University of California
Davis Campus
Tree Resource Analysis

by

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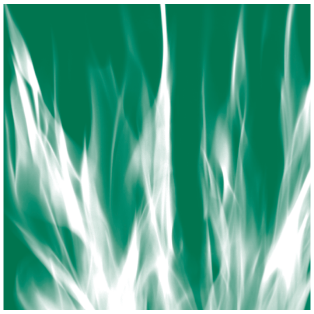
Center for Urban Forest Research
USDA Forest Service, Pacific Southwest Research Station

Technical Report to:

Mr. Sal Genito, Grounds Manager
Facilities: Operations & Maintenance
University of California, Davis

-- December 2004 --



Center for
Urban Forest Research

Areas of Research:


Investment Value


Energy Conservation


Air Quality


Water Quality


Firewise Landscapes

Mission Statement

We conduct research that demonstrates new ways in which trees add value to your community, converting results into financial terms to assist you in stimulating more investment in trees.

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Acknowledgments

We are indebted to the many people who provided assistance and support with various aspects of this project. David Phillips (UCD) and Duane Goosen (UCD) provided valuable data to aid benefit modeling and valuation. Precious help from Chad Delany (CUFR) and Shauna Cozad (UCD) was performed with diligent enthusiasm. Finally, without the initiation and support of this project by Sal Genito (UCD), this work would not have been possible. Thank you.

This report relied on data obtained from other organizations and has not been subjected to the peer-review process.

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Table of Contents

Executive Summary

University of California
Davis Campus Tree Resource Analysis

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As a nationally prominent university and environmental research center, renown for its quality of life, UC Davis maintains trees as an integral component to the campus infrastructure. The tree resource is a lasting component of the campus with a long history that fits well with the long-range perspective of campus planning efforts. As a dynamic resource consisting of a diversity of outdoor spaces, campus trees provide opportunity for over 80 course-related curricula, serving the university's field teaching and research needs. Trees provide a sense of permanence and tradition, invoking social interaction and a sense of place. And the shelter trees provide create space for exposure and respite for individuals and groups. Research indicates healthy trees can mitigate impacts associated with campus built environs such as increased stormwater runoff and energy consumption for heating and cooling buildings. Simply, trees improve campus-life, making UC Davis a more enjoyable place to study, live, work and recreate, while mitigating the campus's environmental impact.

UC Davis believes that the investment in stewardship of the campus forest resource produces benefits that outweigh the costs. However, in an era of dwindling public funds, budget cuts, and increased demand to accommodate more students, there is need to scrutinize expenditures that are deemed "non-essential" such as preserving, planting, maintaining campus trees. Hence, the primary objective of this study is to provide an understanding of the current extent of campus canopy cover and the functionality it provides to the campus community and beyond. Under this premise, this study had three goals:

1. Allow decision-makers to assess and justify the degree of funding and type of management program appropriate for the campus tree resource.
2. Provide critical baseline information for the evaluation, preservation, and future research needed to protect the resource in a cost-efficient manner.
3. Highlight the relevance and relationship of the campus tree resource to campus quality of life issues such as safety, health, education, and development.

To fulfill the three study goals, this analysis utilized an updated tree inventory and remote sensing data combined with tree benefit modeling to produce information on resource structure, function, value and future management needs.

Resource Structure

- Total campus canopy cover was estimated at 189.1 acres, accounting for 21% of the core campus area. Inventoried trees accounted for 62% (116.3 ac) of the cover, while uninventoried woody vegetation (trees and shrubs) accounted for 38% (72.8 ac).
- Tree stocking is high. Trees fill 69% of all planting sites. Planting the 4,092 potential tree sites on the UC Davis core campus could increase tree cover by an additional 9% (76.8 ac), to a total of 30% campus-wide. However, this magnitude of increase may not be feasible given conflicts with underground utilities and other infrastructure.

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- No inventoried species was beyond the commonly held standard that no single species should exceed 10% of the population (Clark et al. 1997). Numbering 717, or 8% of the population, coast redwood was the most widely planted; Chinese hackberry was a close second with 679 trees accounting for 7.5% of all trees together. Campus-wide, diversity was high.

- While new planting is occurring, the present functional engine of the campus forest—existing large, mature trees—may not be regenerated in the future due to the dearth of proven, large-stature trees being planted.

- Management concerns include an estimated 14% of trees that were classified as unhealthy due to water stress, disease, or structural damage.

Resource Function And Value

- During the 2003 fiscal year, campus trees were estimated to produce benefits that totaled $920,000, with the 8,999 inventoried trees accounting for 62% of the total. The net benefit per tree was $62.85. Assuming a campus population of 49,019, trees were producing benefits valued at $18.76 for every student, faculty, and staff person.

- Overall, annual benefits were related to tree size, where large-stature trees typically produced greater benefits. For example, average small (crape myrtle), medium (Chinese pistache), and large (cork oak) trees produced annual benefits totaling $6, $53, and $118 per tree, respectively.

- Electricity and natural gas saved annually from both shading and climate effects totaled 992 MWh and 2,964 Mbtu, respectively, equivalent to $85,742 in retail savings for inventoried trees. This amounted to an average savings of $7.23 per managed tree. The combined total for all campus trees was estimated at $106,000, annually, and amounted to an energy savings of $600 per acre of canopy cover.

- CO_2 reductions varied dramatically by species: the average cork oak on campus reduced atmospheric CO_2 by 349 lbs per year, while the typical flowering plum reduced CO_2 by approximately 4 lbs per year for a benefit of only $0.03. The average per tree reduction was 128 lbs valued at $0.96, annually. Inventoried trees alone reduced 578 tons of CO_2, while the total for all campus trees was 940 tons valued over $14,000 for the year.

- The net air quality benefit for all campus trees was valued at $30,163. Savings per tree averaged $2.06 on an annual basis. BVOC emission rates were offset by ozone uptake.

- The ability of UCD's trees to intercept rain was substantial, estimated at nearly 5 million gallons annually for all trees; inventoried trees accounted for 62% of this amount. The total value of this benefit to the campus was $63,425 when all trees were considered. Average per tree values for inventoried trees ranged between less than $1 to over $12, averaging $4.33, based an average interception of 341gals.

- The estimated total annual benefit associated with shelter and aesthetic benefits was approximately $700,000, annually, or $48/tree on average.

Future Management Needs

- The shift towards small stature species has the potential to reduce the future level of benefits provided by campus trees, as large, functional tree species provide the bulk of all benefits.

- Examining species presently providing high levels of benefits and evaluating Relative Performance Index values and relative age suggests that several species are well-adapted, long-lived, and have the potential to provide reasonable levels of benefits: cork oak, honey locust, deodar cedar, coast live oak, zelkova, stone pine, London plane, canary island pine, and Chinese pistache. Increasing planting numbers of species with these characteristics will provide the foundation for increased benefits and reduced costs into the future.

- Increasing the tree canopy cover requires a multifaceted approach at UC Davis. Plantable spaces must be filled and use of large stature trees must be encouraged wherever feasible. There are nearly 4,092 available tree-planting spaces on the core campus, approximately 54%, 43%, and 3%

of these sites could be filled with large-, medium-, and small-stature trees, respectively. Planting all identified potential sites could increase annual benefits by $271,476, a substantial sum.

- The Campus should begin to systematically evaluate the performance of new introductions. New introductions should comprise 5-10% of the total number of trees planted each year. Testing will identify the tree species that are best adapted to local conditions. After 5-10 year trials, the best performers can be planted in larger numbers to increase diversity and perpetuate the campus forest.

- Future research could provide a scientific basis for developing realistic canopy cover targets, reducing mortality rates, designing plantings that maximize net benefits, and monitoring change. The data contained within this report establish a baseline for this work.

UC Davis campus trees are a dynamic resource. Managers of this resource and the UC Davis community alike can delight in knowing that trees do improve the quality of campus life, but they are also faced with a fragile resource that needs constant care to maximize and sustain these benefits through the foreseeable future. On a campus where growth pressures are high, this is no easy task. The challenge ahead is to better integrate the green infrastructure with the gray infrastructure. This means providing adequate space for trees up-front, and designing plantings to maximize net benefits over the long-term, thereby perpetuating a resource that is both functional and sustainable.

Chapter One—Introduction

University of California
Davis Campus Tree Resource Analysis

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As a nationally prominent university and environmental research center, renown for its quality of life, UC Davis maintains trees as an integral component to the campus infrastructure. The tree resource is a lasting component of the campus with a long history that fits well with the long-range perspective of campus planning efforts. As a dynamic resource consisting of a diversity of outdoor spaces, campus trees provide opportunity for over 80 course-related curricula, serving the university's field teaching and research needs. Trees provide a sense of permanence and tradition, invoking social interaction and a sense of place. And the shelter trees provide create space for exposure and respite for individuals and groups. Research indicates healthy trees can mitigate impacts associated with campus built environs such as increased stormwater runoff and energy consumption for heating and cooling buildings. Simply, trees improve campus-life, making UC Davis a more enjoyable place to study, live, work and recreate, while mitigating the campus's environmental impact.

With total canopy cover estimated at approximately 189 acres, UC Davis believes that the investment in stewardship of the campus forest resource produces benefits that outweigh the costs. However, in an era of dwindling public funds, budget cuts, and increased demand to accommodate more students, there is need to scrutinize expenditures that are deemed "non-essential" such as preserving, planting, maintaining campus trees. Previous work—University of California, Davis Campus Tree Inventory (Davey Resource Group 1998)—has addressed simple frequency reports of campus trees, but questions remain regarding the need for understanding the current extent of campus canopy cover and the functionality it provides. Hence, this analysis utilizes an updated tree inventory (ArborPro 2003) and remote sensing data combined with tree benefit modeling to:

1. Allow decision-makers to assess and justify the degree of funding and type of management program appropriate for the campus tree resource.
2. Provide critical baseline information for the evaluation, preservation, and future research needed to protect the resource in a cost-efficient manner.
3. Highlight the relevance and relationship of the campus tree resource to campus quality of life issues such as environmental health and development.

This report consists of seven chapters and four appendices:

Chapter One—Introduction: Describes the purpose of this study.

Chapter Two—Methodology and Procedures: Describes benefits, procedures and methodology in calculating structure, function, and value of the campus tree resource.

Chapter Three—UCD's Campus Tree Resource: Describes the current structure of the campus tree resource.

Chapter Four—Benefits of UC Davis Campus Trees: Quantifies estimated value of tangible benefits and calculates net benefits for each population segment.

Chapter Five—Future Management: Evaluates current resource issues, posits management challenges, and describes techniques for future research and monitoring.

Chapter Six—Conclusion: Final word on the use of this analysis.

Chapter Seven—Reference: Lists publications cited in the study.

Appendix A—Electronic Inventory and GIS Guide: A table describing location and description of all supporting GIS layers.

Chapter Two—Methodology and Procedures

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This analysis combined remote sensing data along with a campus-wide inventory and benefit modeling to produce four types of information:

1. Resource structure (canopy extent, species composition, diversity, age distribution, health, etc.)
2. Resource function (magnitude of environmental and property value benefits)
3. Resource value (dollar value of benefits realized)
4. Future management needs (sustainability, planting, research and monitoring)

This section describes the inputs and calculations used to derive the afore mentioned outputs: growth modeling, identifying and calculating benefits, estimating magnitude of benefits provided, assessing resource unit values, calculating net benefits, and assessing structure.

Growth Modeling

Growth modeling for this study is based upon tree data collected in the city of Modesto, CA, having similar climate and growing conditions to Davis, CA. Drawn from the Modesto, CA Operations and Maintenance Department's municipal tree database, a stratified random sample of street trees was inventoried to establish relations between tree age, size, leaf area and biomass as a basis for estimating the magnitude of annual benefits derived from municipal tree resources in the San Joaquin Valley region. Estimated to account for 92% of the total municipal street and park tree population, the sample was composed of the 25 most abundant species, and was used to infer growth of all public trees.

To obtain information spanning the life cycle of each species, the sample was stratified into two statistical blocks, a young tree block (planted 1970s-90s) and an old tree block (planted before 1970). Approximately 30 randomly selected trees of each species were selected to survey, 15 per block. Tree measurements included DBH (to nearest 0.1 cm by tape), tree and bole height (to nearest 0.5m by altimeter), crown radius in two directions (parallel and perpendicular to nearest street to nearest 0.5m by tape), severity of pruning, and site index. Replacement trees were sampled when trees from the original sample population could not be located. Tree age was determined from historical planting records provided by the city. When it was suspected that planting dates were inaccurate, increment cores and/or residents helped determine actual planting dates. Fieldwork was conducted May to July 1998.

Crown volume and leaf area were estimated from computer processing of tree crown images obtained using a digital camera. The method has shown greater accuracy than other techniques (±20 percent of actual leaf area) in estimating crown volume and leaf area of open-grown trees (Peper and McPherson 1998).

Non-linear regression was used to fit predictive models—DBH as a function of age—for each of the 25 sampled species. Predictions of leaf surface area (LSA), crown diameter, and height metrics were modeled as a function of DBH using best-fit models (Peper et al. 2001).

Identifying & Calculating Benefits

Annual benefits for UCD campus trees were estimated for the year 2003. Growth rate modeling information was used to perform computer-simulated growth of the existing tree population for one year and account for the associated annual benefits. This "snapshot" analysis assumed that no trees were added to, or removed from, the existing population during the year. However, calculations of CO_2 released due to decomposition of wood from removed trees did consider average annual mortality. The approach directly connects benefits with tree size variables such DBH and LSA. Many functional benefits of trees are related to leaf-atmosphere processes (e.g., interception, transpiration, photosynthesis), and, therefore, benefits increase as tree canopy cover and leaf surface area increase.

Prices were assigned to each benefit (e.g., heating/cooling energy savings, air pollution absorption, stormwater runoff reduction) through direct estimation and implied valuation as environmental externalities. Implied valuation is used to price society's willingness to pay for the environmental benefits trees provide. Estimates of benefits are initial approximations—as some benefits are difficult to quantify (e.g., impacts on psychological health, crime, and violence). In addition, limited knowledge about the physical processes at work and their interactions makes estimates imprecise (e.g., fate of air pollutants trapped by trees and then washed to the ground by rainfall). Therefore, this method of quantification was not intended to account for each penny. Rather, this approach was meant to be a general accounting of the benefits produced by urban trees; an accounting with an accepted degree of uncertainty that can, nonetheless, provide a platform on which decisions can be made (Maco 2003).

Energy Savings

Buildings and paving, along with low canopy and soil cover, increase the ambient temperatures within a community. Research shows that temperatures in cities are steadily increasing by approximately 0.5°F (0.3°C) per decade. Winter benefits of this warming do not compensate for the detrimental effects of magnifying summertime temperatures, especially in hot, arid climates like the Central Valley of California. Because electric demand of cities increases about 1-2% per 1°F (3-4% per °C) increase in temperature, approximately 3-8% of current electric demand for cooling is used to compensate for this urban heat island effect (Akbari et al. 1992).

Warmer temperatures in cities, compared to surrounding rural areas, have other implications. Increases in CO_2 emissions from fossil fuel power plants, municipal water demand, unhealthy ozone levels, and human discomfort and disease are all symptoms associated with urban heat islands. On the UC Davis Campus—effectively a city of nearly 50,000 persons—there are many opportunities to ameliorate the problems associated with hardscape through strategic tree planting and stewardship of existing trees, allowing for campus landscapes that reduce stormwater runoff, conserve energy and water, sequester CO_2, attract wildlife, and provide aesthetic, social, and economic benefits through more sustainable land use developments.

Campus trees modify climate and conserve building-energy use in three principal ways:

1. Shading—reduces the amount of radiant energy absorbed and stored by built surfaces.

2. Transpiration—converts moisture to water vapor and thus cools by using solar energy that would otherwise result in heating of the air.

3. Wind speed reduction—reduces the infiltration of outside air into interior spaces and conductive heat loss where thermal conductivity is relatively high (e.g., glass windows) (Simpson 1998).

Trees and other greenspace near individual building sites may lower air temperatures 5°F (3°C) compared to outside the greenspace (Chandler 1965). At the larger scale of urban climate (6 miles or 10 km square), temperature differences of more than 9°F (5°C) have been observed between city centers and more vegetated periphery areas (Akbari et al. 1992). The relative importance of these effects depends on the size and configuration of trees and other landscape elements (McPherson 1993). Tree spacing, crown spread, and vertical distribution of leaf area influence the transport of cool air and pollutants.

For individual buildings, campus trees can increase energy efficiency in the summer and increase or decrease energy efficiency in winter, depending on placement. Solar angles are important when the summer sun is low in the east and west for several hours each day. Tree shade to protect east—and especially west—walls help keep buildings cool. In the winter, solar access on the southern side of buildings can warm interior spaces.

Trees reduce air infiltration and conductive heat loss from buildings. Rates at which outside air infiltrates into a building can increase substantially with wind speed. In cold, windy weather, the entire volume of air in a poorly sealed, old building may change two to three times per hour. Even in newer or tightly sealed construction, the entire volume of air may change every two to three hours. Trees can reduce wind speed and resulting air infiltration by up to 50%, translating into potential annual heating savings of 25% (Heisler 1986). Reductions in wind speed reduce heat transfer through conductive materials as well. Cool winter winds, blowing against single-pane windows, can contribute significantly to the heating load of buildings by increasing the temperature gradient between inside and outside temperatures. Trees ameliorate this process.

Electricity and Natural Gas Methodology

Calculating annual building energy use per residential unit (Unit Energy Consumption [UEC]) is based on computer simulations that incorporate building, climate and shading effects, following methods outlined by McPherson and Simpson (1999). Changes in UECs from trees (ΔUECs) were calculated on a per tree basis by comparing results before and after adding trees. Building characteristics (e.g., cooling and heating equipment saturations, floor area, number of stories, insulation, window area, etc.) are differentiated by a building's vintage, or age of construction: pre-1950, 1950-1980 and post-1980. Typical meteorological year (TMY2) weather data for Sacramento International Airport were used (Marion and Urban 1995). Shading effects for each tree species were simulated at three tree-building distances, eight orientations and nine tree sizes.

Shading coefficients for tree crowns in-leaf were based on a photographic method is used that estimates visual density. These techniques have been shown to give good estimates of light attenuation for trees in-leaf (Wilkinson 1991). Visual density was calculated as the ratio of crown area computed with and without included gaps. Crown areas were obtained from digital images isolated from background features using the method of Peper and McPherson (2003). Values for trees not measured, and for all trees not in leaf, were based on published values where available (McPherson 1984, Hammond et al. 1980). Values for remaining species were assigned based on taxonomic considerations (trees of the same genus assigned the same value) or observed similarity in the field to known species. Foliation periods for deciduous trees were obtained from the literature (McPherson 1984, Hammond et al. 1980) and consultation with the UCD arborist (Goosen 2004).

Tree distribution by location (e.g. frequency of occurrence at each location) were determined from distance between trees and buildings (setbacks), and tree orientation with respect to buildings specific to UC Davis based on a 1% sample of trees from aerial photos done in the summer of 2004. These distributions were used to calculate average energy savings per tree as a function of distance and direction. Setbacks were assigned to four distance classes: 0-20 ft, 20-40 ft, 40-60 ft and >60 ft. It was assumed that street trees within 60 ft of buildings provided direct shade on walls and windows. Savings per tree at each location were multiplied by tree distribution to determine location-weighted savings per tree for each species and DBH class that was independent of location. Location-weighted savings per tree were multiplied by number of trees in each species/DBH class and then summed to find total savings for the campus. Land use (single family residential, multifamily residential, commercial/ industrial, other) was based on UC Davis building inventory (UC Davis 2004a). The same tree distribution was used for all land uses.

Three prototype buildings were used in the simulations to represent pre-1950, 1950 and post-1980 construction practices for the West Pacific region (Ritschard et al. 1992). Building footprints were modeled as square, which was found to be reflective of average impacts for large building populations (Simpson 2002). Buildings were simulated with 1.5-ft overhangs. Blinds had a visual density of 37%, and were assumed closed when the air conditioner is operating. Summer and winter thermostat settings were 78° F and 68° F during the day, respectively, and 60° F at night. Unit energy consumptions were adjusted to account for saturation of central air conditioners, room air conditioners, and evaporative coolers (Table 1).

Single-Family Residential Adjustments

Unit energy consumptions for other land uses were estimated by adjusting results for simulated single-family residential buildings for type and saturation of heating and cooling equipment, and for various factors that modified the effects of shade and climate modifications on heating and cooling loads, using the expression:

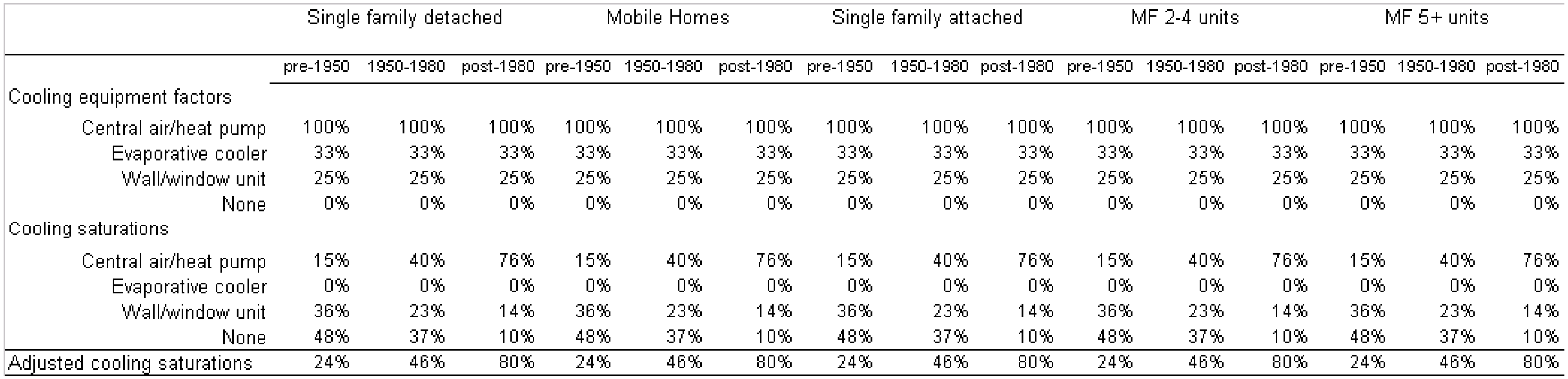
$$\Delta UEC_x = \Delta UEC^{sh}_{SFD} \times F_{sh} + \Delta UEC^{cl}_{SFD} \times F_{cl} \qquad \text{(Equation 1)}$$

where $F_{sh} = F_{equipment} \times APSF \times F_{adjacent\ shade} \times F_{multiple\ tree}$

$F_{cl} = F_{equipment} \times PCF$

and $Fequipment = Sat_{CAC} + Sat_{window} \times 0.25 + Sat_{evap} \times$ (0.33 for cooling and 1.0 for heating).

Table 1. Saturation adjustments for cooling.



	Single family detached			Mobile Homes			Single family attached			MF 2-4 units			MF 5+ units		
	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980
Cooling equipment factors															
Central air/heat pump	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Evaporative cooler	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
Wall/window unit	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
None	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Cooling saturations															
Central air/heat pump	15%	40%	76%	15%	40%	76%	15%	40%	76%	15%	40%	76%	15%	40%	76%
Evaporative cooler	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Wall/window unit	36%	23%	14%	36%	23%	14%	36%	23%	14%	36%	23%	14%	36%	23%	14%
None	48%	37%	10%	48%	37%	10%	48%	37%	10%	48%	37%	10%	48%	37%	10%
Adjusted cooling saturations	24%	46%	80%	24%	46%	80%	24%	46%	80%	24%	46%	80%	24%	46%	80%

Total change in energy use for a particular land use was found by multiplying change in UEC per tree by the number of trees (N):

$$\text{Total change} = N \times \Delta\ UEC_x \qquad \text{(Equation 2)}$$

Subscript *x* refers to residential structures with 1, 2-4 or 5 or more units, *SFD* to single family detached structures which were simulated, *sh* to shade, and *c*l to climate effects.

Estimated shade savings for all residential structures were adjusted by factors that accounted for shading of neighboring buildings, and reductions in shading from overlapping trees. Homes adjacent to those with shade trees may benefit from their shade. For example, 23% of the trees planted for the Sacramento Shade program shaded neighboring homes, resulting in an estimated energy savings equal to 15% of that found for program participants; this value was used here ($F_{\text{adjacent shade}} = 1.15$). In addition, shade from multiple trees may overlap, resulting in less building shade from an added tree than would result if there were no existing trees. Simpson (2002) estimated that the fractional reduction in average cooling and heating energy use per tree were approximately 6% and 5% percent per tree, respectively, for each tree added after the first. Simpson (1998) also found an average of 2.5 to 3.4 existing trees per residence in Sacramento. A multiple tree reduction factor of 85% was used here, equivalent to approximately three existing trees per residence.

In addition to localized shade effects, which were assumed to accrue only to campus trees within 18-60 ft (5-18 m) of buildings; lowered air temperatures and wind speeds from total tree cover (referred to as climate effects) produce a net decrease in demand for summer cooling and winter heating. Reduced wind speeds by themselves may increase or decrease cooling demand, depending on the circumstances. To estimate climate effects on energy use, air temperature and wind speed reductions as a function of total canopy cover were estimated from published values following McPherson and Simpson (1999), then used as input for building energy use simulations described earlier. Peak summer air temperatures were assumed reduced by 0.4 °F for each percentage increase in canopy cover. Wind speed reductions were based on the canopy cover resulting from the addition of the particular tree being simulated to that of the building plus other trees. A lot size of 10,000 ft^2 (929 m^2) was assumed.

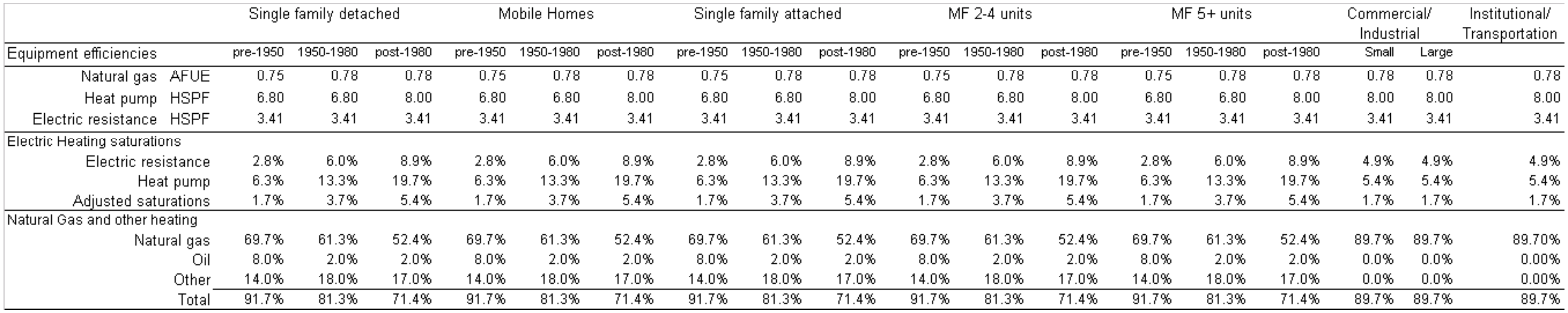
Dollar value of electrical and natural gas energy savings were based on electricity and natural gas prices of \$0.0475 per kWh and \$0.606 per therm, respectively, as paid by the university (Stagner 2004). Cooling and heating effects were reduced based on the type and saturation of air conditioning (Table 1) or heating (Table 2) equipment by vintage. Equipment factors of 33% and 25% were assigned to homes with evaporative coolers and room air conditioners, respectively. These factors were combined with equipment saturations to account for reduced energy use and savings compared to those simulated for homes with central air conditioning ($F_{\text{equipment}}$). Building vintage distribution was combined with adjusted saturations to compute combined vintage/saturation factors for air conditioning (Table 1). Heating loads were converted to fuel use based on efficiencies in Table 2. The "other" and "fuel oil" heating equipment types were assumed natural gas for the purpose of this analysis. Building vintage distributions were combined with adjusted saturations to compute combined vintage/saturation factors for natural gas and electric heating (Table 3).

Multi-Family Residential Analysis

Unit energy consumptions from shade for multi-family residences (MFRs) were calculated from single-family residential UECs adjusted by APSFs to account for reduced shade resulting from common walls and multi-story construction. Average potential shade factors were estimated from potential shade factors (PSFs), defined as ratios of exposed wall or roof (ceiling) surface area to total surface area, where total surface area includes common walls and ceilings between attached units in addition to exposed surfaces (Simpson 1998). Potential shade factor=1 indicates that all exterior walls and roof are exposed and could be shaded by a tree, while PSF=0 indicates that no shading is possible (i.e., the common wall between duplex units). Potential shade factors were estimated separately for walls and roofs for both single and multi-story structures. Average potential shade factors were 0.74 for land use MFR 2-4 units and 0.41 for MFR 5+ units.

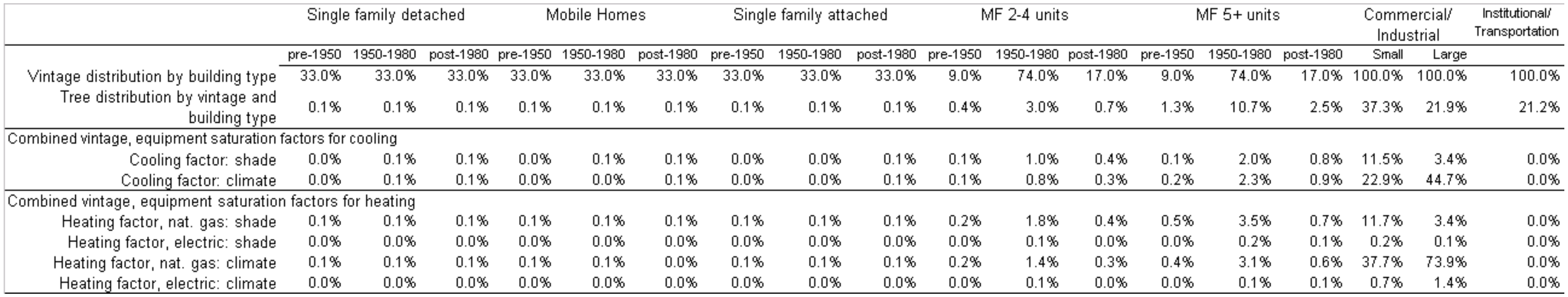
Unit energy consumptions were also adjusted for climate effects to account for the reduced sensitivity of multi-family buildings with common walls to outdoor temperature changes with respect to single-family detached residences. Since estimates for these PCFs were unavailable for multi-family structures, a multi-family PCF value of 0.80 was selected (less than single family detached PCF of 1.0 and greater than small commercial PCF of 0.40; see next section).

Table 2. Saturation adjustments for heating.



		Single family detached			Mobile Homes			Single family attached			MF 2-4 units			MF 5+ units			Commercial/ Industrial		Institutional/ Transportation
Equipment efficiencies		pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	Small	Large	
Natural gas	AFUE	0.75	0.78	0.78	0.75	0.78	0.78	0.75	0.78	0.78	0.75	0.78	0.78	0.75	0.78	0.78	0.78	0.78	0.78
Heat pump	HSPF	6.80	6.80	8.00	6.80	6.80	8.00	6.80	6.80	8.00	6.80	6.80	8.00	6.80	6.80	8.00	8.00	8.00	8.00
Electric resistance	HSPF	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
Electric Heating saturations																			
Electric resistance		2.8%	6.0%	8.9%	2.8%	6.0%	8.9%	2.8%	6.0%	8.9%	2.8%	6.0%	8.9%	2.8%	6.0%	8.9%	4.9%	4.9%	4.9%
Heat pump		6.3%	13.3%	19.7%	6.3%	13.3%	19.7%	6.3%	13.3%	19.7%	6.3%	13.3%	19.7%	6.3%	13.3%	19.7%	5.4%	5.4%	5.4%
Adjusted saturations		1.7%	3.7%	5.4%	1.7%	3.7%	5.4%	1.7%	3.7%	5.4%	1.7%	3.7%	5.4%	1.7%	3.7%	5.4%	1.7%	1.7%	1.7%
Natural Gas and other heating																			
Natural gas		69.7%	61.3%	52.4%	69.7%	61.3%	52.4%	69.7%	61.3%	52.4%	69.7%	61.3%	52.4%	69.7%	61.3%	52.4%	89.7%	89.7%	89.70%
Oil		8.0%	2.0%	2.0%	8.0%	2.0%	2.0%	8.0%	2.0%	2.0%	8.0%	2.0%	2.0%	8.0%	2.0%	2.0%	0.0%	0.0%	0.00%
Other		14.0%	18.0%	17.0%	14.0%	18.0%	17.0%	14.0%	18.0%	17.0%	14.0%	18.0%	17.0%	14.0%	18.0%	17.0%	0.0%	0.0%	0.00%
Total		91.7%	81.3%	71.4%	91.7%	81.3%	71.4%	91.7%	81.3%	71.4%	91.7%	81.3%	71.4%	91.7%	81.3%	71.4%	89.7%	89.7%	89.7%

Table 3. Building vintage distribution and combined vintage/saturation factors for heating and air conditioning.



	Single family detached			Mobile Homes			Single family attached			MF 2-4 units			MF 5+ units			Commercial/ Industrial		Institutional/ Transportation
	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	Small	Large	
Vintage distribution by building type	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	33.0%	9.0%	74.0%	17.0%	9.0%	74.0%	17.0%	100.0%	100.0%	100.0%
Tree distribution by vintage and building type	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.4%	3.0%	0.7%	1.3%	10.7%	2.5%	37.3%	21.9%	21.2%
Combined vintage, equipment saturation factors for cooling																		
Cooling factor: shade	0.0%	0.1%	0.1%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%	0.1%	1.0%	0.4%	0.1%	2.0%	0.8%	11.5%	3.4%	0.0%
Cooling factor: climate	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.1%	0.8%	0.3%	0.2%	2.3%	0.9%	22.9%	44.7%	0.0%
Combined vintage, equipment saturation factors for heating																		
Heating factor, nat. gas: shade	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.2%	1.8%	0.4%	0.5%	3.5%	0.7%	11.7%	3.4%	0.0%
Heating factor, electric: shade	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.2%	0.1%	0.2%	0.1%	0.0%
Heating factor, nat. gas: climate	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.1%	0.1%	0.1%	0.2%	1.4%	0.3%	0.4%	3.1%	0.6%	37.7%	73.9%	0.0%
Heating factor, electric: climate	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.1%	0.7%	1.4%	0.0%

Commercial and Other Buildings

Unit energy consumptions for commercial/industrial (C/I) and industrial/transportation (I/T) land uses due to presence of trees were determined in a manner similar to that used for multi-family land uses. Potential shade factors of 0.40 were assumed for small C/I, and 0.0 for large C/I. No energy impacts were ascribed to large C/I structures since they are expected to have surface to volume ratios an order of magnitude larger than smaller buildings and less extensive glazed area. Average potential shade factors for I/T structures were estimated to lie between these extremes; a value of 0.15 was used here. However, data relating I/T land use to building space conditioning were not readily available, so no energy impacts were ascribed to I/T structures. A multiple tree reduction factor of 0.85 was used and no benefit was assigned for shading of buildings on adjacent lots.

Potential climate factors of 0.40, 0.25 and 0.20 were used for small C/I, large C/I and I/T, respectively. These values are based on estimates by Akbari and others (1990), who observed that commercial buildings are less sensitive to outdoor temperatures than houses.

Changes in UECs due to shade tends to increase with conditioned floor area (CFA) for typical residential structures. As building surface area increases so does the area shaded. This occurs up to a certain point because the projected crown area of a mature tree (approximately 700 to 3,500 ft^2 [65-325 m^2]) can be larger than the building surface areas being shaded. Consequently, more area is shaded with increased surface area. However, for larger buildings, a point is reached at which no additional area is shaded as surface area increases. Therefore, ΔUECs will tend to diminish as CFA increases. Since information on the precise relationships between change in UEC, CFA, and tree size are not known, it was conservatively assumed that ΔUECs don't change in Equation 1 for C/I and I/T land uses.

Atmospheric Carbon Dioxide Reduction

Campus trees can reduce atmospheric CO_2 in two ways:

1. Trees directly sequester CO_2 as woody and foliar biomass while trees grow.
2. Trees near buildings can reduce the demand for heating and air conditioning, thereby reducing emissions associated with electric power production.

On the other hand, vehicles, chain saws, chippers, and other equipment release CO_2 during the process of planting and maintaining trees. And eventually, all trees die and most of the CO_2 that has accumulated in their woody biomass is released into the atmosphere through decomposition. The combustion of gasoline and diesel fuels by vehicle fleets, and equipment such as chainsaws, chippers, stump removers, and leaf blowers also contribute atmospheric CO_2 concentrations. Typically, CO_2 released due to tree planting, maintenance, and other program-related activities is about 2-8% of annual CO_2 reductions obtained through sequestration and avoided power plant emissions (McPherson and Simpson 1999).

Sequestered and Released CO_2 Methodology

Sequestration, the net rate of CO_2 storage in above and below-ground biomass over the course of one growing season, is calculated by species using tree growth equations for DBH and height described above to calculate tree volume with equations from Pillsbury et. al (1998) (see McPherson and Simpson [1999] for additional information). Fresh weight (kg/m3) and specific gravity ratios from Markwardt (1930) were applied to convert volume to biomass.

Carbon dioxide released through decomposition of dead woody biomass varies with characteristics of the wood itself, fate of the wood (e.g., amount left standing, chipped, or burned), and local soil and climatic conditions. Recycling of urban waste is now prevalent, and we assume here that most material is chipped and applied as landscape mulch. Calculations were conservative because they assume that dead trees are removed and mulched in the year that death occurs, and that 80% of their stored carbon is released to the atmosphere as CO_2 in the same year. Total annual decomposition is based on the number of trees in each species and age class that die in a given year and their biomass. Tree survival rate is the principal factor influencing decomposition. Tree mortality for UC Davis was 0.5% for the first five years after out-planting and 1.3% every year thereafter (Genito 2004). Finally, CO_2 released from tree maintenance was estimated to be 0.14 kg CO_2/cm DBH based on U.S. national average figures (McPherson and Simpson 1999).

Avoided CO_2 Emissions Methodology

Reductions in building energy use result in reduced emissions of CO_2. Emissions were calculated as the product of energy use and CO_2 emission factors for electricity and heating. Heating fuel is largely natural gas, with electricity a distant second in this region (EIA 1993). Electricity in 2003 was supplied by the

Western Area Power Administration (71%), Pacific Gas and Electric Company (18%) and a UC Davis cogeneration facility (11%) (Stagner 2004). In 2003, fuel mix for this power was 75% hydroelectric, 13% natural gas, 5% nuclear, and 5% coal calculated as a weighted average of fuel mixes of three suppliers.

CO_2 emissions factors for electricity (lb/MWh) and natural gas (lb/MBtu) weighted by the appropriate fuel mixes are given in Table 4. Fuel mix for Pacific Gas and Electric Company was based on the California eGRID subregion to account for purchased power (U.S. Environmental Protection Agency 2003). Western Area Power Administration was 100% hydroelectric (Western Area Power Administration 2004), and the UC Davis cogeneration facility is 100% natural gas. Emission factors for fossil fuels were based on statewide averages for these fuels (U.S. Environmental Protection Agency 2003). The price of avoided CO_2 was \$0.008/lb based on average high and low estimates for emerging carbon-trading markets (CO2e.com 2002) (Table 4).

Table 4. Emissions factors and implied values for CO_2 and criteria air pollutants. See text for data sources.

	Emission Factor		
	Electricity	Natural gas	Price
	(lb/MWh)	(lb/MBtu)	(\$/lb)
CO_2	276	118	0.008
NO_2	0.298	0.1020	10.31
SO_2	0.165	0.0006	3.00
PM_{10}	0.096	0.0075	15.68
VOCs	0.044	0.0054	4.99
O_3			10.31

Improving Air Quality

Trees on campus provide air quality benefits in five main ways:

1. Absorbing gaseous pollutants (e.g., ozone, nitrogen oxides, and sulfur dioxide) through leaf surfaces.

2. Intercepting particulate matter (e.g., dust, ash, pollen, and smoke).

3. Reducing emissions from power generation by limiting building energy consumption.

4. Releasing oxygen through photosynthesis.

5. Transpiring water and shading surfaces, which lowers local air temperatures, thereby reducing ozone levels.

In absence of the cooling effects of trees, higher air temperatures contribute to ozone formation. Most trees emit various biogenic volatile organic compounds (BVOCs) such as isoprenes and monoterpenes that can also contribute to ozone formation. The ozone-forming potential of different tree species varies considerably on campus. Typical of many California regions, a computer simulation study for the Los Angeles basin found that increased tree planting of low BVOC emitting tree species would reduce ozone concentrations and exposure to ozone, while planting of medium- and high-emitters would increase overall ozone concentrations (Taha 1996).

Avoided Emissions Methodology

Reductions in building energy use also result in reduced emissions of criteria air pollutants from power plants and space heating equipment. This analysis considered volatile organic hydrocarbons (VOCs) and nitrogen dioxide (NO_2)—both precursors of ozone (O_3) formation—as well as sulfur dioxide (SO_2) and particulate matter of <10 micron diameter (PM_{10}). Changes in average annual emissions and their offset values (Table 4) were calculated in the same way as for CO_2, again using utility specific emission factors for electricity and heating fuels.). Values for criteria air pollutants (Table 4) were based on average (2001-2003) emission reduction offset transaction costs for Yolo-Solano Counties (California Air Resources Board 2002, 2003, 2004)

Deposition and Interception Methodology

Trees also remove pollutants from the atmosphere. The hourly pollutant dry deposition per tree is expressed as the product of a deposition velocity $V_d = 1/(R_a+R_b+R_c)$, a pollutant concentration (C), a canopy projection (CP) area, and a time step. Hourly deposition velocities for each pollutant were calculated using estimates for the resistances R_a, R_b, and R_c estimated for each hour for a year using formulations described by Scott et al. (1998). Hourly data from 2001 were selected as representative for modeling deposition based on a review of mean ozone (O_3) concentrations from UC Davis and PM_{10} concentrations from the nearest monitor (Woodland) for years 1995-2003. Hourly concentrations for NO_2 were from UC Davis, while the nearest SO_2 were from North Highlands monitoring station.

Deposition was determined for deciduous species only when trees were in-leaf. A 50% re-suspension rate was applied to PM_{10} deposition. Average (2001-2003) emission reduction offset transaction costs for Yolo-Solano Counties were used to value emissions reductions (California Air Resources Board 2002, 2003, 2004); NO_2 prices were used for ozone since ozone control measures typically aim at reducing NOx. Hourly meteorological data for wind speed and precipitation came from the UC Davis CIMIS (California Irrigation Management Information System) monitoring station (CIMIS 2004).

BVOC Emissions Methodology

Emission of biogenic volatile organic carbon (sometimes called biogenic hydrocarbons or BVOCs) associated with increased ozone formation were estimated for the tree canopy using methods described by McPherson et al. (1998). In this approach, the hourly emissions of carbon as isoprene and monoterpene are expressed as products of base emission factors and leaf biomass factors adjusted for sunlight and temperature (isoprene) or temperature (monoterpene). Hourly emissions were summed to get annual totals. This is a conservative approach, since we do not account for the benefit associated with lowered summertime air temperatures and the resulting reduced hydrocarbon emissions from biogenic as well as anthropogenic sources. The cost of these emissions is based on the average (2001-2003) reduction offset transaction costs for Yolo-Solana Counties (California Air Resources Board 2002, 2003, 2004).

Not included were the values of releasing oxygen through photosynthesis, or the reduction in local air temperature from transpiring water and shading surfaces, which reduces ozone levels.

Reducing Stormwater Runoff and Hydrology

Stormwater runoff is an increasing concern as a significant pathway for contaminants entering local riparian waters. In effort to protect threatened fish and wildlife, stormwater management requirements are becoming increasingly broad, stringent, and costly; cost-effective means of mitigation are needed. Healthy campus trees can reduce the amount of runoff and pollutant loading in receiving waters in three primary ways:

1. Leaves and branch surfaces intercept and store rainfall, thereby reducing runoff volumes and delaying the onset of peak flows.
2. Root growth and decomposition increase the capacity and rate of soil infiltration of rainfall and reduce overland flow.
3. Tree canopies reduce soil erosion and surface transport by diminishing the impact of raindrops on barren surfaces.

Studies that have simulated urban forest effects on stormwater report annual runoff reductions of 2-7%. Annual interception of rainfall by Sacramento's urban forest for the urbanized area was only about 2% due to the winter rainfall pattern and predominance of non-evergreen species (Xiao et al. 1998). However, average interception on land with tree canopy cover ranged from 6-13% (150 gal per tree on average), close to values reported for rural forests. In the city of Modesto, CA, a typical large street tree was estimated to reduce stormwater runoff by approximately 845 gal annually, with a benefit valued at $6.76 per tree (McPherson et al. 1999). A typical street tree in San Francisco was estimated to intercept 1,370 gal ($8.60) annually (Maco et al. 2003). These studies showed that broadleaf evergreens and conifers intercept more rainfall than deciduous species where winter rainfall patterns prevail, but cost of treatment and control varies widely by municipality.

Stormwater Methodology

A numerical simulation model was used to estimate annual rainfall interception (Xiao et al. 1998). The interception model accounts for water intercepted by the tree, as well as throughfall and stem flow. Intercepted water is stored temporarily on canopy leaf and bark surfaces. Once the leaf is saturated, it drips from the leaf surface and flows down the stem surface to the ground or evaporates. Tree canopy parameters include species, leaf area, shade coefficient (visual density of the crown), and tree height. Tree height data were used to estimate wind speed at different heights above the ground and resulting rates of evaporation.

The volume of water stored in the tree crown was calculated from crown projection area (area under tree dripline), leaf area index (LAI, the ratio of leaf surface area to crown projection area), and water depth on the canopy surface, while species-specific shade coefficients and tree surface saturation values influence the amount of projected throughfall. Hourly meteorological data for 2001 from California Irrigation Management Information System (CIMIS) Davis station (latitude: 38°32'09"N; longitude: 121°46'32"W; Station ID: 06) were selected to best represent a typical meteorological year and, consequently, used for this simulation. Annual precipitation during 2001 was 21.4 inches (542.7 mm). A more complete description of the interception model can be found in Xiao et al. (1998).

To estimate the value of rainfall intercepted by these campus trees, stormwater management control costs were based on calculations for a similar study in the city of Davis, CA (Maco and McPherson 2003), where infrastructure and treatment and control facilities are similar (Phillips 2004). Capital infrastructure costs for all related systems—drainage/transit pipes and channels, detention basins, settling ponds, and pump stations—were totaled and annualized over the typical time estimated for complete reinvestment (40 yrs). This figure was summed with annual operation and maintenance for a total estimated yearly expenditure ($1,766,00). Total stormwater runoff for the city was calculated at 933,526,909 gal per year. Dividing total annual expenditure by stormwater runoff implied that the city spent $0.0019/gallon of stormwater managed. However, a price adjustment factor of 0.91 was applied to calculate effective interception from total interception. The adjusted value of rainfall intercepted by trees was $0.0017/gallon.

To calculate water quality benefits on the UC Davis campus, the management cost was multiplied by modeled units of rainfall intercepted after the first 0.28 in had fallen for each event (24-hrs without rain) during the year. Based on surface detention calculations for the campus, this initial abstraction of rainfall seldom results in runoff (NRCS 1986). Thus, interception is not a benefit until precipitation exceeds this amount.

Shelter & Aesthetic Benefits

Trees provide a host of aesthetic, social, economic, and health benefits that should be included in any benefit-cost analysis. One of the most frequently cited reasons that people plant trees is for beautification. Trees add color, texture, line, and form to the landscape. In this way, trees soften the hard geometry that dominates built environments. Research on the aesthetic quality of residential streets has shown that street trees are the single strongest positive influence on scenic quality (Schroeder and Cannon 1983). Research in public housing complexes found that outdoor spaces with trees were used significantly more often than spaces without trees. By facilitating interactions among residents, trees foster safer and more sociable environments (Sullivan and Kuo 1996).

Well-maintained trees increase the value of property. Research suggests that properties with ample tree resource—versus few or no trees—are valued 3-7% higher. One of the most comprehensive studies of the influence of trees on residential property values was based on actual sales prices and found that each large front-yard tree was associated with about a 1% increase in sales price (Anderson and Cordell 1988). Depending on property land use, trees can contribute significantly to the land value.

Scientific studies confirm our intuition that trees in cities provide social and psychological benefits. Humans derive substantial pleasure from trees, whether it is inspiration from their beauty, a spiritual connection, or a sense of meaning (Dwyer et al. 1992; Lewis 1996). Following natural disasters, people often report a sense of loss if the urban forest in their community has been damaged (Hull 1992). Views of trees and nature from homes and offices provide restorative experiences that ease mental fatigue and help people to concentrate (Kaplan & Kaplan 1989). Desk-workers with a view of nature report lower rates of sickness and greater satisfaction with their jobs compared to those having no visual connection to nature (Kaplan 1992). Trees provide important settings for recreation and relaxation.

The presence of trees provides health benefits and improves the well-being of those who live, work and recreate in well treed areas. Physical and emotional stress has both short term and long-term effects. Prolonged stress can compromise the human immune system. Trees also appears to have an "immunization effect," in that people show less stress response if they've had a recent view of trees and vegetation. Hospitalized patients with views of nature and time spent outdoors need less medication, sleep better, and have a better outlook than patients without connections to nature (Ulrich 1985). Trees reduce exposure to ultraviolet light, thereby lowering the risk of harmful effects from skin cancer and cataracts (Tretheway and Manthe 1999).

Other environmental benefits from trees are more difficult to quantify than those previously described, but can be just as important. For example, minimizing noise is an important concern for the typical academic campus. Trucks, trains, and planes can produce noise that exceeds 100 decibels, posing a significant disruption. Vegetation, in conjunction with landforms or solid barriers, can reduce corridor noise by 6-15 decibels. Plants absorb more high frequency noise than low frequency, which is advantageous to humans since higher frequencies are most distressing to people (Miller 1997).

Shelter and Aesthetics Benefits Methodology

As described above, many benefits attributed to urban trees are difficult to translate into economic terms. Beautification, privacy, shade that increases human comfort, wildlife habitat, sense of place and well-being are products that are difficult to price. However, the value of some of these benefits may be captured in the property values for the land on which trees stand. To estimate the value of these "other" benefits, results of research that compares differences in sales prices of houses are used to statistically quantify the difference associated with trees. The amount of difference in sales price reflects the willingness of buyers to pay for the benefits and costs associated with the trees. This approach has the virtue of capturing what buyers perceive to be as both the benefits and costs of trees in the sales price. Some limitations to using this approach on the campus of UC Davis include the difficulty associated with 1) determining the value of individual trees, 2) the need to extrapolate results from studies conducted in the southern U.S. to California, and 3) the need to extrapolate results from trees on residential properties to trees in various locations within a public institution (e.g., park/common areas vs. dormitories).

In an Athens, GA study (Anderson and Cordell 1988), a large front yard tree was found to be associated with a 0.88% increase in average home resale values. Along with identifying the average (weighted) LSA of a typical mature large tree on campus (4,306 ft^2) and using the average annual change in LSA per unit area for trees within each DBH class as a resource unit, this increase was the basis for valuing trees' capacity to increase campus land value.

Assuming the 0.88% increase in property value held true for the campus of UC Davis, each large tree would be worth $3,337 based on the average [2003] Yolo County home sales prices ($379,250) (Lyon Realty 2003). However, not all trees are as effective as front yard residential trees in increasing property values. For example, trees adjacent to multifamily housing units on institutional grounds will not increase the property value at the same rate as trees in front of a single-family home. Therefore, a campus-wide reduction factor (0.498) was applied to prorate trees' value based on the assumption that trees adjacent to differing land-use—single home residential, multi-home residential, institutional building, and other (e.g., park/common area, agricultural, parking lot, etc.)—were valued at 100%, 75%, 50%, and 25%, respectively, of the full $3,337 (McPherson et al. 2001). For this analysis, the reduction factor reflects UCD land-use distributions based on the 2003 Campus Tree Inventory (ArborPro 2003).

Given these assumptions, a typical large tree was estimated to increase property values by $0.39/ft^2 of LSA. For example, it was estimated that a single Chinese pistache tree adds about 112 ft^2 of LSA per year when growing in the DBH range of 6-12 in. During this period of growth, therefore, a single pistache tree effectively added $42.95, annually, to the value of the campus property (112 ft^2 x $0.77/ft^2 x 0.498% = $42.95).

Estimating Magnitude of Benefits

Defined as resource units, the absolute value of the benefits of UCD's campus trees—electricity (kWh/tree) and natural gas savings (kBtu/tree), atmospheric CO_2 reductions (lbs/tree), air quality improvement (NO_2, PM_{10} and VOCs [lbs/tree]), stormwater runoff reductions (precipitation interception [ft^3/tree]) and property value increases (ΔLSA [ft^2/tree])—were assigned prices through methods described above for model trees.

Estimating the magnitude of benefits (resource units) produced by all trees on campus required four procedures: 1) categorizing trees by species and DBH based on the 2003 Campus Tree Inventory, 2) matching significant species with those from the 25 modeled species in Modesto, CA, 3) grouping remaining "other" trees by type, and 4) applying resource units to each tree. Benefits for non-inventoried trees assumed the same distributions and average values as inventoried trees; values were summed proportionately, based on a per unit area of canopy cover.

Categorizing Trees by DBH Class

The first step in accomplishing this task involved categorizing the total number of inventoried trees by relative age (DBH class). The inventory was used to group trees using the following classes:

1. 0-3 in
2. 3-6 in
3. 6-12 in
4. 12-18 in
5. 18-24 in
6. 24-30 in
7. >30 in

Because DBH classes represented a range, the median value for each DBH class was determined and subsequently utilized as a single value representing all trees encompassed in each class. Linear interpolation was used to estimate resource unit values (Y-value) for each of the 25 modeled species for the 7 midpoints (X-value) corresponding to each of the DBH classes assigned to the campus's trees.

Applying Benefit Resource Units to Each Tree

Once categorized, the interpolated resource unit values were matched on a one-for-one basis. For example, out of the 679 inventoried Chinese hackberry (*Celtis sinensis*) trees, 75 were within the 6-12 in DBH class size. The interpolated electricity and natural gas resource unit values for the class size midpoint (9 in) were 66.5 kWh/tree and 226.9 kBtu/tree, respectively. Therefore, multiplying the size class resource units by 75 equals the magnitude of annual heating and cooling benefits produced by this segment of the population: 4,988 kWh in electricity saved and 17,018 kBtu natural gas saved.

Matching Significant Species with Modeled Species

To infer from the 25 municipal species modeled for growth in Modesto, CA to the inventoried tree population of UC Davis, each species representing over 0.5% of the population were matched directly with corresponding model species or, where there was no corresponding tree, the best match was determined by identifying which of the 25 species was most similar in leaf shape/type and habit; size was not necessarily determinant.

Grouping Remaining "Other" Trees by Type

The species that were less than 0.5% of the population were labeled "other" and were categorized according to tree type classes based on tree type (one of four life forms and three mature sizes):

- Broadleaf deciduous - large (BDL), medium (BDM), and small (BDS).
- Broadleaf evergreen - large (BEL), medium (BEM), and small (BES).
- Coniferous evergreen - large (CEL), medium (CEM), and small (CES).
- Palm evergreen – large (PEL), medium (PEM), and small (PES).

Large, medium, and small trees measured >40 ft, 20-40 ft, and <20 ft in mature height, respectively. A typical tree was chosen for each of the above 12 categories to obtain growth curves for "other" trees falling into each of the categories:

BDL Other = Chinese hackberry
BDM Other = Bradford pear (*Pyrus calleryana* 'Bradford')
BDS Other = crape myrtle (*Lagerstroemia indica*)
BEL Other = holly oak (*Quercus ilex*)
BEM Other = camphor tree (*Cinnamomum camphora*)
BES Other = scaled @ 1/3 holly oak
CEL Other = Monterey pine (*Pinus radiata*)
CEM Other = scaled @ 2/3 Monterey pine
CES Other = scaled @ 1/3 Monterey pine
PEL Other = Canary Island palm (*Phoenix canariensis*)
PEM Other = scaled @ 2/3 Canary Island Palm
PES Other = Mexican fan palm (*Washingtonia robusta*)

Where modeled species did not exist—BES Other, CEM Other, CES Other, PEM Other—larger-stature species were scaled down in size metrics to be used as surrogates for "Other" trees falling into these specific categories.

Calculating Net Benefits

It is impossible to quantify all the benefits and costs trees produce. For example, campus trees can increase land values, but students, faculty and staff may also benefit directly from improved health (e.g., reduced exposure to cancer-causing UV radiation) and greater psychological well-being through visual and direct contact with trees. On the cost side, increased health care costs may be incurred because of nearby trees, as with allergies and respiratory ailments related to pollen. The value of many of these benefits and costs are difficult to determine. We assume that some of these intangible benefits and costs are reflected in what we term "shelter and aesthetic benefits." Other types of benefits we can only describe, such as the social, educational, and employment benefits associated with the campus's tree resource.

The campus community obtains additional economic benefits from trees depending on tree location and condition. For example, trees can provide energy savings by lowering wind velocities and subsequent building infiltration thereby reducing heating costs to adjacent buildings. This benefit can extend to the greater campus, as the aggregate effect of many street trees is to reduce wind speed and reduce campus-wide winter energy use. Land value increases from canopy cover extend beyond the campus to local communities. The greater Sacramento Valley benefits from cleaner air and water as a direct result of campus trees. Reductions in atmospheric CO_2 concentrations due to campus trees have global benefits.

Net Benefits Methodology

To assess the total value of annual benefits (B) for each tree (i) in each campus area (j) benefits were summed:

$$B = \sum_{1}^{n} j\left(\sum_{1}^{n} i\left(e_{ij} + a_{ij} + c_{ij} + h_{ij} + p_{ij}\right)\right)$$

where

e = price of net annual energy savings = annual natural gas savings + annual electricity savings

a = price of annual net air quality improvement = PM_{10} interception + NO_2 and O_3 absorption + avoided power plant emissions - BVOC emissions

c = price of annual carbon dioxide reductions = CO_2 sequestered less releases + CO_2 avoided from reduced energy use

h = price of annual stormwater runoff reductions = effective rainfall interception

p = price of aesthetics = annual increase in property value

(Equation 3)

Assessing Structure

Campus tree inventory information, including species composition, DBH, and total number of trees were analyzed using the Campus Tree Inventory conducted by ArborPro in 2003. Campus periphery trees (e.g., trees in the Arboretum and Environmental Horticulture research field) were excluded from the inventory due to differing management practices and purview.

Canopy Cover

High resolution remote sensing data, GIS base layers, and field tree samples were acquired during the summers of 2003 and 2004. Color infrared (IR) aerial photography, covering the entire UC Davis campus, was collected on August 8, 2003 by WAC Corporation, Inc., Eugene, OR. This data included three spectrum bands (near infrared, red, and green). The data were recorded on traditional negative film at 1:4,800 and scanned at 600 dots per inch (DPI). The aerial photography was mosaiced and georeferenced to the GIS base layers (administration boundaries, buildings, parking lots, roads, paths, and tree inventory) using the ArcGIS software platform. Trees and shrubs were separated from non-woody vegetation and non-vegetated cover by evaluating spectral reflectance from the IR imagery. Normalized difference vegetation index (NDVI) and a difference vegetation index (DVI) (Richardson and Everitt 1992; Lillesand and Kiefer 1997) were generated from near-IR and red bands of the study area. The thread values for NDVI (0.2) and DVI (5) were use to map vegetation cover at the pixel level. Where reflectance was ambiguous, trees and shrubs were manually digitized.

Tree Health

Based on spectral characteristics between the near-IR (NIR) and red spectral region, a red-edge health index for all woody campus vegetation was created. A high red-edge value indicates healthy vegetation and a low value indicates senescent, diseased, damaged, or water stressed vegetation.

As a first step, a multiple masking technique (Xiao et al. 2004) was used to perform the tree health mapping for each tree type. A primary mask was created based on land cover types and was subsequently used to mask out all non-vegetation. Remaining vegetation were mapped into four layers based on additional masks created for four tree types: broadleaf deciduous, broadleaf evergreen, conifer, and mixed. The mixed layer included palms, shrubs, and clustered trees—where clustered trees were defined as multiple trees with overlapping crowns that were unable to be isolated as individuals.

A pixel-based analysis of the NDVI value and tree-health condition from a 2004 field survey of 81 trees was performed for each tree type. For each tree type, the thread values for both NDVI and health index were determined based on histogram analysis on both healthy and unhealthy trees from the field sample. All pixels encompassed within each tree crown were classified as healthy or unhealthy based on thread values determined distinct for tree type. The number of healthy pixels, un-healthy pixels, and average NDVI were derived for each tree. At the whole tree level, a tree-health index was calculated based on the ratio of healthy pixels to total pixels for the tree crown. Where 70% or more pixels within a crown were healthy, tree condition was categorized as healthy; below this threshold, trees were classified as unhealthy. The tree-health condition for each tree was assigned based on its health index and average NDVI value. To verify accuracy, a random sample totaling 1186 inventoried trees (13% of total inventory) were field verified for health classification. A confusion matrix was utilized for comparison. Overall, 88% mapping accuracy was found: 86% for deciduous trees, 94% for evergreens, 91% for conifers, and 89% for mixed.

For this analysis, tree health is presented at two different spatial scales: a raster-based map presents information at the pixel level, which includes the tree-health condition and vegetation indexes for each pixel of the tree crown, while a vector-based map presents data at the whole tree level. Additionally, the health index, number of healthy and un-healthy pixels, and averaged vegetation indices were appended to the Campus Tree Inventory (see Appendix A).

University of California
Davis Campus Tree Resource Analysis

Scott E. Maco, Qingfu Xiao, James R. Simpson, E. Gregory McPherson

Stewardship of the UC Davis' campus tree resource involves management of two distinct populations, trees that are within the campus core and managed as part of the campus grounds, and trees that are on the core campus periphery. Core campus grounds trees are generally open grown, planted trees that receive regular maintenance and are part of the Campus Tree Inventory (ArborPro 2003). Periphery trees may constitute pre-existing native trees and those that are considered part of a low intensity land use setting (e.g., natural area, undeveloped land, or arboretum).

Tree Numbers

Based on the Campus Tree Inventory (ArborPro 2003), there were 8,999 trees within the core campus limits. Comprising over half the total population, deciduous trees were the most prevalent tree type (Table 5). Of those, nearly half (49%) were of large mature size. Conifers and broadleaf evergreen species made up the bulk of the remaining trees, with, again, large species dominating the populations. Palms were relatively insignificant in numbers, accounting for less than 1%.

Table 5. Core campus inventoried tree numbers by mature size class and tree type.

Tree type	Mature size			% of total
	Small	Medium	Large	
Broadleaf deciduous	1,110	1,421	2,424	55
Broadleaf evergreen	362	498	956	20
Coniferous	15	240	1,910	24
Palm	36	17	10	1
% of total	17	24	59	100

Canopy Cover Extent and Potential

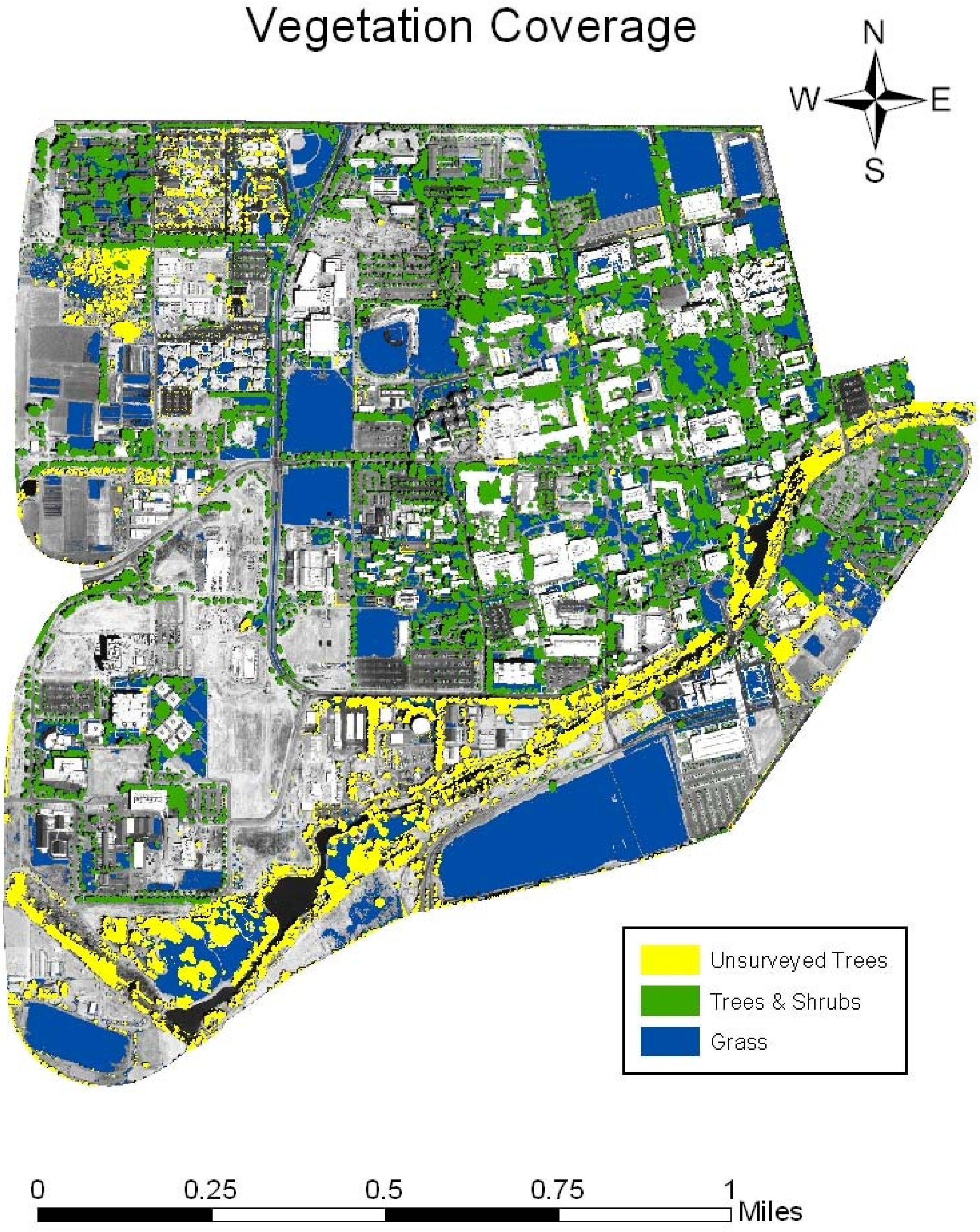
The campus's 8,999 inventoried trees accounted for approximately 13% (116.3 ac) of the total core campus area, while uninventoried woody vegetation (trees and shrubs) accounted for an additional 8% (72.8 ac) (Table 6). Total tree cover was 21% (189 ac). Adding turf and other vegetation on the ground (137.7 ac) increased greenspace cover to approximately 36% (326 ac) (Plate 1). Buildings, streets, sidewalks, water bodies and other land cover types account for 64% (570 ac) of the core campus land area.

Broadleaf deciduous trees provided cover proportional to there numbers. Interestingly, however, broadleaf evergreen trees represented 27% of inventoried cover even though their numbers represented only 20%. On the other hand, cover provided by conifers (18%) was inversely proportional to their numbers (24%).

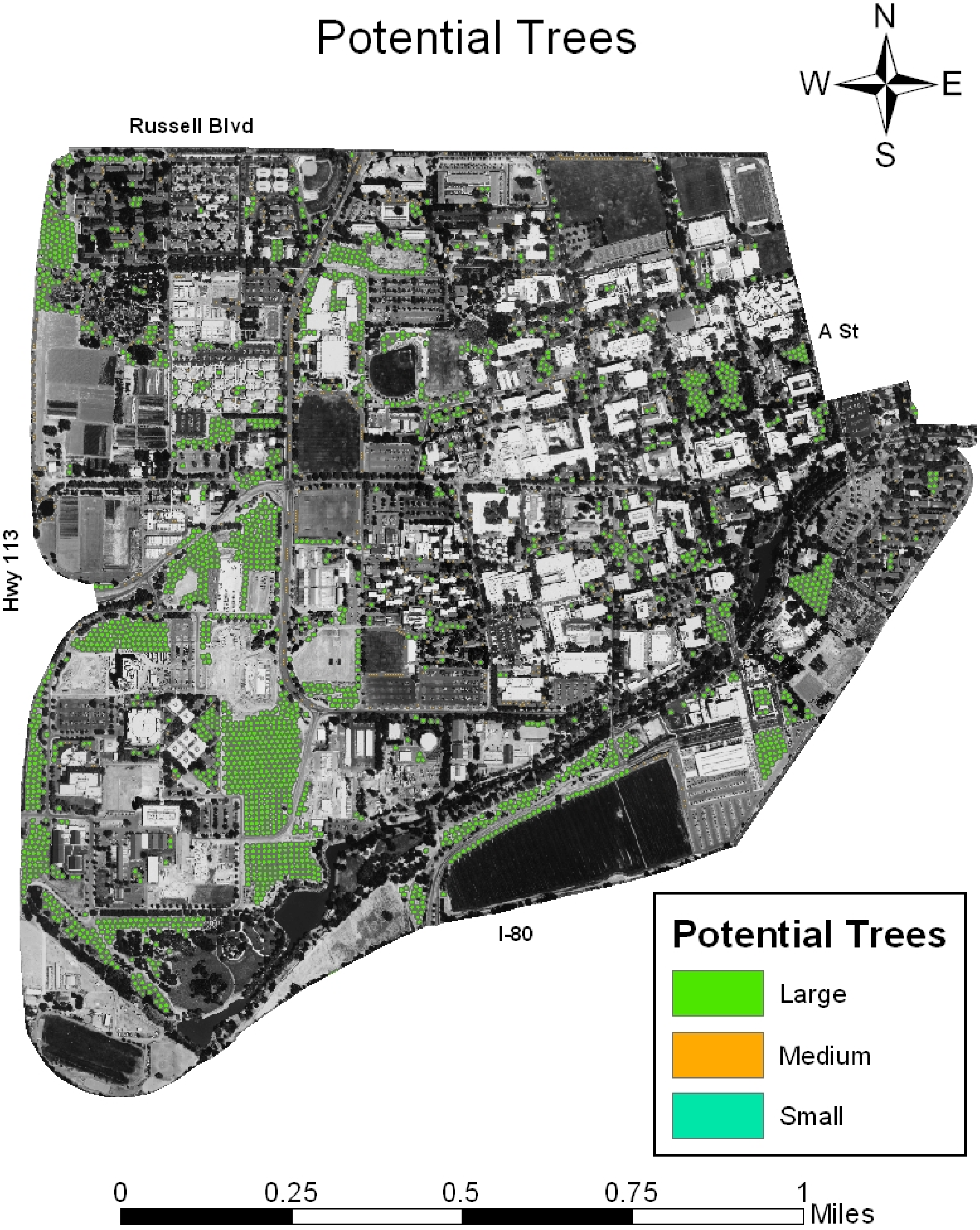
Potential planting sites were estimated by filling empty planting sites with hypothetical trees. Because the largest benefits were associated with larger-stature trees, sites were filled by maximizing use of

Table 6. Vegetated and non-vegetated coverage areas of campus.

Coverage	Area (acres)
Inventoried trees	
Broadleaf deciduous	63.2
Broadleaf evergreen	31.6
Conifer evergreen	20.5
Palm	0.2
Other	1.9
Subtotal	116.3
Uninventoried trees & shrubs	72.8
Non-woody vegetion	137.7
All vegetation	326.8
Non-vegetated area	570.2
Total UCD core area	897.0


Vegetation Coverage
N
W
E
S
Unsurveyed Trees
Trees & Shrubs
Grass
0
0.25
0.5
0.75
1
Miles

--Plate 1--


Potential Trees
N
W
E
S
Russell Blvd
A St
Hwy 113
I-80
Potential Trees
Large
Medium
Small
0
0.25
0.5
0.75
1
Miles

--Plate 2--

large stature trees. Continuing with the primary objective of maximizing future benefits, spaces unable to accommodate large trees were filled with medium-stature trees, followed by small trees as a last resort. Small-, medium-, and large-stature trees required void space of 10 ft, 20 ft, and 40 ft, on-center, in all directions, respectively, for accommodation. The crowns of potential trees did not overlap, so higher densities could be achieved than are presented here.

The campus is relatively well stocked with trees. Sixty-nine percent of the 13,091 tree sites are currently filled. Planting the 4,092 potential tree sites that are not filled has potential to increase tree cover by an additional 9% (76.8 ac) to a total of 30% campus-wide (Plate 2). However, this magnitude of increase may not be feasible given conflicts with underground utilities and other infrastructure.

A total of 2,221 potential sites for large-stature trees were found (64.1 ac). The 1,732 potential sites for medium stature trees encompassed an additional 12.5 acres, while sites only available for small stature trees were few (139), utilizing an area of 0.3 acres.

Species Richness

A total of 209 different tree species and cultivars were inventoried on the core campus. Compared to the mean of 53 species McPherson and Rowntree (1989) reported in their nationwide survey of 22 US cities' street tree populations, the core UCD campus represents a rich assemblage. However, temperate climates afford urban forestry programs with a larger palette than continental climates. The city of Davis, CA manages 98 different taxa (Maco 2001) while Modesto, CA was reported to have 184 trees in their tree inventory (McPherson et al. 1999).

Species Composition

No inventoried species was beyond the commonly held standard that no single species should exceed 10% of the population (Clark et al. 1997). Numbering 717, or 8% of the population, coast redwood (*Sequoia sempervirens*) was the most widely planted; Chinese hackberry was a close second with 679 trees accounting for 7.5% of all trees together (Table 7). Of the 209 species inventoried, 183 constituted less than 1% of the population, individually. The 26 species representing 1% or more of the population constituted approximately 70% of all trees inventoried on the core campus.

Table 7. Core campus tree distribution.

Species	% of Pop.
coast redwood	8.0
Chinese hackberry	7.5
cork oak	4.4
Chinese pistache	4.2
crape myrtle	3.9
ornamental pear	3.8
London plane	3.7
valley oak	3.4
olive	3.3
Canary Island pine	3.2
thornless honey locust	2.4
Italian cypress	2.2
Aleppo pine	2.1
coast live oak	1.8
magnolia	1.7
Other (194 spp.)	44.3
Total	100.0

Using Simpson's diversity index number (C) denotes the probability that two trees, chosen at random, will be of the same species; the lower the number, the more diverse the population (Simpson 1949). For example, *C*=0.10 can be interpreted as having the equivalent of 10 species evenly distributed. Twenty species evenly distributed would have an index value of 0.05, equivalent to each species representing about 5% of the population. The core campus inventory had a calculated index value of 0.03 (*C*), suggesting a diverse population resistant to catastrophic loss. However, a complete understanding of tree diversity in urban settings must reflect concern for local vulnerability (Sanders 1981). Several campus streets and areas are dominated by single species that would not go unnoticed if large-scale loss occurred. These places include large plantings of Chinese hackberry, coast redwood, and cork oak (*Quercus suber*).

Species Importance

Importance values are particularly meaningful to managers because they suggest a community's reliance on the functional capacity of particular species. In other words, importance value (IV) provides meaningful interpretation with respect to the degree UCD might depend on particular campus trees insofar as their environmental benefits are concerned. This evaluation takes into account not only total tree numbers, but their canopy cover and leaf area, providing a useful comparison to the total population distribution.

As a mean of three relative values, importance values (IVs), in theory, can range between 0 and 100; where an IV of 100 suggests total reliance on one species and an IV of 0 suggests no reliance. For the most abundant 1% of all inventoried core campus trees, IVs ranged between 18 (i.e., Chinese Hackberry) and one (e.g., ginkgo [*Ginkgo biloba*]) (Table 8).

The most populous tree—coast redwood—had an IV of 11, similar to its numbers (11.5%). However, due to the large amount of canopy cover and leaf area provided, Chinese hackberry and cork oak surpass the importance of redwood, lowering redwood's rank to third, overall. These three tree species, together, possessed an importance value that summed to 41, whereas their numbers summed to only 29% of the total. From a functional standpoint, these species are considerably more important than their numbers alone would suggest. To a lesser degree, other functionally important trees include Chinese pistache (*Pistacia chinensis*), valley oak (*Q. lobata*), Olive (*Olea europaea*), Canary Island pine (*Pinus canariensis*), thornless honey locust (*Gleditsia triancanthos inermis*), coast live oak (*Q. agrifolia*), and black walnut (*Juglans hindsii*).

Age Structure

The distribution of ages within a tree population influences present and future costs as well as the flow of benefits. An uneven-aged population allows managers to allocate annual maintenance costs uniformly over many years and assure continuity in overall tree canopy cover. An ideal distribution has a high proportion of new transplants to offset establishment-related mortality, while the percentage of older trees declines with age (Richards 1982/83). The age structure for all core campus trees differed from the ideal by having fewer numbers of early functional and functional trees—6-12 in. and 12-18 in. DBH classes, respectfully—while more trees were present in the mature and old classes (18-24 in. and >24in.) (Figure 1).

Age curves for different tree species help explain their relative importance and suggest how tree management needs may change as these species grow older. Figure 1 shows the importance of understanding relative age at different scales. Cork

Table 8. Importance Values (IV) calculated as the mean of tree numbers, leaf area, and canopy cover for the most abundant 1% of all street trees.

Species	# of trees	% of total	Leaf area (ft ^{2})	% of total	Canopy cover (ft ^{2})	% of total	IV
coast redwood	717	11.5	2,816,296	12.0	398,835	8.4	11
Chinese hackberry	679	10.9	4,295,994	18.4	1,107,044	23.3	18
cork oak	400	6.4	4,039,193	17.3	640,997	13.5	12
Chinese pistache	376	6.0	1,049,469	4.5	239,101	5.0	5
crape myrtle	355	5.7	46,773	0.2	17,625	0.4	2
ornamental pear	338	5.4	415,974	1.8	135,380	2.8	3
London plane	331	5.3	270,128	1.2	84,344	1.8	3
valley oak	302	4.8	662,725	2.8	157,864	3.3	4
olive	301	4.8	857,819	3.7	198,455	4.2	4
Canary Island pine	289	4.6	1,129,059	4.8	174,606	3.7	4
thornless honey locust	218	3.5	899,897	3.9	306,044	6.4	5
Italian cypress	196	3.1	85,503	0.4	8,495	0.2	1
Aleppo pine	188	3.0	866,494	3.7	119,065	2.5	3
coast live oak	162	2.6	974,108	4.2	180,350	3.8	4
magnolia	156	2.5	83,953	0.4	26,551	0.6	1
stone pine	150	2.4	870,616	3.7	99,819	2.1	3
deodar cedar	136	2.2	546,678	2.3	79,772	1.7	2
Chinese tallow	124	2.0	599,075	2.6	171,463	3.6	3
Chinese elm	120	1.9	346,957	1.5	92,681	2.0	2
ginkgo	115	1.8	169,948	0.7	25,124	0.5	1
Mondell pine	102	1.6	81,371	0.3	12,308	0.3	1
flowering plum	96	1.5	64,136	0.3	20,087	0.4	1
silver dollar eucalyptus	95	1.5	444,497	1.9	108,230	2.3	2
tulip tree	95	1.5	267,415	1.1	46,278	1.0	1
zelkova	95	1.5	393,835	1.7	73,168	1.5	2
black walnut	94	1.5	1,095,585	4.7	227,259	4.8	4
Total	6,230	100.0	23,373,495	100.0	4,750,945	100.00	100

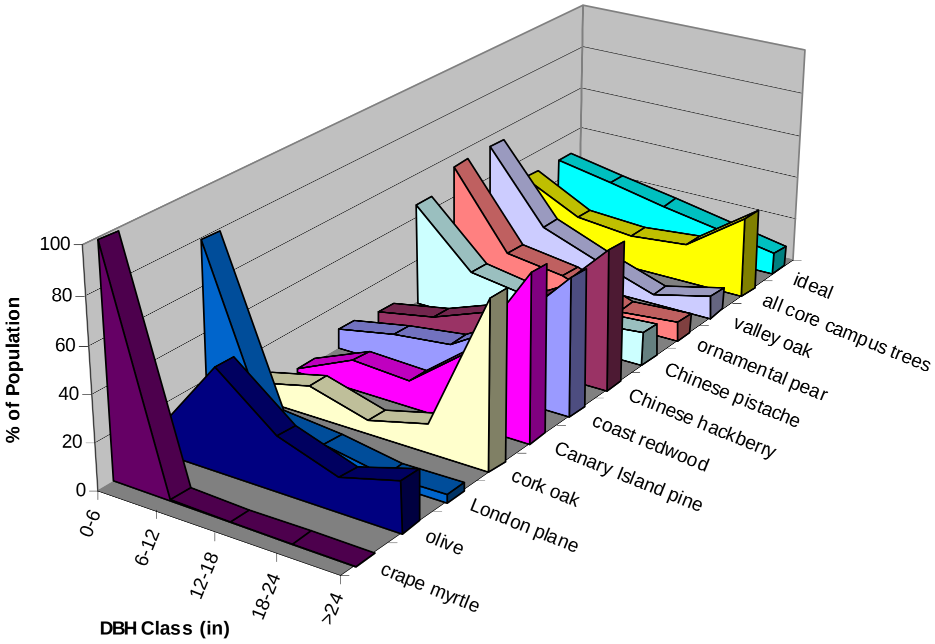


Figure 1. Relative age distribution UCD's 10 most abundant trees.

oak, Canary Island pine, coast redwood, and Chinese hackberry exhibit largely mature to old populations. These trees have provided benefits over a long period of time, and because of their canopy and associated leaf area, are particularly important. With the exception of London plane (*Platanus* x *acerfolia*) and Valley oak, species most frequently planted during the past 10 years—crape myrtle, Chinese pistache, and ornamental pear—are small- to medium-stature trees that likely will not provide the level of benefits larger species afford. Thus, while new planting is occurring, the functional engine of the campus forest may not be perpetuated due to the dearth of large-stature tree planting. Further, the functional capacity provided by the campus's large, old tree population, now, may be lost in the foreseeable future without replacements.

Tree Health

The benefits campus trees provide are directly influenced by their health. For example, trees in poor condition do not provide the same level of shelter and aesthetic benefits that are so highly valued on campus. Similarly, slower growing, unhealthy trees do not provide the same level of CO_2 reductions that an otherwise healthy tree could provide. But reduced functionality is not the only cost. Unhealthy trees indicate poor species performance given site-specific performance and/or mismanagement.

Based on the red-edge health index created for each tree type, and calculated for each tree, an estimated 14% of the trees were classified as unhealthy due to water stress, disease, or structural damage (Table 9). Between tree types, this ranged between 6.9% and 16% at the pixel level (Plate 3) and 9.3% and 15.7% at the whole tree level (Plate 4). Palms were the healthiest; followed by broadleaf evergreens, conifers, and deciduous trees, respectively. The proportion of healthy to unhealthy vegetation was nearly mirrored when pixel level and whole tree level analyses were compared.

Not all inventoried trees could be digitally isolated—hence, their numbers do not equal the inventoried tree total of 8,999—and data are therefore presented as an indicator of overall managed tree health (Plate 4). The pixel level data and associated map (Plate 3) describe the entire woody vegetation resource on campus, including arboretum and periphery trees not included in the Campus Tree Inventory. Additionally, it is important to remember that the pixel level GIS layer can be examined at a resolution fine enough to locate problem areas within the crown of individual


Tree Health:
Pixel Scale
N
W
E
S
Russell Blvd
A St
Hwy 113
I-80
Tree Health
🟩 Healthy
🟥 Unhealthy
0
0.25
0.5
0.75
1
Miles

--Plate 3--


Tree Health:
Tree Scale
N
W
E
S
Russell Blvd
A St
Hwy 113
I-80
Tree Health
🟩 Healthy
🟥 Unhealthy
0
0.25
0.5
0.75
1
Miles

--Plate 4--

Table 9. Campus tree health calculated at both the pixel and whole tree levels.

TYPE	Pixel level					Whole tree level				
	Pixels			%		Trees[b]			%	
	H[a]	UNH[a]	Total	H	UNH	H	UNH	Total	H	UNH
BDL	1,196,861	239,905	1,436,766	83.3	16.7	1,494	323	1,817	82.2	17.8
BDM	465,909	74,327	540,236	86.2	13.8	939	131	1,070	87.8	12.2
BDS	153,975	31,619	185,594	83.0	17.0	574	107	681	84.2	15.8
Total	1,816,745	345,851	2,162,596	84.0	16.0	3,007	561	3,568	84.3	15.7
BEL	643,191	73,709	716,900	89.7	10.3	551	72	623	88.4	11.6
BEM	132,362	15,232	147,594	89.7	10.3	258	37	295	87.4	12.6
BES	96,852	9,782	106,634	90.8	9.2	183	26	209	87.7	12.3
Total	872,405	98,723	971,128	89.8	10.2	992	135	1,127	88.0	12.0
CEL	512,734	92,656	605,390	84.7	15.3	890	132	1,022	87.1	12.9
CEM	7,557	1,310	8,867	85.2	14.8	38	8	46	83.2	16.8
CES	1,682	353	2,035	82.7	17.3	4	1	6	78.9	21.1
Total	521,973	94,319	616,292	84.7	15.3	932	141	1,073	86.9	13.1
PEL	3,895	183	4,078	95.5	4.5	9	0	9	100.0	0.0
PEM	1,113	40	1,153	96.5	3.5	4	4	8	50.0	50.0
PES	4,314	466	4,780	90.3	9.7	26	0	26	100.0	0.0
Total	9,322	689	10,011	93.1	6.9	39	4	43	90.7	9.3
Grand Total	3,220,445	539,582	3,760,027	85.6	14.4	4,970	841	5,811	85.5	14.5

a: H = Health UNH = Unhealthy

b: Numbers do not reflect inventoried tree totals because all tree crowns could not be isolated as individual trees.

trees. The whole tree analysis is coarser, differentiated between individual crowns only.

The relative condition of tree species provides an indication of their suitability to local growing conditions, as well as their performance. Species with larger percentages of trees in healthy condition are likely to provide greater benefits at less cost than species with more trees classified as unhealthy. Abundant species rated as having the best condition, overall, were cork oak, coast live oak, Italian stone pine (*P. pinea*), and cherry plum (*Prunus cerasifera*). These species appear widely adapted to growing conditions throughout campus. Amongst abundant species having had the lowest health ratings were Chinese hackberry, valley oak, and crape myrtle, tulip poplar (*Liriodendron tulipifera*), and glossy privet (*Ligustrum lucidum*), some of which are still being currently planted in high numbers (i.e., valley oak and crape myrtle) (Figure 1).

Land-Use

Distribution of trees by land-use followed the basic composition of the campus, with the largest number of trees associated with non-housing campus buildings (32%) and significant numbers associated with streets (20%), courtyard/circulation areas (19%), parking lots (17%), and student housing (10%) (Figure 2).

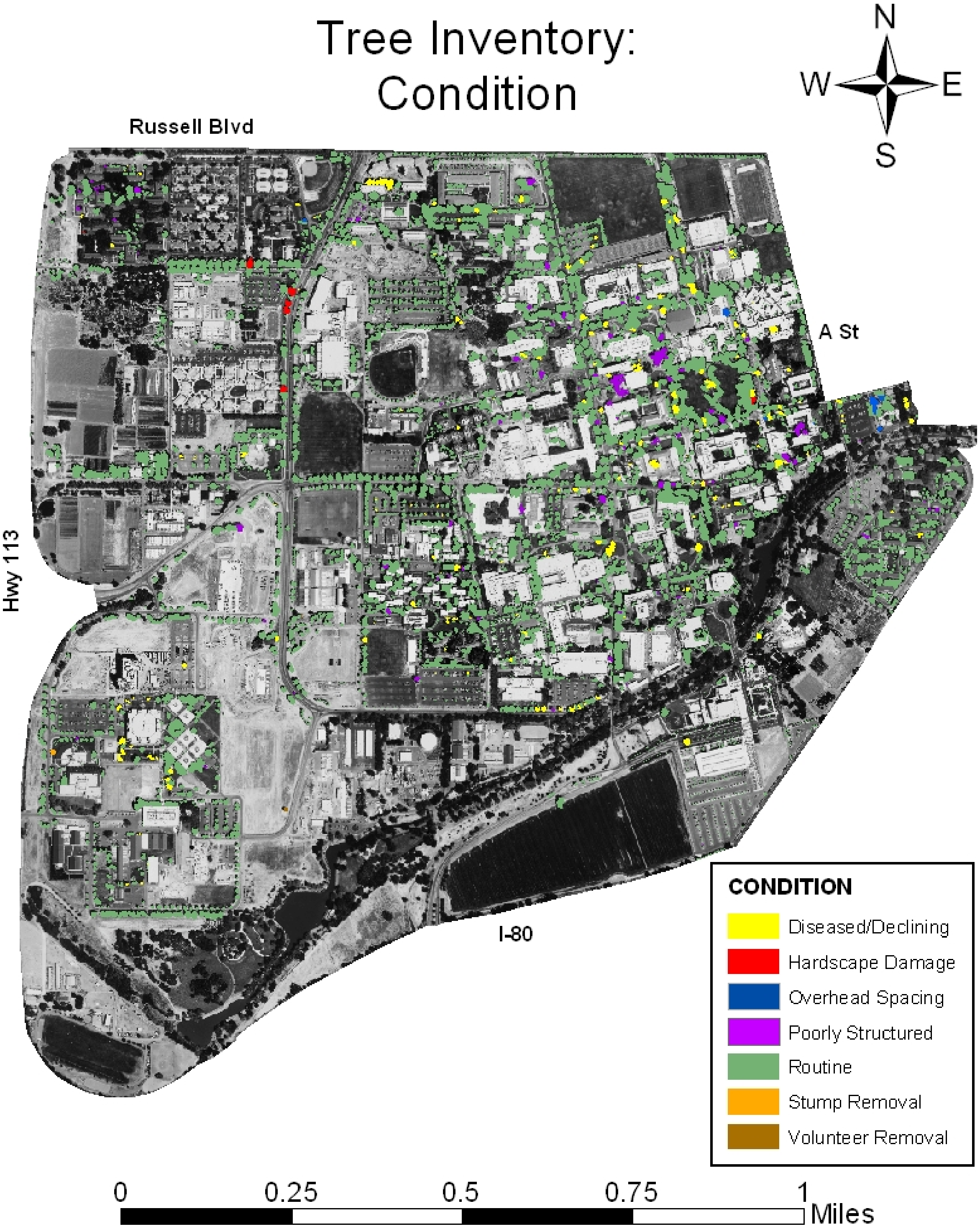
Maintenance Needs

General

Understanding species distribution, age structure, and tree condition may aid in determining proper pruning cycle length, but it is important to understand the actual pruning and maintenance needs of the campus forest resource. Not only will this provide clues to whether or not the pruning is adequate, but what level of risk and liability is associated with the city's street tree population.

Tree Conflicts

The campus is fortunate to be afforded the setting and resources to limit tree conflicts that are so often associated with trees positioned in the urban matrix. Root-infrastructure conflicts are of particular concern to tree managers due to the large costs associated with repairs. Sidewalk heave provides the additional burden associated with potential legal costs from trip and fall incidents. Campus managers appear to be doing an excellent job in all but eliminating these problems—only seven inventoried trees were associated with hardscape damage (Plate 5). Equally low in numbers were conflicts between trees and overhead utility lines. The combination of underground utility lines and good planting decisions


Tree Inventory:
Condition
N
W
E
S
Russell Blvd
A St
Hwy 113
I-80
CONDITION
🟨 Diseased/Declining
🟥 Hardscape Damage
🟦 Overhead Spacing
🟪 Poorly Structured
🟩 Routine
🟧 Stump Removal
🟫 Volunteer Removal
0
0.25
0.5
0.75
1
Miles

--Plate 5--

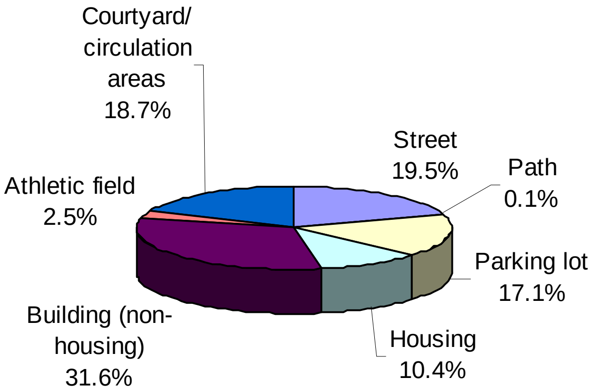


Figure 2. Distribution of core campus trees by land-use.

where lines do exist have limited overhead utility conflicts to 13 trees.

Corrective Maintenance

Not considering the remotely sensed health analysis, above, 5% of the 8,999 inventoried trees needed corrective maintenance to address poor structure, disease and/or decline (Table 10) (Plate 5). Accounting for approximately 10% of the total, Chinese hackberry dominated those inventoried as diseased or declining. Red gum (*Eucalyptus camaldulensis*), valley oak, desert gum (*E. rudis*) and cork oak were other species with significant numbers of diseased/declining trees. Hackberry (11.6%) also accounted the most numbers within the category of poorly structured trees, but was closely followed by deciduous magnolia species (9.3%). Other significant poorly structured species were Aleppo pine (*P. halepensis*), raywood ash (*Fraxinus oxycarpa* 'Raywood'), and Japanese flowering cherry (*P. serrulata*).

Table 10. Top five species representing two categories of management concern.

Management concern	1st (%)	2nd (%)	3rd (%)	4th (%)	5th (%)	# of trees
Diseased/declining	Chinese hackberry (9.7)	red gum (6.7)	valley oak (5.7)	desert gum (4.7)	cork oak (4.7)	299
Poorly structured	Chinese hackberry (11.6)	magnolia (9.3)	Aleppo pine (5.2)	raywood ash (4.1)	Japanese flowering cherry (4.1)	172

Chapter Four—Benefits of UC Davis Campus Trees

University of California
Davis Campus Tree Resource Analysis

Scott E. Maco, Qingfu Xiao, James R. Simpson, E. Gregory McPherson

Introduction

Estimates of benefits are initial approximations—as some benefits and are intangible or difficult to quantify (e.g., impacts on psychological health, crime, and violence). Also, limited knowledge about the physical processes at work and their interactions make estimates imprecise (e.g., fate of air pollutants trapped by trees and then washed to the ground by rainfall). Tree growth and mortality rates are highly variable and benefits—and costs—depend on the specific conditions at the site (e.g., tree species, growing conditions, maintenance practices). Therefore, this method of quantification was not intended to account for every penny. Rather, this approach was meant to be a general accounting of the benefits produced by UC Davis campus trees; an accounting with an accepted degree of uncertainty that can nonetheless, provide a platform on which decisions can be made (Maco and McPherson 2003).

Electricity and Natural Gas Results

Electricity and natural gas saved annually from both shading and climate effects totaled 992 MWh and 2,964 Mbtu, respectively, equivalent to $85,742 in retail savings for inventoried trees (Table 11). This

Table 11. Annual net annual energy savings produced by UCD trees.

Species	Total Electricity (MWh)	Total Natural Gas (MBtu)	Total ($)	% of Total Tree Numbers	% of Energy Savings	Avg. $/tree
coast redwood	57	182	3,790	8	6	5.29
Chinese hackberry	158	416	10,039	8	15	14.78
cork oak	95	249	6,014	4	9	15.03
Chinese pistache	35	119	2,406	4	4	6.40
crape myrtle	3	13	212	4	0	0.60
ornamental pear	21	73	1,420	4	2	4.20
London plane	13	47	900	4	1	2.72
valley oak	24	68	1,538	3	2	5.09
olive	30	92	1,980	3	3	6.58
Canary Island pine	42	133	2,804	3	4	9.70
thornless honey locust	44	139	2,914	2	4	13.37
Italian cypress	3	12	210	2	0	1.07
Aleppo pine	34	105	2,254	2	3	11.99
coast live oak	27	73	1,700	2	3	10.49
magnolia	4	17	285	2	0	1.83
stone pine	36	110	2,395	2	4	15.97
deodar cedar	11	35	737	2	1	5.42
Chinese tallow	25	77	1,637	1	3	13.20
Chinese elm	14	40	888	1	1	7.40
ginkgo	4	14	265	1	0	2.31
Mondell pine	3	11	207	1	0	2.02
flowering plum	3	13	214	1	0	2.23
silver dollar eucalyptus	16	46	1,036	1	2	10.91
tulip tree	7	26	499	1	1	5.25
zelkova	11	31	691	1	1	7.27
black walnut	33	77	2,017	1	3	21.45
Other species	242	746	16,027	31	25	5.79
Inventoried tree total	992	2,964	65,078	100	100	7.23
Univentoried tree total	621	1,855	40,737	NA	NA	NA
Core campus total	1,613	4,819	105,814	NA	NA	NA

amounted to an average savings of $7.23 per managed tree. The combined total for all campus trees was estimated at $106k, annually, and amounted to an energy savings of $600 per acre of canopy cover.

In general, larger trees produced larger benefits, with deciduous and broadleaf evergreens producing the largest savings. Because the campus is largely comprised of institutional buildings, the winter penalty evergreens assume due to blocking sunlight to heated buildings is not as dramatic as it would be in single-family residential settings. The higher benefits associated with large broadleaf evergreens reflect this fact (Table 12).

Table 12. Average annual per tree energy benefit ($) by tree type.

Tree Type	Avg. $/tree
Lg. Deciduous	10.05
Med. Deciduous	6.29
Sm. Deciduous	1.44
Lg. Brdlf Evrgrn	12.38
Med. Brdlf Evrgrn	6.02
Sm. Brdlf Evrgrn	2.13
Lg. Conifer	7.36
Med. Conifer	1.32
Sm. Conifer	1.72
Lg. Palm	7.98
Med. Palm	3.69
Sm. Palm	0.69
Inventoried tree total	7.23

Atmospheric Carbon Dioxide Reductions

Carbon dioxide reductions by trees are dependent on individual sequestration rates, emission reductions from energy savings, mortality, and the amount of maintenance the trees are provided. Trees sequester CO_2, but maintenance and mortality release CO_2 back into the atmosphere. Avoided emissions from reduced energy use are highly dependent on the fuel mix used to produce electricity delivered locally. As Table 13 shows, CO_2 reductions vary dramatically by species: the average cork oak on campus reduces atmospheric CO_2 by 349 lbs per year, while the typical flowering plum reduces CO_2 by approximately 4 lbs per year for a paltry benefit of $0.03. The average per tree reduction was 128 lbs valued at $0.96, annually. Inventoried trees alone reduced 578 tons of CO_2, while the total for all campus trees was 940 tons valued at over $14,000 for the year. Coast redwood and cork oak account for an estimated 29% of this value. Sequestration rates were nearly seven times greater than avoided emissions from power plants, reflecting UCD's relatively clean fuel mix.

Air Quality Improvement

Avoided and BVOC Emissions Result

The small value of avoided air pollutant emissions of nitrogen dioxide (NO_2), small particulate matter

Table 13. Annual net CO_2 reductions of UCD trees.

Species	Sequestered (lb)	Decomposition Release(lb)	Maintenance Release (lb)	Avoided (lb)	Net Total (lb)	Total ($)	% of Total Tree Numbers	% of Total $	Avg. $/tree
coast redwood	222,066	29,577	11,180	11,998	193,307	1,450	8	17	2.02
Chinese hackberry	91,387	35,144	10,679	33,577	79,141	594	8	7	0.87
cork oak	211,275	83,730	7,970	20,128	139,702	1,048	4	12	2.62
Chinese pistache	13,307	3,858	2,661	7,521	14,309	107	4	1	0.29
crape myrtle	823	93	663	592	658	5	4	0	0.01
ornamental pear	12,177	2,748	2,190	4,371	11,610	87	4	1	0.26
London plane	9,837	1,494	1,316	2,747	9,774	73	4	1	0.22
valley oak	19,817	4,342	2,021	5,037	18,491	139	3	2	0.46
olive	46,891	8,689	3,216	6,360	41,346	310	3	4	1.03
Canary Island pine	70,921	11,741	5,003	8,913	63,089	473	3	5	1.64
thornless honey locust	62,545	6,603	3,009	9,261	62,194	466	2	5	2.14
Italian cypress	2,311	122	541	606	2,253	17	2	0	0.09
Aleppo pine	58,566	11,016	3,808	7,214	50,955	382	2	4	2.03
coast live oak	59,209	20,541	2,373	5,631	41,925	314	2	4	1.94
magnolia	826	297	760	812	581	4	2	0	0.03
stone pine	64,051	13,667	3,795	7,733	54,321	407	2	5	2.72
deodar cedar	43,102	5,636	2,179	2,335	37,622	282	2	3	2.07
Chinese tallow	15,746	3,700	1,617	5,240	15,669	118	1	1	0.95
Chinese elm	10,957	2,258	1,096	2,899	10,502	79	1	1	0.66
ginkgo	8,321	1,024	587	807	7,516	56	1	1	0.49
Mondell pine	3,261	326	464	616	3,086	23	1	0	0.23
flowering plum	604	233	562	610	420	3	1	0	0.03
silver dollar eucalyptus	35,832	9,690	1,469	3,390	28,062	210	1	2	2.22
tulip tree	10,196	1,529	946	1,539	9,260	69	1	1	0.73
zelkova	7,020	2,159	734	2,241	6,368	48	1	1	0.50
black walnut	17,331	10,247	2,041	6,934	11,978	90	1	1	0.96
Other species	298,004	81,545	25,457	51,402	242,404	1,818	31	21	0.66
Inventoried tree total	1,396,381	352,011	98,338	210,510	1,156,542	8,674	100	100	0.96
Univentoried tree total	874,089	220,347	61,556	131,773	723,958	5,430	NA	NA	NA
Core campus total	2,270,470	572,359	159,895	342,283	1,880,500	14,104	NA	NA	NA

(PM_{10}), and volatile organic compounds (VOCs) was a consequence of moderate energy savings and relatively clean electricity generation fuel mix (Table 14). The inventoried tree total was only $84. And with the addition of univentoried trees, the annual benefit totaled $137 for the campus. More significant, however, were detrimental biogenic volatile organic compound (BVOC) emissions from trees. Many of the dominant campus species had high emission rates that resulted in considerable releases which sum to a net environmental cost (Table 14). Particularly high emitting species were cork oak (6.6 lbs/tree/yr), coast live oak (3.9 lbs/tree/yr), silver dollar eucalyptus (3.1 lbs/tree/yr), tulip tree (5 lbs/tree/yr), and black walnut (2.9 lbs/tree/yr). The sum of all inventoried tree emissions were over 5 tons, amounting to an environmental cost valued at $50,525; the combined total for all trees was approximately 8 tons, costing $82,152.

Table 14. Annual biogenic volatile organic compound (BVOC) emissions.

Species	BVOC (lb)	Avg. $/tree
coast redwood	571	-3.97
Chinese hackberry	1,056	-7.76
cork oak	2,646	-33.01
Chinese pistache	446	-5.92
crape myrtle	0	0.00
ornamental pear	0	0.00
London plane	172	-2.60
valley oak	163	-2.69
olive	0	0.00
Canary Island pine	179	-3.10
thornless honey locust	123	-2.81
Italian cypress	14	-0.35
Aleppo pine	138	-3.65
coast live oak	638	-19.66
magnolia	0	0.00
stone pine	138	-4.60
deodar cedar	111	-4.07
Chinese tallow	0	0.00
Chinese elm	85	-3.55
ginkgo	35	-1.52
Mondell pine	13	-0.63
flowering plum	0	0.00
silver dollar eucalyptus	291	-15.29
tulip tree	479	-25.17
zelkova	0	0.00
black walnut	269	-14.30
Other species	2,558	-4.61
Inventoried tree total	10,125	-5.61
Univentoried tree total	6,338	-5.61
Core campus total	16,463	-5.61

Deposition and Interception Result

Annual pollutant uptake by tree foliage (pollutant deposition and particulate interception) was 3 tons of combined uptake for inventoried trees and 4.8 tons for all campus trees, together. The total value of this benefit for all street trees was $101,287, or about $6.92 per tree (Table 15). Ozone uptake accounted for approximately 60% of the total benefit, while PM_{10} (29%) and NO_2 (8%), and SO_2 (3%) accounted for the remainder.

Net Air Quality Improvement

While the net weight of pollutants removed was negative due to high BVOC emission rates, the net value associated with ozone uptake made the net air quality savings produced by campus trees positive (Table 16). As a result, net annual air quality benefits for all campus trees were $30,163. Savings per tree averaged $2.06 on an annual basis.

Stormwater Runoff Reductions

The ability of UCD's trees to intercept rain was substantial, estimated at nearly 5 million gallons annually for all trees (Table 17); inventoried trees accounted for 62% of this amount. The total value of this benefit to the campus was $63,425 when all trees were considered. Average per tree values for inventoried trees ranged between less than $1 to over $12, averaging $4.33, based on an average interception of 341 gals annually.

When averaged throughout the tree population, certain species were much better at reducing stormwater runoff than others (Table 17). Leaf type and area, branching pattern and bark, as well as tree size and shape all affected the amount of precipitation trees can intercept and hold to avoid direct runoff. Broadleaf evergreens (e.g., cork oak and coast live oak) and conifers (e.g., Aleppo pine and stone pine) generally performed better than deciduous trees that have no leaves during the winter rainy period. Small deciduous trees—flowering plum, crape myrtle, and magnolia—provided negligible stormwater runoff reduction benefits to the campus.

Shelter and Aesthetic Benefits

The estimated total annual benefit associated with human shelter and aesthetic benefits was approximately $700,000, annually, or $48/tree on average (Table 18). As expected, this value was somewhat lower than similar analyses conducted in

Table 15. Annual pollutant uptake of UCD campus trees.

Species	Deposition O3 (lb)	Deposition PM10 (lb)	Deposition NO2 (lb)	Deposition SO2 (lb)	Total $	Avg. $/tree
coast redwood	36	19	5	2	664	0.93
Chinese hackberry	639	300	86	27	11,099	16.35
cork oak	605	309	87	30	10,886	27.22
Chinese pistache	147	68	20	6	2,548	6.78
crape myrtle	6	3	1	0	107	0.30
ornamental pear	75	38	10	3	1,335	3.95
London plane	32	17	4	1	581	1.76
valley oak	77	38	10	3	1,352	4.48
olive	87	51	12	4	1,631	5.42
Canary Island pine	19	10	3	1	350	1.21
thornless honey locust	108	51	14	4	1,872	8.59
Italian cypress	1	1	0	0	27	0.14
Aleppo pine	16	8	2	1	284	1.51
coast live oak	147	76	21	7	2,660	16.42
magnolia	17	8	2	1	307	1.97
stone pine	17	9	2	1	306	2.04
deodar cedar	7	4	1	0	129	0.95
Chinese tallow	79	39	11	3	1,391	11.22
Chinese elm	40	20	5	2	701	5.84
ginkgo	13	6	2	1	224	1.95
Mondell pine	1	1	0	0	26	0.26
flowering plum	14	6	2	1	240	2.50
silver dollar eucalyptus	68	37	10	3	1,243	13.09
tulip tree	14	8	2	1	255	2.68
zelkova	41	20	6	2	718	7.56
black walnut	190	85	25	8	3,253	34.61
Other species	1,026	501	142	46	18,106	6.54
Inventoried tree total	3,521	1,734	487	159	62,293	6.92
Univentoried tree total	2,204	1,085	305	100	38,994	6.92
Core campus total	5,726	2,819	792	259	101,287	6.92

Table 16. Net annual air pollutant benefit of UCD campus trees.

Species	Net Total (lb)	Total ($)	% of Total Tree Numbers	% of Total $	Avg. $/tree
coast redwood	- 507	- 2,104	8	- 11	- 2.93
Chinese hackberry	- 3	6,989	8	38	10.29
cork oak	- 1,613	- 1,118	4	- 6	- 2.79
Chinese pistache	- 204	587	4	3	1.56
crape myrtle	10	120	4	1	0.34
ornamental pear	127	1,483	4	8	4.39
London plane	- 117	- 208	4	- 1	- 0.63
valley oak	- 35	688	3	4	2.28
olive	155	1,841	3	10	6.12
Canary Island pine	- 146	- 501	3	- 3	- 1.73
thornless honey locust	56	1,464	2	8	6.72
Italian cypress	- 11	- 37	2	0	- 0.19
Aleppo pine	- 110	- 367	2	- 2	- 1.95
coast live oak	- 386	- 226	2	- 1	- 1.39
magnolia	29	339	2	2	2.17
stone pine	- 109	- 346	2	- 2	- 2.31
deodar cedar	- 98	- 408	2	- 2	- 3.00
Chinese tallow	132	1,544	1	8	12.45
Chinese elm	- 19	354	1	2	2.95
ginkgo	- 14	74	1	0	0.64
Mondell pine	- 10	- 34	1	0	- 0.34
flowering plum	23	265	1	1	2.76
silver dollar eucalyptus	- 173	- 63	1	0	- 0.67
tulip tree	- 455	- 2,104	1	- 11	- 22.14
zelkova	68	794	1	4	8.36
black walnut	39	2,231	1	12	23.73
Other species	- 839	7,294	31	39	2.63
Inventoried tree total	- 4,209	18,551	100	100	2.06
Univentoried tree total	- 2,634	11,612	100	100	2.06
Core campus total	- 6,843	30,163	100	100	2.06

Table 17. Annual stormwater reduction benefits of UCD campus trees.

Species	Total Rainfall Interception (gal)	Total ($)	% of Total Tree Numbers	% of Total $	Avg. $/tree
coast redwood	473,605	6,023	8	15.44	8.40
Chinese hackberry	264,727	3,367	8	8.63	4.96
cork oak	390,462	4,965	4	12.73	12.41
Chinese pistache	54,248	690	4	1.77	1.83
crape myrtle	2,879	37	4	0.09	0.10
ornamental pear	37,637	479	4	1.23	1.42
London plane	23,227	295	4	0.76	0.89
valley oak	38,804	493	3	1.27	1.63
olive	108,096	1,375	3	3.52	4.57
Canary Island pine	205,669	2,615	3	6.70	9.05
thornless honey locust	47,097	599	2	1.54	2.75
Italian cypress	15,495	197	2	0.51	1.01
Aleppo pine	154,970	1,971	2	5.05	10.48
coast live oak	112,135	1,426	2	3.66	8.80
magnolia	4,685	60	2	0.15	0.38
stone pine	151,793	1,930	2	4.95	12.87
deodar cedar	92,245	1,173	2	3.01	8.63
Chinese tallow	36,756	467	1	1.20	3.77
Chinese elm	22,089	281	1	0.72	2.34
ginkgo	6,186	79	1	0.20	0.68
Mondell pine	14,763	188	1	0.48	1.84
flowering plum	3,561	45	1	0.12	0.47
silver dollar eucalyptus	60,309	767	1	1.97	8.07
tulip tree	12,367	157	1	0.40	1.66
zelkova	17,126	218	1	0.56	2.29
black walnut	58,917	749	1	1.92	7.97
Other species	657,556	8,362	31	21.44	3.02
Inventoried tree total	3,067,401	39,008	100	100	4.33
Univentoried tree total	1,920,093	24,418	NA	NA	NA
Core campus total	4,987,494	63,425	NA	NA	NA

Table 18. Total annual increases in shelter and aesthetics benefits from UCD campus trees.

Species	Total ($)	% of Total Tree Numbers	% of Total $	Avg. $/tree
coast redwood	53,270	8	12	74.30
Chinese hackberry	35,702	8	8	52.58
cork oak	36,178	4	8	90.45
Chinese pistache	15,957	4	4	42.44
crape myrtle	1,816	4	0	5.12
ornamental pear	10,179	4	2	30.12
London plane	23,423	4	5	70.76
valley oak	22,709	3	5	75.19
olive	17,014	3	4	56.52
Canary Island pine	13,734	3	3	47.52
thornless honey locust	19,281	2	4	88.45
Italian cypress	5,730	2	1	29.23
Aleppo pine	8,741	2	2	46.49
coast live oak	10,499	2	2	64.81
magnolia	839	2	0	5.38
stone pine	6,763	2	2	45.09
deodar cedar	10,273	2	2	75.54
Chinese tallow	9,523	1	2	76.80
Chinese elm	8,385	1	2	69.87
ginkgo	5,903	1	1	51.33
Mondell pine	3,873	1	1	37.97
flowering plum	524	1	0	5.46
silver dollar eucalyptus	5,713	1	1	60.14
tulip tree	5,769	1	1	60.73
zelkova	5,722	1	1	60.23
black walnut	4,147	1	1	44.12
Other species	92,599	31	21	33.44
Inventoried tree total	434,268	100	100	48.26
Univentoried tree total	271,838	100	100	48.26
Core campus total	706,106	100	100	48.26

California communities where land use is dominated by high value single-family residential properties. For example, street trees in Santa Monica averaged $65/tree (McPherson and Simpson 2002) and San Francisco street trees averaged $70/tree (Maco et al. 2003). Several species produced a disproportional advantage with respect to shelter and aesthetic benefits on campus. For example, coast redwood represented 8% of the total inventoried tree population yet produced 12% of the total property value benefits. More dramatic was cork oak. Averaging over $90/tree/yr, this species produced 100% more benefit than numbers alone would suggest. In general, large, fast growing species produced the greatest benefit.

Total Annual Benefits

During the 2003 fiscal year, campus trees were estimated to produce benefits that totaled $920,000, with the 8,999 inventoried trees accounting for 62% of the total (Table 19). The net benefit per tree was $62.85. Assuming a campus population of 49,019 (UC Davis 2004b), trees were producing $18.76 in benefits for every student, faculty, and staff person.

Table 19. Annual benefit summary of UCD campus trees.

Benefit	Total ($)	$/capita	$/tree
Environmental			
Energy	65,078	1.33	7.23
CO2	8,674	0.18	0.96
Air Quality	18,551	0.38	2.06
Stormwater	39,008	0.80	4.33
Environmental Subtotal	131,311	2.68	14.59
Property Increase	434,268	8.86	48.26
Inventoried tree total	565,579	11.54	62.85
Univentoried tree total	354,034	7.22	62.85
Core campus total	919,613	18.76	62.85

Approximately one quarter of the annual benefits were attributed to environmental values. Of this, energy savings and stormwater interception—benefits that are locally realized—were 80% of this value, a substantial sum of about $7 and $4 per tree, respectively. Net air quality improvements accounted for approximately 14% ($2/tree) of the environmental total, while CO_2 benefits summed to 7% ($1/tree). Trees effects on human comfort, aesthetics, property values, and other intangible benefits accounted for about three quarters of total benefits ($48/tree), amounting to an annual value of over $700,000 when all trees were considered.

While species varied in their ability to produce benefits, common characteristics of trees within tree type classes aid in identifying the most beneficial campus trees (Figure 3). Comparatively, large trees produced the most benefits, but typical large broadleaf evergreens proved most beneficial: 18% more than a typical large deciduous, 31% more than a large conifer, and 40% more than a large palm. However, individual benefits did not always follow the same pattern. For example, air quality benefits were negative for large broadleaf evergreens, but $5.56 and $9.33 for large deciduous and palm trees, respectively, on a per tree basis. If a manager was interested in planting trees primarily for air quality improvement, low BVOC emitting species would be an important consideration. If stormwater mitigation was the primary concern, emphasis would be on planting large broadleaf evergreen or coniferous trees.

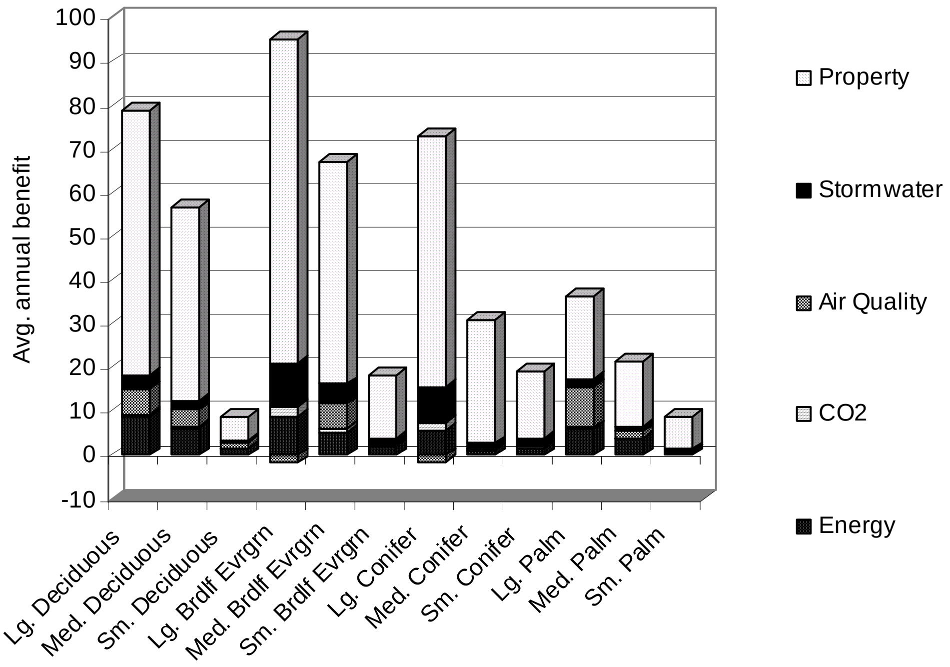


Figure 3. Average annual benefits per tree by tree types.

Chapter Five—Future Management

University of California
Davis Campus Tree Resource Analysis

Scott E. Maco, Qingfu Xiao, James R. Simpson, E. Gregory McPherson

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Trees are only one component of a functional campus ecosystem. On many campuses, they are the most important component, defining the values of the campus community, thereby providing a portal to the academic amenities offered. On other campuses, trees are treated with less concern than are common areas and sports fields. In any case, universities must seek to maintain a functional forest that is both healthy and safe. UC Davis, with a forested canopy area of 189 acres, has dedicated over a fifth of its total area to trees—there is no doubt that trees are valued as an integral component of the campus.

UC Davis trees reflect the values, lifestyles, preferences, and aspirations of the academic community. It is a dynamic legacy; on one-hand dominated by trees planted early in the university's history and at the same time constantly changing as new trees are planted and others mature. Although this study provides a "snapshot" in time of the resource, it also serves as an opportunity to speculate about the future. Given the status of the tree canopy cover, what future trends are likely, what management challenges will arise, and how can net benefits be increased and sustained?

Achieving resource sustainability will produce long-term net benefits to the university's area of influence while reducing the associated costs incurred with managing the resource. Structural features of a sustainable campus tree population include adequate complexity (species and age diversity), well-adapted healthy trees, appropriate tree numbers, and strategic management into the future.

Resource Complexity

With only coast redwood and Chinese hackberry showing dominance in numbers, species diversity appeared adequate when considering only inventoried trees. But planting for population stability requires more than simply planting "other trees" to diversify the population. Figure 4 displays new tree planting trends. Some of these species (e.g., ornamental pear, Chinese pistache) have not proven to be well adapted or to have the longevity needed to produce long-term benefits the campus depends on. Other species will not attain the large stature that is needed to provide functional benefits (e.g., crape myrtle, Italian cypress). Moreover, there is danger of overplanting crape myrtle, London plane, and Chinese pistache.

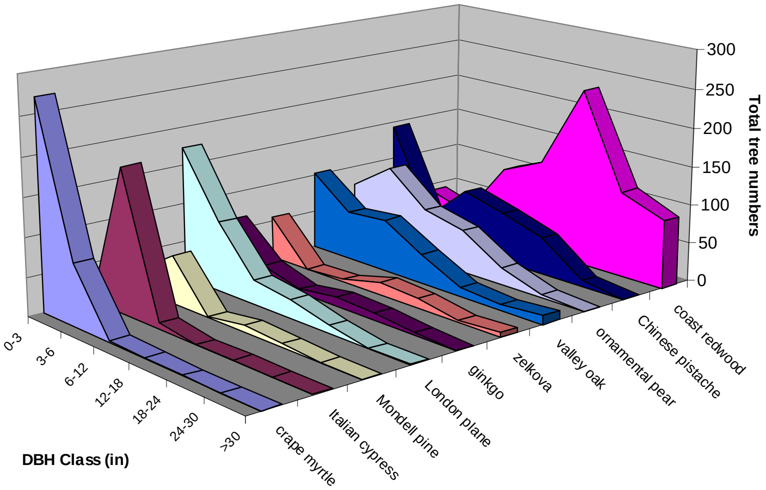

Figure 1. Trees currently planted in the largest numbers on UCD campus.

Relying too heavily on these three species may result in future catastrophic loss if pest, disease, or drought were to strike.

Figure 5 shows that large, long-lived tree species were those that reach functional age. Substantial tree numbers in large DBH classes indicate adaptability amongst these trees. Of all species displayed, only coast redwood is currently being planted in significant numbers. The shift towards the unproven and short-lived species displayed in Figure 4 has the potential to reduce the future level of benefits provided by campus trees, as the large, functional trees in Figure 5. provide the bulk of all benefits.

However, simply reverting back to planting the established species in Figure 5 is not necessarily the answer. Presumably most of these species are not planted because they require intensive management or are prone to disease. However, evaluation of species relative performance can help managers decide which species to invest in new plantings.

Recent pruning and tree age may be factors, but tree health is likely to be an overriding indicator of selecting well-adapted and appropriate trees. Table 20 displays relative performance index (RPI) values of significant campus species based on the proportion of each tree classified as "healthy" or "unhealthy."

An RPI value of '1' indicates those species that typified campus-wide tree health, having approximately 85% of its constituents in "healthy" condition. Any value higher than '1' indicated species that had proportionately more individuals classified as 'healthy'. Likewise, index values below '1' were species with below average health ratings when compared with all other campus trees.

Species that are representative of large, mature trees should be considered for review. While these species may persist, they do not necessarily age gracefully. For example, coast redwood, cork oak, coast live oak, and stone pine appear to be good planting choices because they are trees proven to attain large-stature and remain relatively healthy throughout there long lives. On the other hand, Chinese hackberry, black walnut, and Aleppo pine are aging with lower than average health ratings when compared to all species.

Most newly outplanted tree species have RPI values that appear to be inline with the campus average—they will likely age without significant health issues. However, the RPI can be used to identify species with health problems early on. For example, ginkgo, crape myrtle, and valley oak are all currently being planted in high numbers, while at the same time underperforming in their health ratings. Because there are few mature specimens on campus with which to compare, managers should scrutinize the idea of planting large numbers of these species before

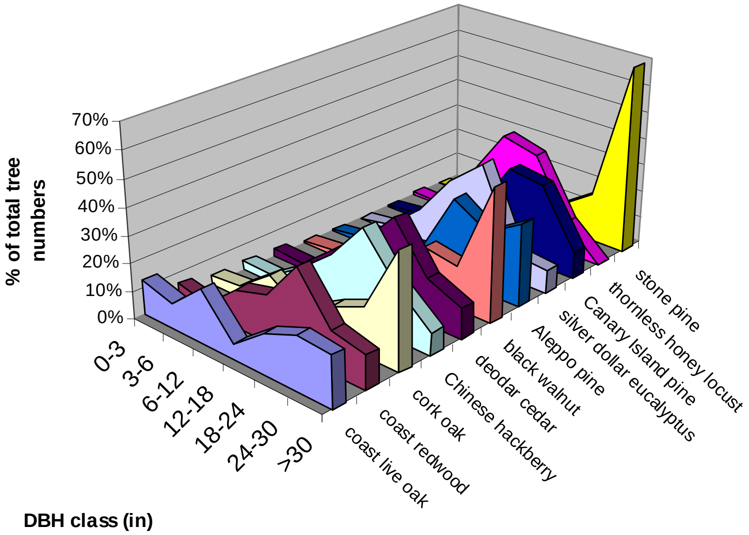

Figure 5. Age distribution of established UC Davis trees. These species produce the largest average annual benefits on a per tree basis and the bulk of all benefits afforded the campus.

Table 20. Relative performance index for significant UCD campus tree species.

Species	RPI	Species	RPI
Chinese hackberry	0.93	black walnut	0.94
cork oak	1.15	Aleppo pine	0.70
Chinese pistache	1.02	southern magnolia	1.15
London plane	1.03	shamel ash	1.07
coast redwood	1.06	Japanese black pine	0.83
ornamental pear	1.05	golden rain tree	1.12
valley oak	0.90	little-leaf linden	1.08
crape myrtle	0.93	ginkgo	0.92
olive	0.98	peach	1.14
thornless honey locust	1.03	white mulberry	1.18
Canary Island pine	1.04	American elm	1.18
coast live oak	1.13	incense cedar	1.14
Chinese tallow	1.06	African sumac	1.18
crabapple	1.08	raywood ash	0.63
deodar cedar	1.05	Japanese pagoda	1.14
stone pine	1.15	evergreen pear	1.18
Mondell pine	1.01	Japanese flowering cherry	1.13
flowering plum	1.10	Western redbud	0.99
Chinese elm	0.94	edible apple species	1.18
tulip tree	0.81	basket oak	1.13
zelkova	1.06	liquidambar	0.49
glossy privet	0.85	all trees	1.00

the are proven to be a good choice in the long-term. The combination of examining species presently providing high levels of benefits and evaluating RPI values and relative age suggests that several species appeared to be well-adapted, long-lived, and have the potential to provide reasonable levels of benefits: cork oak, honey locust, deodar cedar, coast live oak, zelkova, stone pine, and Canary Island pine. Increasing numbers of species with these characteristics will provide the foundation for increased benefits and reduced costs into the future.

At the same time, managers should begin to systematically evaluate the performance of new introductions. New introductions should comprise 5-10% of the total number of trees planted each year. Testing will identify the tree species that are best adapted to local conditions. After 5-10 year trials, the best performers can be planted in larger numbers to increase overall complexity, and thereby promoting a more stable campus canopy cover.

Resource Extent

Canopy cover, or more precisely the amount and distribution of leaf surface area, is the driving force behind the tree resource's ability to produce benefits for the campus and beyond. As canopy cover increases, so too do the benefits afforded by leaf area. It is important to remember, however, that trees represent only 58% of campus vegetation cover. In other words, the benefits the campus community realizes from all vegetation is far greater than the values found through this analysis. But due to their location and prominence, trees are typically the most expensive component to manage. Maximizing the return on this investment is contingent upon maximizing and maintaining the canopy cover of these trees.

Planting Potential

Increasing the tree canopy cover requires a multifaceted approach at UC Davis. Plantable spaces must be filled and use of large stature trees must be encouraged wherever feasible. There are 4,092 available tree-planting spaces on the core campus; approximately 54%, 43%, and 3% of these sites could be filled with large-, medium-, and small-stature trees, respectively. Excluding palms, the average large tree provided $81.08/year in benefits—medium trees averaged $51.55 and small trees averaged only $15.20, annually. Given these data, planting all identified potential sites could increase annual benefits by $271,476, a substantial sum.

Tracking Canopy Cover Change

This analysis has found existing tree canopy covers 21% of the campus and there is potential to increase this cover by an additional 9% to 30% if all available planting sites were filled. Is it realistic to achieve this level of canopy cover given conflicts between trees, underground utilities, and other infrastructure? When thinking about setting canopy cover targets and tracking canopy cover change over the long-term a number of factors need to be considered. These factors form an equation that provides a conceptual basis for planning and monitoring campus canopy cover:

$$CT = CB + CN + CG - CM \qquad \text{(Equation 4)}$$

where,

CT = total canopy cover

CB = existing, or base canopy cover

CN = increase from new tree planting

CG = growth of the existing canopy

CM = mortality or loss of canopy cover

Existing canopy cover (CB) could be established based on data from this analysis. Though in the future, CB will change when periodic monitoring finds that canopy cover has increased or decreased from the previous base value. CT becomes CB for the subsequent analysis.

Increase in canopy cover from new tree planting (CN) can be tracked annually through planting records. A continuously updated tree inventory would include these trees. If GPS coordinates were collected as an inventory field, the locations of new plantings could be added to the GIS layers in this analysis to track their spatial distribution.

Growth of the existing canopy (CG) can be modeled using the same species-specific growth curves utilized in this study. However, a better approach is to develop empirical relations that predict growth based on measurements for trees of different species, size, and site conditions on campus. For example, canopy cover from a random sample of trees could be measured from the years 1995 and 2003 campus imagery to calculate average annual growth. Tree inventory data would facilitate detailed analysis of relations between growth and tree species, size class, and site (e.g., turf, parking lot, plaza, streetside). These data would make it possible to reliably predict future CG for primary species at selected times in the future.

CM is mortality or loss of canopy cover. Management can influence mortality through more intensive care of over-mature trees, improved establishment of transplants, better protection for young trees, and more proactive pest/disease monitoring. However, to some extent, mortality is unpredictable and uncontrollable, such as with vandalism, lightening, new building/road construction, and the inevitable loss of senescent trees. Tracking CM can be accomplished through analysis of tree removal records, updating of the tree inventory when removals occur, and via imagery analysis.

Utilizing the above equation, a continued monitoring analysis could identify the average annual amount of canopy removal, average annual canopy gain, how mortality is distributed among different tree species and size classes, which parts of campus are losing or gaining canopy most rapidly, and primary reasons for tree removal. The data contained within this report establishes a baseline for this work. With this information, strategic approaches to achieving the desired level of canopy cover could be implemented on campus.

Suggested Future Research

1. Develop a “forest simulator” program that will grow the existing campus tree canopy based on an analysis of planting and mortality rates and growth of existing trees. Using imagery from 1995 and 2003, tree growth can be measured and relations established between tree canopy growth and species, size, and site. The forest simulator program would use these data, along with assumed planting and mortality rates. Output would show how canopy cover is likely to expand and decrease at 5-year intervals for a 50-year planning period. This innovative technology will make it possible to set realistic canopy cover targets, calculate future benefits, identify management needs, and estimate budget requirements.

2. Begin tracking and reporting canopy cover change. On an annual basis:

    a. Compile a record of trees planted and enter these into the Campus Tree Inventory.

    b. Compile a record of trees removed and enter these into the inventory. Additional data on reason for removal would be valuable.

    c. Estimate canopy growth for existing trees based on the analysis proposed above.

3. Every five years, obtain aerial imagery and perform a geospatial canopy cover analysis to provide a new benchmark, calibrate the estimates of tree growth, establish new canopy cover targets, update the management plan, and identify budget needs.

Chapter Six—Conclusion

University of California
Davis Campus Tree Resource Analysis

Scott E. Maco, Qingfu Xiao, James R. Simpson, E. Gregory McPherson

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This analysis described structural characteristics of the campus tree population and used tree growth data to assess the benefits trees afford the campus community. In addition, future management and research priorities are identified. Our approach is based on new research and established statistical methods, with the intent of providing baseline data for canopy cover management and a general accounting of the benefits produced by campus trees. This report highlights the value of the campus tree resource, and provides a first step towards developing a long-term management and monitoring program.

Trees cover 21% of the core campus and provide approximately $920,000 in annual benefits. Shelter and aesthetic benefits are most pronounced, but environmental benefits are also significant; especially energy savings, stormwater control, greenhouse gas reductions, and air quality improvement.

UC Davis campus trees are a dynamic resource. Managers of this resource and the academic community alike can delight in knowing that trees improve the quality of campus life, but they are also faced with a fragile resource that needs constant care to maximize and sustain these benefits through the foreseeable future. On a campus where growth pressures are high, this is no easy task. The challenge ahead is to better integrate the green infrastructure with the gray infrastructure. This means providing adequate space for trees up-front, and designing plantings to maximize net benefits over the long-term, thereby perpetuating a resource that is both functional and sustainable.

This analysis has provided the information necessary for resource managers to weigh the greater needs of campus management with the more specific needs of campus trees. The structural indices outlined above—canopy extent, diversity index, importance values, health classification, age distribution tables, etc.—along with benefit data, provide the requisite information for short- and long-term resource management.

Finally, this document is intended to act as a baseline for future research and monitoring. In contracting this analysis, UC Davis has shown its desire to leave a legacy of tree stewardship that will benefit the future, and to develop a model program that will be emulated by other institutions.

Chapter Seven—References

University of California Davis Campus Tree Resource Analysis

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Appendix A:

Electronic Inventory and GIS Guide

(See attached DVD)

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