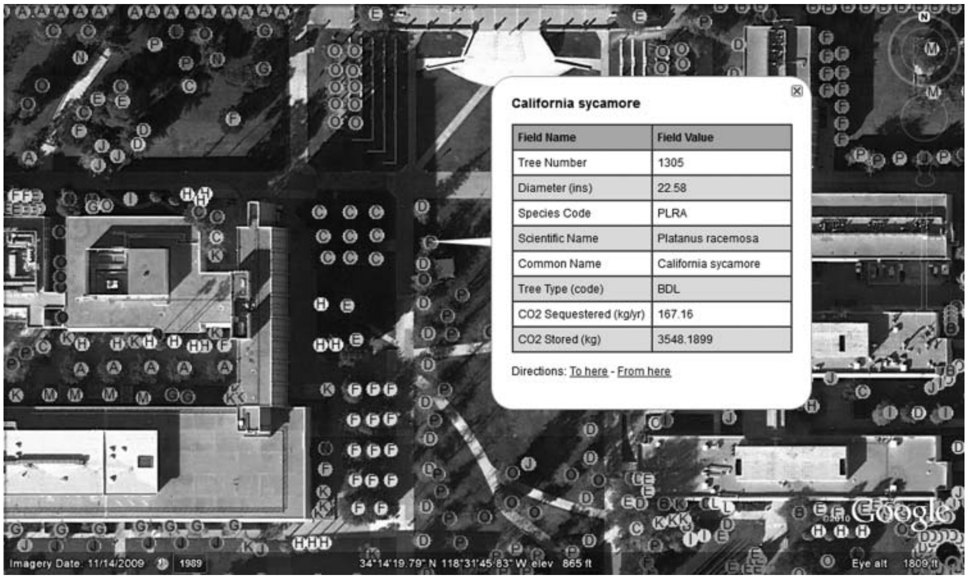

Figure 2. Web browser image of Google Earth plug-in showing pop-up window with selected tree information.

sequestration by trees can offset less than one percent of this. An average CSUN student emits roughly one tonne of carbon dioxide per year in commuting to the campus (CSUN 2010), so campus trees offset the commutes of approximately 150 students—a small fraction of the roughly 35,000 student commuters.

DISCUSSION

Carbon Sequestration

Carbon sequestration amounts presented above are based on (volume) tree growth rates. From these, the mass growth per year can be computed using data on the density and the chemical composition of the woody material (Sedjo 1989; Lamlom and Savidge 2003). The uncertainty in sequestration rates stems primarily from the variability of growth rate between and within species. These are based on three parameters—species, climate zone, and diameter (dbh) (Pillsbury, Reimer, and Thompson 1998). The U.S. Forest Service used six reference cities in California, each representative of a different climate zone. For the CSUN campus the South Coast and Valley climate zone is represented by Santa Monica (McPherson *et al.* 2001). Because Santa Monica is a coastal location it is cooler and wetter than Northridge; however, campus growth rates may exceed the samples because of warmer weather and ample irrigation. As mentioned earlier, the CTCC growth curves for each city are derived from field samples using regression. One significant limitation encountered is that only 10 percent of our species are represented in the sample trees, and thus it was necessary to map each species to the closest CTCC equivalent (by type and growth rate). This leads to uncertainty in the calculated carbon sequestration rates.

Another factor contributing to error is that growth of each species is terminated at a maximum size—determined by the largest sample tree encountered in the study. Many trees

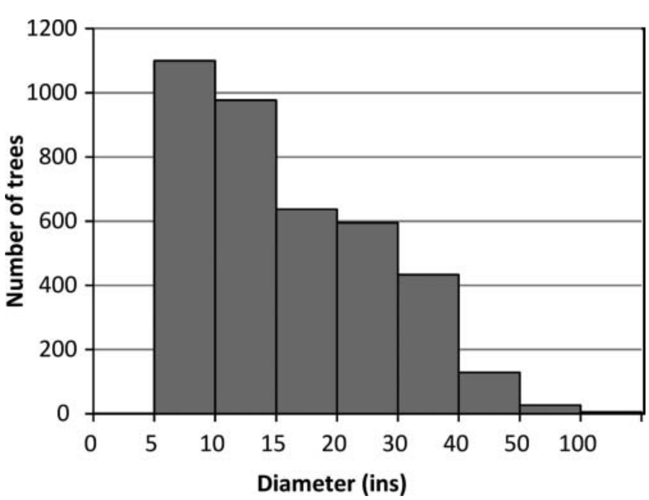

Figure 3. Histogram of tree diameters on campus.

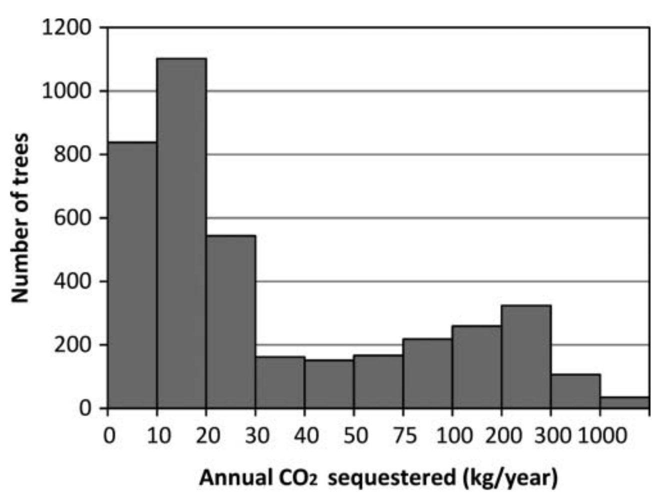

Figure 4. Histogram of computed annual carbon sequestration amounts (kg CO_2/yr).

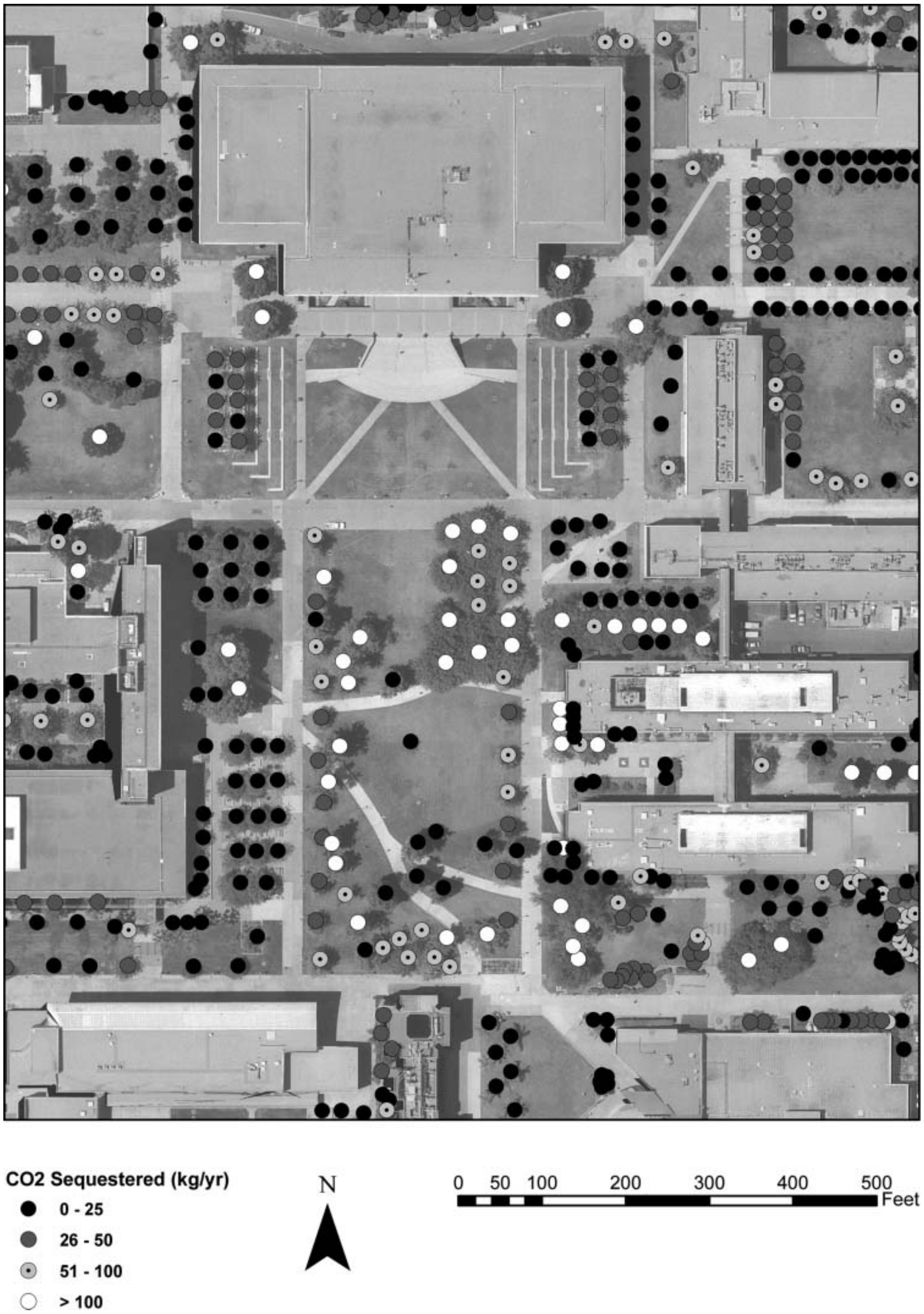

Figure 5. Map of annual CO_2 sequestration rates on campus.

on campus exceed this maximum and are thus assumed to have stopped growing. This is likely to lead to an underestimate of carbon uptake.

In order to set an upper boundary on sequestration rates, the calculations were repeated assuming all trees grow like *Eucalyptus ficifolia* (the fastest growing in the model). This calculation yielded a total carbon dioxide uptake of 320 tonnes per year, a factor of two greater than the estimate given above. Most of this difference results from the projected uptake rate for large trees—particularly those with a diameter greater than two feet—that may have stopped growing if they have reached maturity, or may be consuming carbon dioxide at rates as high as or higher than 300 kg/year if they are still growing. Without the availability of data on mature trees such as these, there will remain considerably uncertainty in the computed value.

It is instructive to compare our results with those of an inventory of 4,051 trees conducted at Eastern Illinois University (EIU 2011) where biomass was estimated in much the same manner, using regression equations based on dbh and species. Carbon content and CO_2 sequestration were derived from these biomass estimates. At EIU, the total dry weight biomass of the trees was calculated to be 2,310 tonnes (570 kg/tree) with a carbon content of 1,591 tonnes and total lifetime CO_2 sequestration of 5,828 tonnes (3.67 times the carbon content). This compares to our dry weight biomass total of 1,725 tonnes (442 kg/tree), carbon content of 862 tonnes, and total CO_2 sequestration of 3,170 tonnes. Biomass estimates (per tree) are thus about 22 percent smaller for our campus. This is not surprising as our campus is much younger and has many new plantings so trees are likely to be less mature. This, coupled with the difference in climate and species on the two campuses, suggests that the results are compatible. However, the carbon (and CO_2) contents are disproportionately different (393 kg/tree at EIU compared to 221 kg/tree at CSUN). Communication with the authors at EIU indicate that they employed the same factor of 50 percent for the carbon content of wood as utilized in the study presented here and based on data for forty-one North American species, which gave a range for these of 46–55 percent (Lamlon and Savidge 2003). Thus the reason for the larger difference in carbon content may be a result of differences in the way that EIU treated wet weight to dry weight conversions or aboveground biomass to total biomass.

Trees indirectly reduce CO_2 emissions through their shading effects (McPherson *et al.* 1999, 2001), and when planted within forty feet or so of buildings can provide a significant reduction in summer cooling costs, particularly for south-facing rooms. The use of well-positioned deciduous trees allows sunlight to reach buildings during winter when additional light and heat may be desirable but shade them during summer (Heisler 1986). The CCTC software can be employed to estimate energy savings from the shading effects of trees, and from this the savings in carbon dioxide emissions computed based on the fuel mix of the local utility provider.

Carbon offset programs may benefit from faster growing trees, but a decision about which trees to plant should be based on a number of criteria including the nature and purpose of the tree (to provide shade, beautify, provide habitat, attract pollinators, etc.), whether or not it is native, the space available, maintenance requirements, water availability, and cost (CUFR 2010). Over the past decade, the paradigm has shifted from a focus on beautification to one that encompasses all the environmental and social benefits of trees (McPherson 2006). Although carbon sequestration should be included in this list as a factor in decision making, there are also problematic issues associated with the planting of fast growing trees for carbon offsets including the possibility of monoculture plantations and the introduction of invasive species (Suzuki 2011).

Learning Experience

Although the tree inventory project (Venkateswaran 2009) was initially directed at quantifying the carbon footprint of the campus, the project addressed the university's sustainability and educational objectives by providing a hands-on learning environment for students. For many students it fostered an interest in sustainability, as they learned about carbon emissions and sequestration, and the project exposed them to the basics of arboriculture and biogeography. As in other field-based GIS projects, students were appreciative of the opportunity to learn new techniques (Carlson 2007). Because the project was not designed as a learning tool in geography, the learning was for the most part unmeasured. If planned in advance, learning outcomes could have been assessed through the implementation of pre- and post-questionnaires and testing materials to measure changes in student knowledge, interest, and understanding of concepts. In particular, it would be instructive to measure whether a student's ability to design and undertake field studies was improved by this experience. One of the most inspiring aspects of the project was that it started off as part of the GHG accounting process and evolved into one that had multiple benefits. The number of students who heard about the project and wanted to get involved resulted in more volunteers than the project could accommodate. Students and alumni read about the project on our Web page and contacted the department to take part. More than half of the students who took part declared that this was the most memorable part of their undergraduate experience.

Although the project described here was carried out by a team of student interns, depending on campus area, tree density, etc. it could be feasible for a similar one to be carried out by an undergraduate geography class during the course of a semester. It can be logistically difficult to incorporate field-based exercises into classes because of the transportation to sites that it generally requires. However, field exercises are essential in the geosciences, and this project provides another effective field experience on campus (Hudak 2003). One could structure a class around the project and incorporate the topics of climate change, carbon sequestration, habitat, biodiversity, water, climate, and arboriculture within the class while giving students experience in working on a group project, using GIS, and gaining field measurement experience. It could be carried out by a class of 12–18 students over the course of a semester, or could provide a good summer school project.

Other Tree Inventories and Analysis Tools

CSUN is not unique in its implementation of a tree inventory, and over the past few years other universities have conducted similar projects. Examples are Utah State University (USU 2011), Indiana University–Purdue University–Indianapolis (IUPUI 2011), the University of Missouri, St Louis (UMSL 2011), the University of Washington (UW 2011), the University of Texas at Austin (UTA 2011). In addition many municipalities have produced tree inventories including the city of Ottawa (Ottawa 2011a), Chico (Gregory and Fairbanks 2010), Boston (Boston 2011) and Washington, D.C. (Washington 2011). Most inventories were conducted for tree management and maintenance purposes, and some have been useful in identifying highly destructive pests such as wood-boring beetles (Ottawa 2011b). Inventories are also useful for analyses of species and size diversity, tracking tree health, and for public information purposes. In some cases researchers have analyzed the benefits of trees using iTree (2011)—a software tool from the U.S. Forest Service, which provides the same kinds of analyses available through the CCTC tool, including carbon storage and sequestration and energy savings. iTree can also be used to compute water storage benefits when tree canopy data is available. In this study, the CCTC tool was chosen over iTree because it allows for computation on a tree-by-tree basis within the tree inventory database whereas iTree produces an overall summary of benefits. Incorporating data for each tree individually in the GIS geodatabase allows for easier implementation of what-if analyses and database update.

CITYgreen (2011) is another software tool for the analysis of the benefits of trees and is available (for purchase) as an extension to ArcGIS. It requires the user to digitize tree canopies from an aerial image, and provides the same output data as iTree including stormwater runoff analysis. It also incorporates the same carbon storage and sequestration model developed by the U.S. Forest Service and included in iTree and CCTC. The choice of CCTC over CITYgreen was made for the same reasons as the choice over iTree, for greater control of data on a tree by tree basis.

Many of the tree inventories listed above either did not report carbon storage/sequestration data or report it only as a summary for the entire campus. By including the computation in the tree record data (as also done by EIU), the data have added flexibility, allowing students to pursue further what-if research questions on different tree mixes (such as investigating the carbon sequestration associated with purely native trees), and allow for automatic update of the carbon calculations when trees are planted or removed.

Facilities Management

The tree inventory, including the GIS geodatabase, atlas, and maps, was transferred to the facilities management unit of the university for use and maintenance. It has been employed in facilities planning and construction to reduce the need for exploratory site visits, and will be used by grounds staff to track tree maintenance. Although the facilities staff have access to GIS software, they have not previously used it. Students have customized the GIS interface for their use, including adding custom functions for staff to easily perform common functions, like *Add a tree*, *Remove a tree*, *Schedule maintenance*. Fields were also added to the tree database to allow staff to store additional information, like planting date, tree removal date, reason for tree removal, and a maintenance flag to indicate a need for and the type of maintenance required. Students were hired to provide GIS training to the staff and, in a separate project, to develop a GIS of other resources on campus (including fire hydrants, piping, light poles, bicycle racks, and academic spaces). The facilities staff will be responsible for all future updates to the database, which will be shared with other units on campus through a server. Thus the project served to create a bridge between facilities management and the academic side of the institution that will lead to partnership opportunities in the future.

Summary

The student learning, community, and university benefits of the study are summarized in Table 1. These benefits included student training in field measurements, an online resource for facilities planning, and a tree guide for the community, among others. This study began by looking at campus trees as a carbon sink. Although the trees on campus are beneficial in many other ways, as a sink for carbon dioxide they only offset a relatively small proportion of total emissions, amounting to approximately 154 tonnes per year, or less than one percent of campus emissions. This total is roughly equivalent to eight times the U.S. per capita emissions rate and thus offsets the GHG emissions of eight typical U.S. residents.

Table 1. Project benefits for students, the university, and the community.

Student/Learning Benefits	University and Community Benefits
Student training in making and recording field measurements	A tree guide for the community to use in identifying tree species on campus, and in learning about campus trees.
Student understanding of the use of GIS software to record locations and "join" to spreadsheet data	An online resource that can be used to identify trees by species, type, size, carbon sequestration, or to find memorial trees.
Student understanding of custom programming inside a spreadsheet application	An online resource for facilities planning to use in planning for new construction.
Increased student understanding of tree types and tree identification methods	A (geo)database of trees to be used and maintained by physical plant management in scheduling tree maintenance, conducting arborist assessments, recording planting and trimming dates, and reporting plantings and tree removals.
Student understanding of the way in which trees sequester carbon dioxide and the process by which this can be estimated	A database of carbon storage and sequestration data that can be included in the annual campus GHG inventory. (Accurate information will require annual measurement of the tree diameters. Alternatively, an estimate can be made by employing an average growth rate to all trees using the CUFR model.)
Student experience in working on a team	The establishment of a good partnership between the facilities unit and the academic unit of the campus.

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