CUFR Tree Carbon Calculator - Help Menu

Developed by the Center for Urban Forest Research Pacific
Southwest Research Station
US Forest Service

In partnership with the California Department of Forestry and Fire Protection

Contents

Address questions not answered in what follows, including Frequently Asked Questions, to **psw_cufr@fs.fed.us**

1. Introduction

This Annex describes how to use the CUFR Tree Carbon Calculator (CTCC) to estimate the amount of biomass and carbon stored in a tree, as well as the amount sequestered annually. The CTCC provides information on the effects of tree shade on residential heating and cooling energy use for energy conservation trees. Portions of the CTCC are common to both the carbon storage and energy conservation projects; the latter has additional data and output requirements, which are denoted with "§" in the text that follows. Final sections describe the methods used to determine effects of trees on heating and cooling and potential areas of uncertainty.

The CTCC is intended as "proof of concept" software that is in the testing phase. It is provided "as is" without warranty of any kind. It returns results for a single tree at a time, requiring that project totals be determined external to the calculator.

A note on units: Carbon reporting currently uses a hybrid of SI and English units, for example kg/MBtu and kg/gal (ARB 2007). The CTCC follows a similar convention. The most common unit for tree dbh (diameter at breast height, 4.5 ft) measurement is inches, which is used in the CTCC, while outputs are given in kilograms.

2. Background

The CTCC is programmed in an Excel spreadsheet. It is designed to provide carbon-related information for a single tree located in one of six California climate zones. The user must enter information on the size or age of the tree and species for carbon storage. Additional inputs are required for an energy conservation project. CTCC outputs can be used to estimate GHG benefits for existing trees or to forecast future benefits.

Tree size data are based on growth curves developed from samples of about 900 street trees representing approximately 20 predominant species in each of the six regional reference cities. Biomass equations and calculations used in the CTCC to derive total CO_2 stored, total stored aboveground, and annual CO_2 sequestered are described in **Section 4** below. To determine effects of tree shade on building energy performance, over 12,000 simulations were conducted for each reference city using different combinations of tree sizes, locations, and building vintages. More detailed information on procedures can be found in each region's Community Tree Guide (McPherson et al. 1999, 2000, 2003, 2004).

Users should recognize that conditions vary within regions, and data from the CTCC may not accurately reflect their rate of tree growth, microclimate, or building characteristics. When conditions are different it may be necessary to apply biomass equations manually using adjusted tree growth data and perform building energy simulations with modified weather and tree data to more accurately depict effects of trees on GHGs.

3. CTCC Step-by-Step Instructions

Start the CTCC by opening the 'CarbonCalculatorNN.xls' workbook. The associated files for each region ('XXX carbon-biomass.xls' and 'XXXSim.xls') must be located in the same folder and will load automatically. "NN" refers to the revision number (18 as of 1 June 2008).

3.1. Collecting and Entering Initial Project Data

Certain data apply to a GHG tree project as a whole. These data are entered into shaded areas in [CarbonCalculator]CTCC (**Figure 1**).

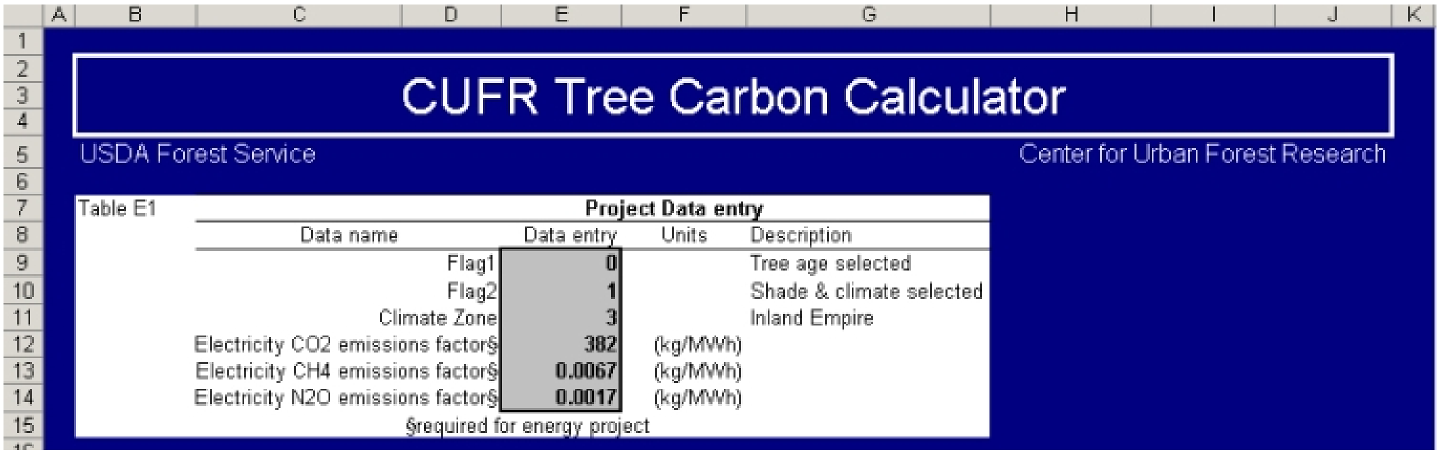


Figure 1. Project-related data entry section of CTCC. Shaded area are cells for data input. §required for energy project

The rows in the CTCC data entry section represent the following:

Flag1: *Age or DBH*. For new projects in which GHG benefits are being predicted into the future, age data should be used. For existing projects where trees have been measured, dbh data should be used. Refer to Appendix B for detailed instructions for measuring dbh. Enter 0 to use tree age input and 1 to use dbh input.

Flag2: The CTCC can calculate the energy benefits based solely on shade or general climate benefits of trees can be included (i.e., lower summer air temperatures, reduced wind speeds). Shade benefits can be calculated with more accuracy than climate benefits. Climate benefits are associated with planting large numbers of trees in the same area so that their aggregate effect is measurable. Shade benefits are minimal for trees located more than 60-ft from buildings. Enter 0 to calculate shade benefits only. Enter 1 to calculate shade and climate benefits.

Climate zone: Identify which of 6 California regions applies to your project (**Figure 2**). Region boundaries are approximate, and the climate of cities within each region can differ considerably. Match Cooling Degree Days and Heating Degree Days for the project location with those in **Table 1** if in doubt. Selecting the appropriate region is important because site climate influences space heating and cooling requirements and potential energy savings from trees.

Figure 2. California climate zones.

Table 1. California regions for CUFR Tree Carbon Calculator.

Climate Region	Reference City	CDD[1]	HDD[2]
North and Central Coast	Berkeley	142	2862
South Coast	Santa Monica	679	1274
Inland Empire	Claremont	1863	1475
Central Valley	Modesto	1248	2666
Desert	Glendale, AZ	4364	1027
Mountains	Fort Collins, CO	696	6128

[1]CDD=Cooling Degree Days
[2]HDD=Heating Degree Days
Western Regional Climate Center 1971-2000 normals, 65°F baseline

Emissions factors: For energy conservation projects only, assign utility-specific emission factors for carbon dioxide, methane, and nitrous oxide for cooling (electricity). Electricity emissions factors differ regionally because of utility-specific differences in the mix of fuels used to generate electricity. Contact your local electricity supplier to obtain the most accurate values for your location. Alternatively, electricity emissions factors for California's major utilities are listed in **Table 2** and utility service areas shown in **Fig. 3.** Emission factors for space heating will differ depending on heating fuel type used in each building, hence are entered in the building data section that follows.

Table 2a. Electricity emissions factors (California Air Resources Board 2007).

	Electrical Generation

Utility	Average Emissions Factor (kg/MWh)		
	CO_2	Methane	Nitrous Oxide
LADWP	727	0.0030	0.0017
SCE	483	0.0030	0.0017
SDG&E	511	0.0030	0.0017
PG&E	241[a]	0.0030	0.0017
California	395[a,b]	0.0030	0.0017

[a] results for PG&E include Sacramento Municipal Utility District (SMUD)
[b] includes irrigation districts and municipal utilities

Table 2b. Natural gas emissions factors (California Air Resources Board 2007).

Utility	Natural Gas Heating Emissions Factor (kg/MBtu)			Fuel Oil Heating Emissions Factor (kg/MBtu)		
	CO_2	Methane	Nitrous Oxide	CO_2	Methane	Nitrous Oxide
LADWP	53.1	0.0059	0.00010	73	0.0014	0.00010
SCE	53.1	0.0059	0.00010	73	0.0014	0.00010
SDG&E	53.1	0.0059	0.00010	73	0.0014	0.00010
PG&E	53.1	0.0059	0.00010	73	0.0014	0.00010
California	53.1	0.0059	0.00010	73	0.0014	0.00010

Greenhouse gases covered by California's Global Warming Solutions Act (AB32) are carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Since the latter three account for only about 1.5% of total greenhouse gas emissions in the United States (EIA 2007) and represent over 25 different gases, they are excluded from the current analysis. Methane and nitrous oxide emissions are multiplied by their respective GWPs (**Table 3**) to obtain the equivalent CO2 emissions.

Table 3. 100-year global warming potential (GWP) estimates of greenhouse gases (EIA 2007)

Gas	GWP
Carbon Dioxide	1
Methane	23
Nitrous Oxide	296

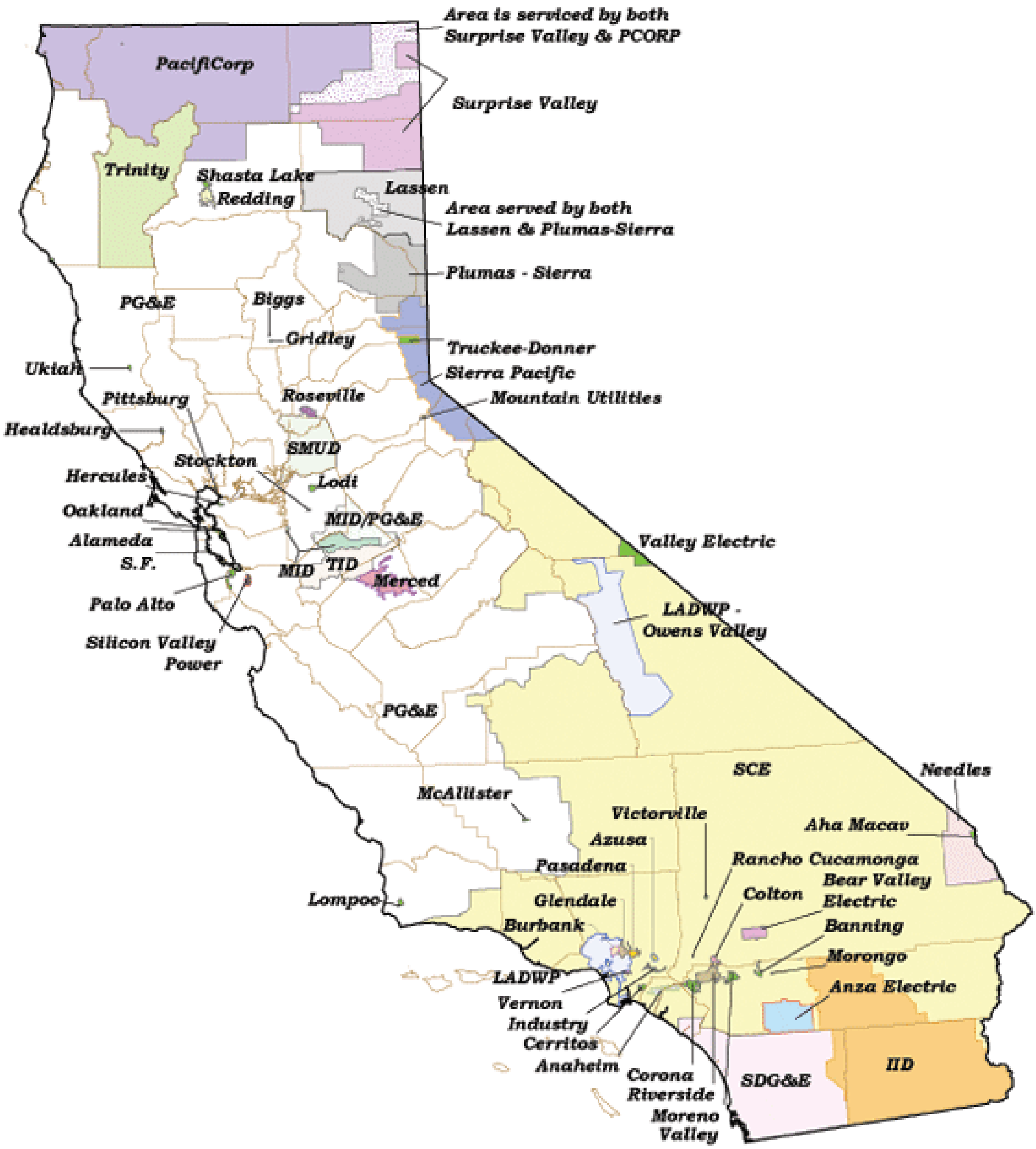


Figure 3. California electric utility service areas (CEC 2007). IID Imperial Irrigation District, LADWP Los Angeles Dept. of Water and Power, MID Modesto Irrigation District, PG&E Pacific Gas & Electric, SCE Southern California Edison, SDG&E San Diego Gas & Electric, SMUD Sacramento Municipal Utility District, SPP Sierra-Pacific Power, TID Turlock Irrigation District

3.2. Collecting Initial Tree Data

Data on individual trees are entered into the CTCC next. As the CTCC currently functions, trees must be entered one at a time and the results recorded by hand. To keep track of initial input data, we recommend the use of spreadsheet such as shown below (included in worksheet [CarbonCalculatorNN]Data Template) (**Fig. 4**).

Tree ID	Species code	Dbh (in) or Age	Condition	§Azimuth	§Distance	§Trees/ building	§Vintage	§AC equipment	§Heating equipment	§Energy	Heating emissions factor CO2§	Heating emissions factor CH4§	Heating emissions factor N2O§
Tree and Building Data													
1	BRPO	10	alive	7	2	0	3	1	1	yes	53.1	0.0059	0.0001
2	CICA	40	alive	3	1	1	1	1	1	yes	53.1	0.0059	0.0001
3	CICA	40	alive	3	1	0	1	0	0	yes	0	0	0
4	CICA	40	alive	3	1	1	1	0	1	yes	53.1	0.0059	0.0001
5	CICA	40	alive	3	1	1	1	1	4	yes	73	0.0059	0.0001
6													

Figure 4. Example template for compiling tree- and building-related data. § indicates fields for energy projects only

The columns represent the following:

TreeID: This is a unique number assigned to each tree for use as individual tree identification. IDs from an existing tree inventory may be used.

Species Code: This is a 2 to 6 character code consisting of the first two letters of the genus name and the first two letters of the species name followed by two optional numbers to distinguish two species with the same four-letter code (USDA National Plants Database). The complete lists of species for the 6 climate zones are included below.

There are 20-30 species in each climate zone. If you want to calculate carbon and energy results for a species not included in the list, choose the species from the same climate zone with the most similar mature size and growth rate.

Climate Zone 1 - North/Central Coast			Climate Zone 2 - South Coast		
Sp Code	**Botanic Name**	**Common Name**	**Sp Code**	**Botanic Name**	**Common Name**
ACME	*Acacia melanoxylon*	Black acacia	CACI	*Callistemon citrinus*	Lemon bottlebrush
ACPA	*Acer palmatum*	Japanese maple	CEDE	*Cedrus deodara*	Deodar cedar
CICA	*Cinnamomum camphora*	Camphor tree	CESI3	*Ceratonia siliqua*	Carob
EUGL	*Eucalyptus globulus*	Blue gum eucalyptus	CICA	*Cinnamomum camphora*	Camphor tree
FRVE	*Fraxinus velutina*	Velvet ash	CUAN	*Cupaniopsis anacardioides*	Carrotwood
GIBI	*Ginkgo biloba*	Ginkgo	EUFI81	*Eucalyptus ficifolia*	Redflower gum
LIST	*Liquidambar styraciflua*	Sweetgum	FIBE	*Ficus benjamina*	Benjamin fig
LITU	*Liriodendron tulipifera*	Tulip tree	JAMI	*Jacaranda mimosifolia*	Jacaranda
MAGR	*Magnolia grandiflora*	Southern magnolia	LIST	*Liquidambar styraciflua*	Sweetgum
PIBR2	*Pinus brutia*	Turkish pine; East Mediterranean pine	MAGR	*Magnolia grandiflora*	Southern magnolia
PICH	*Pistacia chinensis*	Chinese pistache	MEQU	*Melaleuca quinquenervia*	Cajeput tree
PICO5	*Pinus contorta var. bolanderi*	Bolander beach pine	MEEX	*Metrosideros excelsius*	New Zealand Christmas tree
PIRA	*Pinus radiata*	Monterey pine	PIBR2	*Pinus brutia*	Turkish pine; East Mediterranean pine
PIUN	*Pittosporum undulatum*	Victorian box	PICA	*Pinus canariensis*	Canary Island pine
PLAC	*Platanus hybrida*	London planetree	PICO5	*Pinus contorta var. bolanderi*	Bolander beach pine
PRCE	*Prunus cerasifera*	Cherry plum	PIUN	*Pittosporum undulatum*	Victorian box
PYCA	*Pyrus calleryana*	Callery pear	PLAC	*Platanus X acerifolia*	London plane

PYKA	*Pyrus kawakamii*	Evergreen pear	POMA	*Podocarpus macrophyllus*	Yew podocarpus
QUAG	*Quercus agrifolia*	Coast live oak	SCTE	*Schinus terebinthifolius*	Brazilian pepper
ROPS	*Robinia pseudoacacia*	Black locust	TRCO	*Tristaniopsis conferta*	Brisbane box
SESE	*Sequoia sempervirens*	Coast redwood			
ULAM	*Ulmus americana*	American elm			
ULPA	*Ulmus parvifolia*	Chinese elm			

Climate Zone 3 - Inland Empire			**Climate Zone 4 - Central Valley**		
Sp Code	**Botanic Name**	**Common Name**	**Sp Code**	**Botanic Name**	**Common Name**
BRPO	*Brachychiton populneus*	Bottle tree	ACSA1	*Acer saccharinum*	Silver maple
CICA	*Cinnamomum camphora*	Camphor tree	BEPE	*Betula pendula*	European white birch
EUSI	*Eucalyptus sideroxylon*	Red ironbark	CESI4	*Celtis sinensis*	Chinese hackberry
FRUH	*Fraxinus uhdei*	Shamel ash	CICA	*Cinnamomum camphora*	Camphor tree
FRVE	*Fraxinus velutina 'Modesto'*	Modesto ash	FREX_H	*Fraxinus excelsior 'Hessei'*	Hesse ash
GIBI	*Ginkgo biloba*	Ginkgo	FRHO	*Fraxinus holotricha*	Moraine ash
JAMI	*Jacaranda mimosifolia*	Jacaranda	FRAN_R	*Fraxinus angustifolia 'Raywood'*	Raywood ash
LAIN	*Lagerstroemia indica*	Common crapemyrtle	FRPE_M	*Fraxinus pennsylvanica 'Marshall'*	Marshall ash
LIST	*Liquidambar styraciflua*	Sweetgum	FRVE	*Fraxinus velutina 'Modesto'*	Modesto ash
LITU	*Liriodendron tulipifera*	Tulip tree	GIBI	*Ginkgo biloba*	Ginkgo
MAGR	*Magnolia grandiflora*	Southern magnolia	GLTR	*Gleditsia triacanthos*	Honeylocust
PIBR2	*Pinus brutia*	Turkish pine; East Mediterranean pine	KOPA	*Koelreuteria paniculata*	Goldenrain tree
PICA	*Pinus canariensis*	Canary Island pine	LAIN	*Lagerstroemia indica*	Common crapemyrtle
PICH	*Pistacia chinensis*	Chinese pistache	LIST	*Liquidambar styraciflua*	Sweetgum
PICO5	*Pinus contorta var. bolanderi*	Bolander beach pine	MAGR	*Magnolia grandiflora*	Southern magnolia
PLAC	*Platanus X acerifolia*	London plane	PIBR2	*Pinus brutia*	Turkish pine; East Mediterranean pine
PLRA	*Platanus racemosa*	California sycamore	PICH	*Pistacia chinensis*	Chinese pistache
PYCA	*Pyrus calleryana*	Callery pear	PICO5	*Pinus contorta var. bolanderi*	Bolander beach pine
QUAG	*Quercus agrifolia*	Coast live oak	PIRA	*Pinus radiata*	Monterey pine
QUIL2	*Quercus ilex*	Holly oak	PITH	*Pinus thunbergiana*	Japanese black pine
SCMO	*Schinus molle*	California pepper tree	PLAC	*Platanus hybrida*	London planetree
SCTE	*Schinus terebinthifolius*	Brazilian pepper tree	PYCA_B	*Pyrus calleryana 'Bradford'*	Callery pear 'Bradford'
			PYKA	*Pyrus kawakamii*	Evergreen pear
			QUIL2	*Quercus ilex*	Roble negro
			ZESE	*Zelkova serrata*	Japanese zelkova

Climate Zone 5 - Desert			**Climate Zone 6 - Mountains**		
Sp Code	**Botanic Name**	**Common Name**	**Sp Code**	**Botanic Name**	**Common Name**
ACFA	*Acacia farnesiana*	Sweet acacia	ACPL	*Acer platanoides*	Norway maple
ACSA3	*Acacia salicina*	Willow acacia	ACSA1	*Acer saccharinum*	Silver maple
BRPO	*Brachychiton*	Bottle tree	ACSA2	*Acer saccharum*	Sugar maple

	populneus				
CEFL	*Cercidium floridum*	Blue palo verde	CEOC	*Celtis occidentalis*	Northern hackberry
CHLI	*Chilopsis linearis*	Desert willow	FRAM	*Fraxinus americana*	White ash
EUMI2	*Eucalyptus microtheca*	Coolibah gum	FRPE	*Fraxinus pennsylvanica*	Green ash
FRUH	*Fraxinus uhdei*	Evergreen ash	GLTR	*Gleditsia triacanthos*	Honeylocust
FRVE	*Fraxinus velutina*	Velvet ash	GYDI	*Gymnocladus dioica*	Kentucky coffee tree
MOAL	*Morus alba*	White mulberry	ILOP	*Ilex opaca*	American holly
OLEU	*Olea europaea*	Olive	MAGR	*Magnolia grandiflora*	Southern magnolia
PAAC	*Parkinsonia aculeata*	Jerusalem thorn	MA2	*Malus sp.*	Apple
PIBR2	*Pinus brutia*	Turkish pine; East Mediterranean pine	PICO5	*Pinus contorta var. bolanderi*	Bolander beach pine
PICH	*Pistacia chinensis*	Chinese pistache	PINI	*Pinus nigra*	Austrian pine
PICO5	*Pinus contorta var. bolanderi*	Bolander beach pine	PIPO	*Pinus ponderosa*	Ponderosa pine
PIEL2	*Pinus eldarica*	Afghan pine	PIPU	*Picea pungens*	Blue spruce
PIHA	*Pinus halepensis*	Aleppo pine	POSA	*Populus sargentii*	Plains cottonwood
PRCH	*Prosopis chilensis*	Chilean mesquite	PR	*Prunus species*	Plum
QUVI	*Quercus virginiana*	Live oak	PY	*Pyrus species*	Pear
RHLA	*Rhus lancea*	African sumac	QUMA1	*Quercus macrocarpa*	Bur oak
ULPA	*Ulmus parvifolia*	Chinese elm	QUNI	*Quercus nigra*	Water oak
			TIAM	*Tilia americana*	American basswood
			TICO	*Tilia cordata*	Littleleaf linden
			ULAM	*Ulmus americana*	American elm
			ULPU	*Ulmus pumila*	Siberian elm

Age or DBH: For projects that are projecting GHG benefits into the future, age data should be used. For projects where trees have been measured, dbh data should be used. DBH is the diameter-at-breast height of the trunk of the tree measured 4.5 ft (1.4m) above the ground. If trees are multiple-stemmed or on a slope, consult **Appendix B** for detailed instructions of proper measurement techniques.

Condition: Record whether tree is dead or alive. The carbon stored in dead trees is eligible to be reported or to be used for wood products or bioenergy projects. Only live trees, however, are eligible for energy conservation projects.

Azimuth: For energy conservation projects, record the compass bearing or azimuth of the tree from the nearest building. Azimuth is taken with a compass, as in **Figure 5**, the coordinate of tree taken from imaginary lines extending from walls of the nearest conditioned space (heated or air-conditioned space—may not be same address as tree location):

1: N = North (337.5-22.5°)
2: NE = Northeast (22.5-67.5°)
3: E = East (67.5-112.5°)
4: SE = Southeast (112.5-157.5°)
5: S = South (157.5-202.5°)
6: SW = Southwest (202.5-247.5°)
7: W = West (247.5-292.5°)
8: NW = Northwest (292.5-337.5°)
9: NA = No building for reference (>18 m setback)

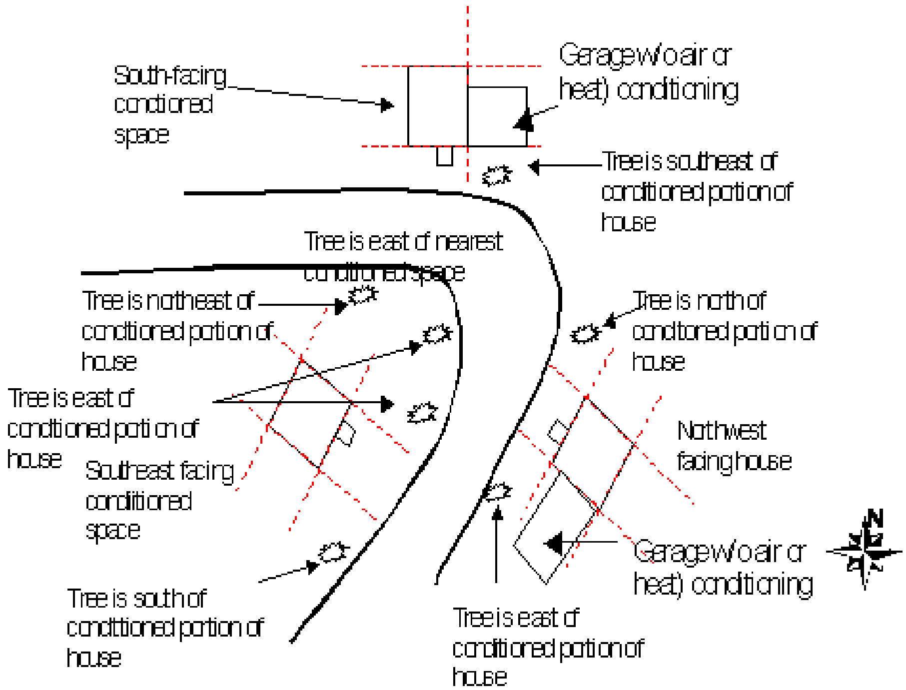


Figure 5. How orientation from tree to building should be measured. Shows imaginary lines extending from walls and associated tree orientation.

Distance: For energy conservation projects, record distance from tree to nearest air-conditioned/heated space. Evaluate as:

1: 0-8 m (0-25 ft, or 'adjacent')
2: 8.1-12 m (25.1-40 ft, or 'near')
3: 12.1-18 m (40.1-60 ft, or 'far')
4: >18 m (>60 ft)

Trees/building: For energy conservation projects, record the presence of existing trees within 18 m (60 ft) of the building. Count only trees greater than 12 m (40 ft) tall, or capable of growing to this size, located within 18 m (60 ft) of the east-, south-, or west-facing walls. Existing trees includes project trees that have already been added to the data base. If such a tree already exists around a property, the building is considered "shaded" and additional project trees will not be considered to have an energy benefit. Only their carbon storage benefit can be considered.

Vintage: For energy conservation projects, assign the correct vintage to each eligible residential building. A vintage consists of buildings of similar age, construction type, floor area, and energy efficiency characteristics. Detailed information on each vintage is listed in below in **Section 4.** Although the exact characteristics of each vintage change regionally, the names remain constant and general distinguishing features are:

1: Pre-1950 vintage - low insulation levels, small conditioned floor area (CFA), large window area:CFA ratios,
2: 1950-1980 vintage - more ceiling insulation, lower window area:CFA ratios
3: Post-1980 vintage - more wall insulation, more CFA, lower window area:CFA ratios

AC Equipment: For energy conservation projects, identify the type of air conditioning equipment in the building nearest to the tree. Choices for air conditioning equipment are

0: None
1: Central air/heat pump
2: Evaporative cooler
3: Wall/window unit

Heating Equipment: For energy conservation projects, identify the type of heating equipment in the building nearest to the tree. Choices for heating equipment are:

0: None
1: Natural gas
2: Oil/other fossil
3: Electric resistance (not currently implemented)

4: Heat pump

Energy: Based on the condition of the tree and the presence of additional existing trees, determine whether the tree qualifies as eligible for an energy conservation project.

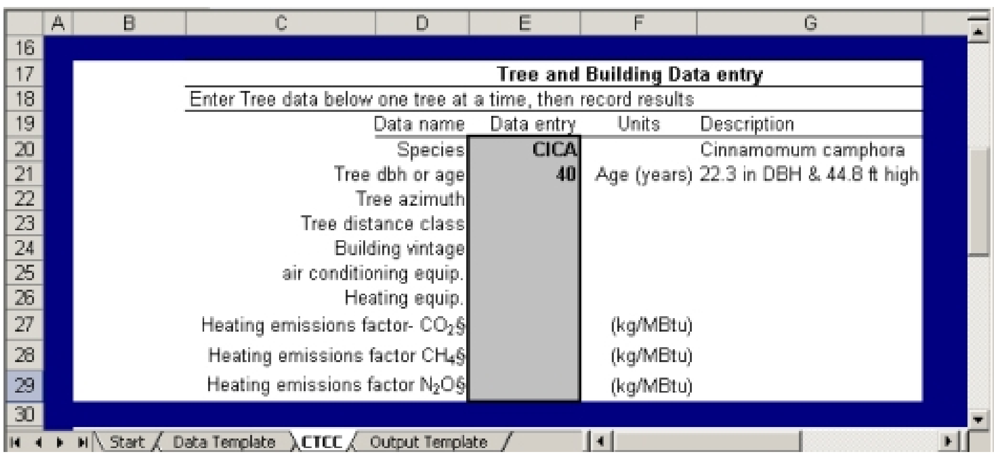
Heating Emission Factors: In contrast to electricity emission factors, which should be constant across a project, emission factors for space heating will differ depending on heating fuel type used in each building. See **Table 2** for the most common heat sources.

Once tree data have been collected, each tree can be entered individually into the CTCC.

3.3. Determining Tree Biomass and Carbon Storage

Instructions for using the CTCC to measure carbon storage by project trees are given below. For instructions on using the CTCC to estimate energy conservation benefits at the same time, see **3.4** below.

1. Enter species and dbh or age data (e.g. as recorded in **Figure 4**) for one tree into the CTCC Tree and Building data entry section (**Figure 6**). Entries related to energy conservation are blank. **Figure 7** shows the CTCC output for carbon storage.
2. Record CO_2 sequestration (lb/tree/year), total CO_2 stored (lb/tree), and above ground biomass (dry weight, lb/tree) from **Figure 7** in a separate location. For example, **Figure 8** is included as an optional form in worksheet [CarbonCalculatorNN]Output Template.
3. Calculate emission reductions for all project trees by repeating steps 1 through 3 above for each tree, recording the results as illustrated in **Figure 8**, which facilitates totaling results over all trees for the project.

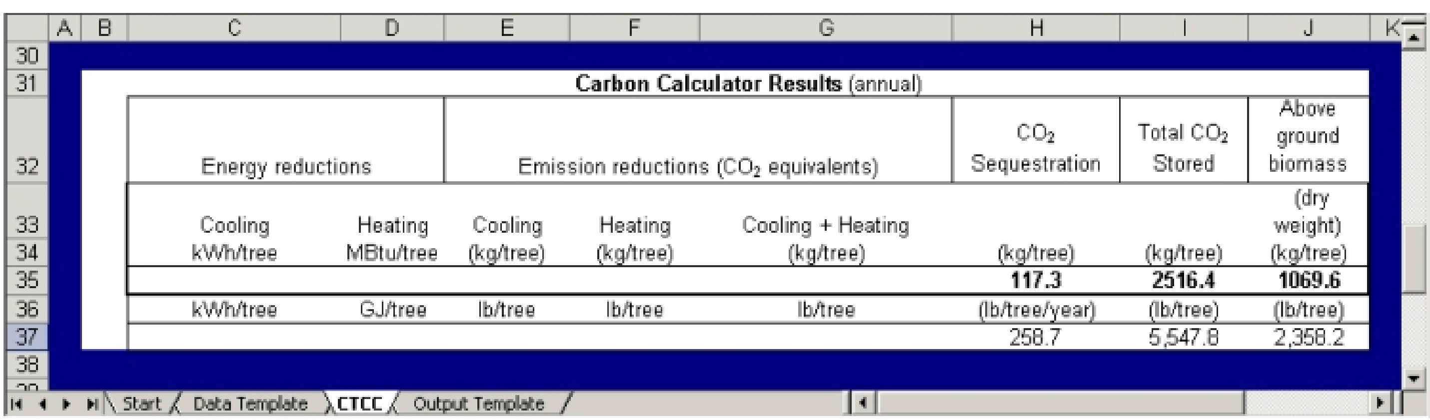


Tree and Building Data entry

Enter Tree data below one tree at a time, then record results

Data name	Data entry	Units	Description
Species	CICA		Cinnamomum camphora
Tree dbh or age	40	Age (years)	22.3 in DBH & 44.8 ft high
Tree azimuth			
Tree distance class			
Building vintage			
air conditioning equip.			
Heating equip.			
Heating emissions factor- CO_2§		(kg/MBtu)	
Heating emissions factor CH_4§		(kg/MBtu)	
Heating emissions factor N_2O§		(kg/MBtu)	

Figure 6. Tree-related data entry section for carbon storage project only (shaded area of [CarbonCalculatorNN.xls]CTCC).



Carbon Calculator Results (annual)

Energy reductions		Emission reductions (CO_2 equivalents)			CO_2 Sequestration	Total CO_2 Stored	Above ground biomass (dry weight)
Cooling kWh/tree	Heating MBtu/tree	Cooling (kg/tree)	Heating (kg/tree)	Cooling + Heating (kg/tree)	(kg/tree)	(kg/tree)	(kg/tree)
					117.3	2516.4	1069.6
kWh/tree	GJ/tree	lb/tree	lb/tree	lb/tree	(lb/tree/year)	(lb/tree)	(lb/tree)
					258.7	5,547.8	2,358.2

Figure 7. Output section of CTCC: carbon storage project only, CICA (camphor tree), year 40 ([CarbonCalculatorNN.xls]CTCC)

Summary of Carbon Calculator Results (annual)

Tree ID	Species code	Energy reductions: Cooling (kWh/tree)	Energy reductions: Heating (MBtu/tree)	Emission reductions (CO2 equivalents): Cooling (kg/tree)	Emission reductions (CO2 equivalents): Heating (kg/tree)	Emission reductions (CO2 equivalents): Cooling + Heating (kg/tree)	CO2 Sequestration (kg/tree)	Total CO2 Stored (kg/tree)	Above ground biomass (dry weight) (kg/tree)
1	BRPO						11.2	54.4	23.1
2	CICA						117.3	2516.4	1069.6
3	CICA						117.3	2516.4	1069.6
4	CICA						117.3	2516.4	1069.6
5	CICA						117.3	2516.4	1069.6
Total							481	10,120	4,302

Start / Data Template / CTCC / **Output Template**

Figure 8. Example output summary table for results from CTCC for carbon storage project only.

3.4. Determining Reduction in GHG Emissions from Tree Shade and Carbon Storage

If carbon storage benefits AND energy conservation benefits are calculated, data are entered in the CTCC as indicated below.

1. Enter tree and building data for one tree into the Carbon Calculator (**Figure 9**).
2. Record tree shade effects on building heating (kBtu/tree/year) and cooling (kWh/tree/year) from **Figure 10** in another location. For example, as in Figure 11. Tree shade effects on energy are converted to mass of CO_2 by multiplying energy units (kWh and KBtu) by utility-specific emission factors in the CTCC.
3. Calculate emission reductions for all project trees by repeating steps 1 to 2 described above for each time interval, then recording the results into a summary table like that illustrated in **Figure 11**, which facilitates totaling results over all trees for the project.

Tree and Building Data entry

Enter Tree data below one tree at a time, then record results

Data name	Data entry	Units	Description
Species	CICA		Cinnamomum camphora
Tree dbh or age	40	Age (years)	22.3 in DBH & 44.8 ft high
Tree azimuth	3		E
Tree distance class	1		Adj
Building vintage	1		pre-1950
air conditioning equip.	1		Central air/heat pump
Heating equip.	1		natural gas
Heating emissions factor- CO_2§	53.1	(kg/MBtu)	
Heating emissions factor CH_4§	0.0059	(kg/MBtu)	
Heating emissions factor N_2O§	0.0001	(kg/MBtu)	

Start / Data Template / **CTCC** / Output Template

Figure 9. Tree- and building-related data entry section for energy conservation project (shaded areas of [CarbonCalculatorNN.xls]CTCC. Data for carbon storage project are included as a subset.

Carbon Calculator Results (annual)

Energy reductions		Emission reductions (CO_2 equivalents)			CO_2 Sequestration	Total CO_2 Stored	Above ground biomass (dry weight)
Cooling kWh/tree	Heating MBtu/tree	Cooling (kg/tree)	Heating (kg/tree)	Cooling + Heating (kg/tree)	(kg/tree)	(kg/tree)	(kg/tree)
722.39	**0.040**	**276.1**	**2.1**	**278.2**	**117.3**	**2516.4**	**1069.6**
kWh/tree	GJ/tree	lb/tree	lb/tree	lb/tree	(lb/tree/year)	(lb/tree)	(lb/tree)
722.39	0.042	608.7	4.7	613.4	258.7	5,547.8	2,358.2

Figure 10. Output section of CTCC: energy conservation and carbon storage project ([CarbonCalculatorNN.xls]CTCC) for tree in **Table 9.**

Summary of Carbon Calculator Results (annual)

Tree ID	Species code	Energy reductions		Emission reductions (CO2 equivalents)			CO2 Sequestration	Total CO2 Stored	Above ground biomass (dry weight)
		Cooling (kWh/tree)	Heating (MBtu/tree)	Cooling (kg/tree)	Heating (kg/tree)	Cooling + Heating (kg/tree)	(kg/tree)	(kg/tree)	(kg/tree)
1	BRPO	21.67	-0.004	8.3	-0.2	8.1	11.2	54.4	23.1
2	CICA	722.39	0.040	275.6	2.1	277.8	117.3	2516.4	1069.6
3	CICA	0	0	0	0	0.0	117.3	2516.4	1069.6
4	CICA	0	0.040	0	2.1	2.1	117.3	2516.4	1069.6
5	CICA	722.39	0.012	275.6	0.7	276.3	117.3	2516.4	1069.6
Total		1,466	0.088	560	5	564	481	10,120	4,302

Figure 11. Example output summary table for results from CTCC for combined carbon storage/energy conservation project.

3.5. Description of CTCC Outputs

Carbon Calculator results are presented for five variables in English and SI units.

- Energy reductions – effect of the tree on annual energy consumption for air conditioning (kWh/tree) and heating (MBtu or GJ/tree)
- Emissions reductions – effect of the tree on GHG emissions associated with generation of electricity and combustion of heating fuels. These values are calculated using specified emission factors for each GHG and presented as annual kg and lb/tree in CO2 equivalents. A negative value indicates increased emissions associated with tree shade obstructing winter solar heat gain.
- CO_2 sequestration – annual amount of CO_2 sequestered as biomass in kg and lb per tree. This is calculated as the difference between the total amount of CO2 stored in the tree in year x minus the amount stored in year x-1. A value of 0.0 here indicates no tree growth.
- Total CO_2 stored - total amount of CO_2 stored in the tree due to growth over many years.
- Above ground biomass – total amount of biomass stored aboveground in dry weight. This amount excludes foliar and root biomass.

3.6. Copying CTCC Outputs to a Summary Table

To create a summary table as in **Figure 11** with CTCC outputs for individual trees, special steps are required. All cells on the 'CTCC' page of the workbook except the gray input section have been locked (using the Excel 'protect' feature) to prevent inadvertent user modification. To copy values from the Results section, this lock can be overridden by going to "Tools" in the main menu, clicking on "Protection", then selecting "Unprotect Sheet". This allows output cells to be selected and data to be copied. If data are to be pasted into another excel workbook, then the user should select “Edit” from the main menu, click on “Paste Special”, then select “Values” in the dialog box (necessary since formulas actually populate these cells), and finally click on “OK”. For example, cells C35:J35 can be copied from the ‘CTCC’ page and then pasted as values into successive rows in columns C:J of the ‘Output Template’ page to create a table of results.

4. Methods

4.1. Tree Biomass and Carbon Storage

Sampling and curve-fitting

To obtain the primary data—DBH, tree height, and number of years after planting—required to predict carbon storage and sequestration, growth equations predicting age, DBH, and tree height were derived from data collected in six reference cities (see Appendix B).

A stratified random sample of 650-1000 street trees per city, drawn from each city’s municipal tree database, was inventoried to establish relations between tree age, size, leaf area and biomass. Samples were composed of the 20-22 most abundant species in each city; from these data, growth of all trees is inferred based on taxonomic relationships. For those species that cannot be matched taxonomically, growth equations were assigned based on similar tree structure (stem, branch, leaf).

To obtain information spanning the life cycle of predominant tree species, the inventory was stratified into nine DBH classes:

- 0–3 in (0–7.6 cm)
- 3–6 in (7.6–15.2 cm)
- 6–12 in (15.2–30.5 cm
- 12–18 in (30.5–45.7 cm)
- 18–24 in (45.7–61.0 cm)
- 24–30 in (61.0–76.2 cm)
- 30–36 in (76.2–91.4 cm)
- 36–42 in (91.4–106.7 cm)
- >42 in (>106.7 cm)

Thirty to sixty randomly selected trees of each species were selected to survey, along with an equal number of alternative trees. Tree measurements included DBH (to nearest 0.1 cm by sonar measuring device), tree crown and crown base (to nearest 0.5 m by altimeter), crown diameter in two directions (parallel and perpendicular to nearest street to nearest 0.5 m by sonar measuring device), tree condition and location. Replacement trees were sampled when trees from the original sample population could not be located. Tree age (number of years after planting) was determined by municipal tree managers. Fieldwork was conducted during summer months, June-August, from 1998 through 2003.

Linear and non-linear regression was used to fit predictive models—with DBH as a function of age—for each of the 20-22 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. 2003).

Tree-size modeling: extrapolation and capping

All species in the CTCC were grown to a minimum of 100 years after initial planting date. For shorter-lived species (e.g. Prunus sp., Pyrus sp.), growth is capped at the maximum DBH and height values for that region. For example, in Berkeley, California, the largest Pyrus calleryana present in the city database was 21in DBH and 40-ft tall at 52 years, its maximum size. Therefore, tree size is capped at those dimensions in the CTCC so that the same DBH, height, and carbon storage values are reported for all years from 52 through 100. Since tree sizes are capped, no annual sequestration is currently reported after the capping point.

There were also species measured that had not yet reached mature sizes within the respective cities. Where local data were available on mature size for that region, we used the equations to grow the trees to that maximum size, extrapolating beyond the measured data. For example, the largest Liquidambar styraciflua sampled in Berkeley measured 28-in DBH and 64-ft tall at 58 years. However, in the Oakland Hills, adjacent to Berkeley stand several Liquidambar trees planted 100 years ago, the largest measuring 37-in DBH and 72-ft tall. We used our equations to extrapolate from the dimensions of the 58-yr old tree to those of the 100-yr old tree. However, if no regional information was available on maximum tree size for a species, growth was capped at the less than mature size value. Therefore, if information had not been available on the larger Liquidambar described above, tree size, carbon storage and annual sequestration would have been capped at the lower values, using the same method as described for the Pyrus calleryana example above.

Calculating and Predicting Biomass and Carbon

The following sections describe how measured tree size data are used with biomass equations to calculate tree volume and stored carbon.

Equations are presented for 26 open-grown urban tree species. To be consistent with biomass equations used in the Forest Protocol, foliar biomass is not included in the formulations. Additional biomass equations have been adapted from the literature on natural and native forest biomass for use in urban settings. We have also used the urban species equations to develop two general equations for broadleaf trees and conifers. These equations are used in the CTCC. Complete listings of equations are available in Tables 4 and 5. Table 4 lists equations based on measurements of dbh and height or dbh only, derived from data collected on open-grown trees.

Estimating Biomass and Carbon using Volumetric Equations

Estimating biomass and carbon using volumetric equations is a two-step process that entails 1) calculating green volume and 2) converting green volume to dryweight biomass and then carbon (C) and stored carbon dioxide equivalents (CO_2). Tables 4 and 5 provide examples of volumetric equations and biomass density factors for common urban species (Pillsbury et al. 1998; McHale 2008). Table D4 equations estimate volume (m^3/tree) from diameter at breast height (dbh in centimeters) and height (ht in meters) measurements. Dryweight density factors were obtained by multiplying Markwardt and Wilson's (1935) values for specific gravity based on volume when green by 1,000 kg/m^3.

1. Use equations for dbh and height (or equations for dbh only if necessary) to calculate volume.

Example:

Volume in cubic meters (V) for a 15.6-m tall hackberry (*Celtis occidentalis*) with a 40.4-cm dbh is calculated as:

$V = 0.002245 \times (40.4)^{2.118} \times (15.6)^{-0447} = 1.66\ m^3$ **[Eq. 1]**

Dryweight Biomass Calculation

2. Determine dryweight (DW) biomass and carbon stored by applying DW biomass density factors in Table 4, incorporating belowground biomass, and calculating carbon.

a. Convert from volume to DW biomass by multiplying V by the species-specific DW density factor for *Celtis occidentalis* (490 kg/ m^3).

For hackberry, DW would be calculated as:

$DW = 1.66\ m^3 \times 490\ kg/\ m^3 = 813.40\ kg$ **[Eq. 2]**

b. The equations given here only calculate volume (and hence biomass) for the aboveground portion of the tree. Add the biomass stored belowground by multiplying the DW biomass by 1.28 (Husch et al. 1982; Tritton and Hornbeck 1982; Wenger 1984).

c. For total DW biomass, including belowground roots calculate:

$\text{Total DW} = 813.40\ kg \times 1.28 = 1041.15\ kg$ **[Eq. 3]**

d. Convert DW biomass into kilograms of carbon (C) by multiplying by the constant 0.50 (Lieth 1963; Whittaker and Likens 1973):

$C = 1041.15\ kg \times 0.5 = 520.58\ kg$ **[Eq. 4]**

e. Convert stored carbon into stored carbon dioxide (CO_2) by multiplying by the constant 3.67 (molecular weight of carbon dioxide) as follows:

$CO_2 = 520.588\ kg \times 3.67 = 1910.53\ kg$ **[Eq. 5]**

f. Stored carbon dioxide is to be reported in metric tons. Therefore, results calculated in kilograms must be multiplied by 0.001 to convert to metric tons.

Freshweight biomass calculation

For applications where estimates of FW biomass are required FW density factors are also included in Table 4. To calculate FW biomass:

a. Convert from volume to FW biomass by multiplying V by the species-specific FW density factor for *Celtis occidentalis* (801 kg/ m^3).

For hackberry, FW would be calculated as:

$FW = 1.66\ m^3 \times 801\ kg/\ m^3 = 1329.66\ kg$

b. To add the FW biomass stored belowground by multiplying the FW biomass by 1.28. For total FW biomass, including belowground roots calculate:

Total FW = 1329.66 kg x 1.28 = 1701.96 kg

c. Note that the two general equations in Table 4 produce FW biomass. To convert to DW biomass, multiply the broadleaf FW by 0.56 and the conifer FW by 0.48 (Stanek and State 1978; Phillips 1981 ; Husch et al. 1982; Nowak 1994). Then follow steps c and d above to obtain carbon (C) and carbon dioxide (CO_2) .

Estimating biomass and carbon using forest-derived equations

Biomass calculated using equations derived from native or natural forest trees (listed in Table 4) must be adjusted by a factor of 0.80 when applied to open-grown, urban trees (Nowak 1994) because of differences in biomass allocation between the tree populations.

Unlike the equations used above, the forest equations listed produce DW biomass in kilograms rather than FW biomass. Therefore the step involving the species-specific DW density factor (step 2a above) does not need to be incorporated. The calculation for CO_2 stored is:

$CO_2 = DW \times 1.28 \times 0.5 \times 3.67$ **[Eq. 6]**

Error in predicting future growth, carbon and biomass

The volume equations were developed from trees that may differ in size from the trees in your sample or inventory. The dbh ranges for trees sampled to develop the volume and biomass equations are listed where known at the end of the annex (Tables 4 and 5). Applying the equations to trees with dbh outside of this range may increase the error in your predictions.

Your tree growth may differ significantly from tree growth models used by the CTCC. Therefore, it is important to attempt to quantify differences at the beginning of the project and through subsequent monitoring, to assess differences. It is also better to err on the side of underestimating carbon stocks rather than overestimating.

Initial suggestions for evaluating growth include contacting local arborists and other tree experts (e.g., local university extension offices, city tree managers) to evaluate the growth presented here. Obtaining information on “typical” annual growth is important – whether a species normally grows 1 cm per year or 3 cm per year is helpful. Asking arborists for average annual dbh growth when trees are young, adolescent, middle-aged and senescent can allow for further comparison with data produced by the CTCC.

Table 4. Volume equations for 26 urban tree species requiring dbh (cm) only or dbh (cm) and height (m) measurements to calculate volume (McHale 2008, Pillsbury et al 1998). Density factors are listed for converting volume to freshweight (FW) and dryweight (DW), and two FW general biomass equations derived from these species are also listed.

	Species	DBH Range (cm)	Volume (m^3)	FW Density for Vol to FW Conversion kg/m^3	DW Density for Vol to DW Conversion kg/m^3
	Acacia longifolia	15.0 - 57.2	$=0.0283168466\ (0.048490 * (dbh/2.54)^{2.347250})$	953	630
	Acer platanoides	9.7 - 102.1	$=0.0019421 * dbh^{1.785}$	772	480
	Acer saccharinum	13.2 - 134.9	$=0.000363 * dbh^{2.292}$	721	440
	Celtis occidentalis	10.9 - 119.4	$=0.0014159 * dbh^{1.928}$	801	490
	Ceratonia siliqua	15.5 - 71.4	$=0.0283168466(0.066256 * (dbh/2.54)^{2.128861})$	953	630
D	Cinnamomum camphora	12.7 - 68.8	$=0.0283168466(0.031449 * (dbh/2.54)^{2.534660})$	849	520
B	Cupressus macrocarpa	15.7 - 146.6	$=0.0283168466(0.035598 * (dbh/2.54)^{2.495263})$	352	460
H	Eucalyptus globulus	15.5 - 130.0	$=0.0283168466(0.055113 * (dbh/2.54)^{2.436970})$	1121	620
	Fraxinus pennsylvanica	14.7 - 122.7	$=0.0005885 * dbh^{2.206}$	785	530
O	Fraxinus velutina 'Modesto'	14.5 - 84.8	$=0.0283168466(0.022227 * (dbh/2.54)^{2.633462})$	732	517
N	Gleditsia triancanthos	9.1 - 98.3	$=0.0005055 * dbh^{2.220}$	977	600
L	Gymnocladus dioicus	10.2 - 36.8	$=0.0004159 * dbh^{2.059}$	769	550
Y	Jacaranda mimosifolia	17.3 - 59.7	$=0.0283168466(0.036147 * (dbh/2.54)^{2.486248})$	657	380
	Liquidambar		2.560469		

	styraciflua	14.0 - 54.4	=0.0283168466(0.030684 * (dbh/2.54))	801	440
	Magnolia grandiflora	14.5 - 74.2	$=0.0283168466(0.022744 * (dbh/2.54)^{2.622015})$	945	460
	Pinus radiata	16.8 - 105.4	$=0.0283168466(0.019874 * (dbh/2.54)^{2.666079})$	401	440
	Pistacia chinensis	12.7 - 51.3	$=0.0283168466(0.019003 * (dbh/2.54)^{2.808625})$	833	435
	Platanus acerifolia	15.5 - 73.9	$=0.0283168466(0.025170 * (dbh/2.54)^{2.673578})$	833	460
	Populus sargentii	6.4 - 136.7	$=0.0020891 * dbh^{1.873}$	785	370
	Quercus ilex	12.7 - 52.1	$=0.0283168466(0.025169 * (dbh/2.54)^{2.607285})$	1177	755
	Quercus macrocarpa	10.9 - 100.1	$=0.0002431 * dbh^{2.415}$	993	580
	Tilia cordata	11.2 - 64.5	$=0.0009359 * dbh^{2.042}$	673	320
	Ulmus americana	17.5 - 114.3	$=0.0018 * dbh^{1.869}$	865	460
	Ulmus parvifolia chinensis	17.3 - 55.9	$=0.0283168466(0.028530 * (dbh/2.54)^{2.639347})$	903	540
	Ulmus pumila	15.5 - 131.6	$=0.0048879 * dbh^{1.613}$	903	540
	Zelkova serrata	14.5 - 86.4	$=0.0283168466(0.021472 * (dbh/2.54)^{2.674757})$	903	540
	General Broadleaf	6.4 - 136.7	$=0.280285*(dbhcm)^{2.310647}$	Eqtn produces FW	Multiply FW by 0.56
	General Conifer	6.4 - 136.7	$=0.05654*(dbhcm)^{2.580671}$	Eqtn produces FW	Multiply FW by 0.48
	Acacia longifolia	15.0 - 57.2	$=0.0283168466(0.01406 * (dbh/2.54)^{2.18649} * (3.28*ht)^{0.46736})$	953	630
	Acer platanoides	9.7 - 102.1	$=0.001011 * dbh^{1.533} * ht^{0.657}$	772	480
	Acer saccharinum	13.2 - 134.9	$=0.000238 * dbh^{1.998} * ht^{0.596}$	721	440
D	Celtis occidentalis	10.9 - 119.4	$=0.002245 * dbh^{2.118} * ht^{-0.447}$	801	490
B	Ceratonia siliqua	15.5 - 71.4	$=0.0283168466(0.00857 * (dbh/2.54)^{1.79584} * (3.28*ht)^{0.92667})$	953	630
H	Cinnamomum camphora	12.7 - 68.8	$=0.0283168466(0.00982 * (dbh/2.54)^{2.13480} * (3.28*ht)^{0.63404})$	849	520
	Cupressus macrocarpa	15.7 - 146.6	$=0.0283168466(0.00576 * (dbh/2.54)^{2.26035} * (3.28*ht)^{0.63013})$	352	460
a	Eucalyptus globulus	15.5 - 130.0	$=0.0283168466(0.00309 * (dbh/2.54)^{2.15182} * (3.28*ht)^{0.83573})$	1121	620
n	Fraxinus pennsylvanica	14.7 - 122.7	$=0.000414 * dbh^{1.847} * ht^{0.646}$	785	530
d	Fraxinus velutina 'Modesto'	14.5 - 84.8	$=0.0283168466(0.00129 * (dbh/2.54)^{1.76296} * (3.28*ht)^{1.42782})$	732	517
	Gleditsia triancanthos	9.1 - 98.3	$=0.000489 * dbh^{2.132} * ht^{0.142}$	977	600
H	Gymnocladus dioicus	10.2 - 36.8	$=0.000463 * dbh^{1.545} * ht^{0.792}$	769	550
E	Jacaranda mimosifolia	17.3 - 59.7	$=0.0283168466(0.01131 * (dbh/2.54)^{2.18578} * (3.28*ht)^{0.54805})$	657	380
I	Liquidambar styraciflua	14.0 - 54.4	$=0.0283168466(0.01177 * (dbh/2.54)^{2.31582} * (3.28*ht)^{0.41571})$	801	440
G	Magnolia grandiflora	14.5 - 74.2	$=0.0283168466(0.00449 * (dbh/2.54)^{2.07041} * (3.28*ht)^{0.84563})$	945	460
H	Pinus radiata	16.8 - 105.4	$=0.0283168466(0.00533 * (dbh/2.54)^{2.22681} * (3.28*ht)^{0.66899})$	401	440
T	Pistacia chinensis	12.7 - 51.3	$=0.0283168466(0.00292 * (dbh/2.54)^{2.19157} * (3.28*ht)^{0.94367})$	833	435
	Platanus acerifolia	15.5 - 73.9	$=0.0283168466(0.01043 * (dbh/2.54)^{2.43642} * (3.28*ht)^{0.39168})$	833	460
	Populus sargentii	6.4 - 136.7	$=0.001906 * dbh^{1.806 * ht^{0.134}}$	785	370
			1.82158		

	Quercus ilex	12.7 - 52.1	$=0.0283168466(0.00431 * (dbh/2.54) * (3.28*ht)^{1.06269})$	1177	755
	Quercus macrocarpa	10.9 - 100.1	$=0.000169 * dbh^{1.956} * ht^{0.842}$	993	580
	Tilia cordata	11.2 - 64.5	$=0.000945 * dbh^{1.617} * ht^{0.59}$	673	320
	Ulmus americana	17.5 - 114.3	$=0.0012 * dbh^{1.696} * ht^{0.405}$	865	460
	Ulmus parvifolia chinensis	17.3 - 55.9	$=0.0283168466(0.01046 * (dbh/2.54)^{2.32481} * (3.28*ht)^{0.49317})$	903	540
	Ulmus pumila	15.5 - 131.6	$=0.000338 * dbh^{0.855 * ht^{2.041}}$	903	540
	Zelkova serrata	14.5 - 86.4	$=0.0283168466(0.00666 * (dbh/2.54)^{2.36318} * (3.28*ht)^{0.55190})$	903	540

Table 5. Dryweight biomass equations from the forest literature. Use constants to add roots, convert to carbon and CO_2. Biomass is reduced to 80% of original predicted value to account for less biomass in urban trees.

Spcode	Botanic	Common	Model	Source and DBH Range
ACRU	Acer rubrum	Red maple	$=(0.1970*(dbh^{2.1933}))*0.80$	Ter-Mikaelian, Nova Scotia 0-35 cm red maple
ACSA2	Acer saccharum	Sugar maple	$=(0.1791*(dbh^{2.3329}))*0.80$	Ter-Mikaelian, Maine 3-66 cm sugar maple
PRSE2	Prunus serotina	Black cherry	$=(0.0716*(dbh^{2.6174}))*0.80$	Ter-Mikaelian, West VA 5-50 cm black cherry
QURU	Quercus rubra	Northern red oak	$=(0.1130*(dbh^{2.4572}))*0.80$	TerMikaelian, West VA 5-50 cm red oak
FRAM	Fraxinus americana	White ash	$=(0.1063*(dbh^{2.4798}))*0.80$	Ter-Mikaelian, West VA 5-50 cm white ash
TIAM	Tilia americana	American basswood	$=(0.0617*(dbh^{2.5328}))*0.80$	Ter-Mikaelian, West VA 5-50 cm basswood
BENI	Betula nigra	River birch	$=(0.0692*(dbh^{2.6606}))*0.80$	Ter-Mikaelian, West VA 5-50 cm black birch
Palms	General palms	General palms	=(6.0*ht(m)+0.8)+(0.8*ht(m)+0.9)	Frangi and Lugo, 1985
Hardwoods	General hardwoods	General hardwoods	=((EXP(-2.437+2.418*(LN(dbh)))+EXP(-3.188 + 2.226*(LN(dbh)))))*0.8	Tritton and Hornbeck, Northeast, 10-50 cm

4.2. Energy Conservation and Reduced Emissions

Tree Shade and Energy Conservation

Tree shade reduces summer air conditioning demand, but can increase heating energy use by intercepting winter sunshine (Heisler 1986; Simpson and McPherson 1998). Trees intercept solar radiation that would otherwise fall on building windows, walls and roofs thereby reducing heat transfer to the building interior, which in turn reduces demand for cooling in summer. In winter, the same reduction in solar gain can increase heating load. The latter can be true even for deciduous trees, where leafless branches can still block up to 30% of solar radiation (Heisler 1982).

Measured and Modeled Energy Conservation Benefits Attributed to Shade

Energy-saving benefits from shading trees around typical residences have been measured in the field and estimated from computer simulations. Shading from shrubs and trees in Florida (Parker 1983) and Pennsylvania (DeWalle et al.1983) resulted in cooling savings of 30% and greater. Meier (1990/91) reviewed results from five studies that measured energy savings from landscaping and reported that air conditioning energy savings commonly measured 25-50%. Akbari et al. (1997) found measured savings were 47 and 26% from 16 containerized trees ~2.4 to 6 m (~8 to 20 ft) high shading south and west facing walls and windows of homes in Sacramento, California. Computer simulations for three cities (Sacramento, Phoenix, and Lake Charles) found that three mature trees around energy-efficient homes cut annual air conditioning demand by 25 to 43% and peak cooling demand by 12 to 23% (Huang and others 1987). On a per tree basis, energy simulations from 12 U.S. cities found that annual energy savings for cooling from a well-placed 25-ft tall deciduous tree ranged from 100 to 400 kWh (10 to 15%) (McPherson and Rowntree 1993). Simpson and McPherson (1998) found that the average savings per tree based on simulation of 254 residential properties was approximately 7% per tree.

Climate Effects of Trees and Energy Conservation

Climate effects, which can be defined as lowered air temperature and wind speed due to the presence of urban trees, can reduce demand for both cooling and heating. In summer, lower air temperatures and wind speeds reduce conduction gains due to lower inside-outside temperature differentials, as well as wind-driven infiltration of warm air. Reduced wind speed can also increase cooling load by reducing natural ventilation, if used. In winter, air temperature reductions are minimal, but lower wind speeds act to reduce infiltration of cold air and heating loads.

Measured and Modeled Energy Conservation Benefits Attributed to Climate Effects

Maximum midday air temperature reductions of from 0.4 to 2.0 °C have been reported in the literature for neighborhood or larger scale changes in canopy cover (Huang et al. 1987, Taha et al. 1991, Sailor et al. 1992, Myrup et al. 1993, Wilkin and Jo 1993. For Sacramento in particular, Huang et al. (1987) simulated a decrease of 1.2 °C for a 10% city-wide canopy cover increase. Sailor et al. 1992 estimated a decrease of 0.36 °C per 10% cover increase based on regression analysis of measurements at 15 residential locations scattered throughout Sacramento. Cover was determined for ~100 acre areas surrounding each measurement location; substantial scatter was observed in the data. Taha et al. (1991) consistently found midday air temperature reductions of ~1 °C/10% cover difference for an orchard compared to a dry field in Davis, California; reductions occasionally reached 2.4 °C/10% cover difference. An air temperature decrease of 1°C produced a simulated reduction of 11% in annual residential air conditioning energy use (kWh) in Sacramento (Huang et al. 1987). Sailor et al. (1992) estimated a 13% reduction in cooling degree days, which are closely related to annual kWh, per 1°C drop in air temperature. McPherson (1994) found annual kWh savings of 2% per 1°C temperature decrease for various construction types in Chicago.

Building Energy Performance Simulations

Calculations of annual building energy use per residential unit (unit energy consumption [UEC]) were based on computer simulations that incorporated building, climate, and shading effects, following methods outlined by McPherson and Simpson (1999). Changes in UECs due to the effects of 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. For example, all houses from 1950–1980 vintage are assumed to have the same floor area, and other construction characteristics. Shading effects for approximately 20 of the most common tree species were simulated in each climate zone for three tree-to-building distances (0–20 ft, 20–40 ft, 40–60 ft), eight orientations (cardinal and inter-cardinal point of the compass) and for nine tree sizes. It was assumed that street trees greater than 60 ft from buildings provided no direct shade on walls and windows and hence no energy-related benefit.

Prototype buildings were simulated to represent pre-1950, 1950–1980, and post-1980 construction practices for each climate zone (**Table 6**). Building footprints were modeled as square, which was found to reflect average impacts for a large number of buildings (Simpson 2002). Buildings were simulated with 1.5-ft overhangs. Blinds had a visual density of 37%, and were assumed to be closed when the air conditioner was operating. Thermostat settings were 78°F for cooling and 68°F for heating, with a 60°F night setback in winter. Unit energy consumptions are adjusted in the CTCC to account for different types of heating and cooling equipment (**Table 7**) and efficiencies (**Table 8**).

Table 6. Building data by climate zone (Ritschard et al. 1992). CFA is conditioned floor area, and SEER (Seasonal Energy Efficiency Ratio) and AFUE (Annual Fuel Utilization Efficiency) are measures of heating and cooling equipment efficiencies.

								R Values (hr*ft^2 - °F/Btu)					
Climate Region	**Vintage**	**Stories**	**CFA (m^2)**	**Glazing Area (m^2)**	**No. Panes**	**Wall Type**	**Foundation Type**	**Wall**	**Ceiling**	**Floor**	**Found.**	**Cooling SEER**	**Heating AFUE**
Mountains	Pre 1950	1	90.6	16.4	2	Wood	Basement	7	11	0	0	8	0.75
	1950-1980	1	100.3	18.2	2	Brick	Slab	7	11	0	0	8	0.75
	Post 1980	2	192.3	24.4	2	Wood	Basement	13	31	11	0	10	0.78
North, Central, & South Coast	Pre 1950	1	90.6	16.4	2	Wood	Crawl	7	7	0	0	8	0.75
	1950-1980	1	129.1	22.5	1	Stucco	Crawl	7	11	0	0	8	0.75
	Post 1980	2	192.3	30.2	2	Stucco	Slab	11	25	0	0	10	0.78
Central Valley	Pre 1950	1	90.6	16.4	2	Wood	Basement	7	11	0	0	8	0.75
	1950-1980	1	100.3	18.2	2	Brick	Slab	7	11	0	0	8	0.75
	Post 1980	1	154.2	16.6	2	Stucco	Slab	13	29	0	5	10	0.78
	Pre	1	90.6	16.4	2	Wood	Basement	7	11	0	0	8	0.75

	1950												
Desert	1950-1980	1	100.3	18.2	2	Brick	Slab	7	11	0	0	8	0.75
	Post 1980	1	154.2	16.6	2	Stucco	Slab	13	27	0	0	10	0.78

Weather data for typical meteorological years (TMY2) from each climate zone were used (National Solar Radiation Data Base 2006).

Table 7. Cooling equipment factors

	Building Vintage		
	pre-1950	**1950-1980**	**post-1980**
Central air/heat pump	1	1	1
Evaporative Cooler	0.33	0.33	0.33
Window/Wall Unit	0.25	0.25	0.25
None	0	0	0

Table 8. Heating and cooling equipment efficiencies.

	Building Vintage		
	pre-1950	**1950-1980**	**post-1980**
Natural Gas	1	1	1
Heat Pump	0.110	0.115	0.098
Electric Resistance	0.220	0.229	0.229
None	0	0	0

Single-Family Residence Adjustments

Unit energy consumptions for simulated single-family residences were adjusted for type and saturation of heating and cooling equipment, and for various factors (F) that modify the effects of shade and climate on heating and cooling loads. For cooling we have:

$\Delta UEC_c = \Delta UEC^{raw}{}_c * F_c$ **[Eq.1]**

where
$F_c = F_{c\_equipment} * F_{adjacent\ shade} * F_{multiple\ tree}$
$F_{c\_equipment} = Sat_{CAC} + Sat_{window} * 0.25 + Sat_{evap} * 0.33$

For heating we have: $\Delta UEC_h = \Delta UEC^{raw}{}_h * F_h$ **[Eq.2]**

where
$F_h = F_{h\_equipment} * F_{adjacent\ shade} * F_{multiple\ tree}$
$F_{h\_equipment} = Sat_{NG}$

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

Total Change = $N * \Delta UEC_x$ **[Eq.3]**

Where subscript *x* refers to cooling or heating.

Cooling and heating effects are reduced based on the type of air conditioning or heating equipment and 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 ($F_{c\_equipment}$).

Shading Effects

Shading effects for approximately 20 of the most common tree species were simulated in each climate zone for three tree-to-building distances (0–20 ft, 20–40 ft, 40–60 ft), eight orientations (cardinal and inter-cardinal point of the compass) and for nine tree sizes. It was assumed that street trees greater than 60 ft from buildings provided no direct shade on walls and windows and hence no energy-related benefit due to tree shade.

The shading coefficients of the trees in leaf (gaps in the crown as a percentage of total crown silhouette) were estimated using a photographic method that has been shown to produce good estimates (Wilkinson 1991). Crown areas were obtained using the method of Peper and McPherson (2003) from digital photographs of trees from which background features were digitally removed. Values for tree species that were not sampled, and leaf-off values for use in calculating winter shade, were based on published values where available (McPherson 1984; Hammond et al. 1980). Where published values were not available, visual densities were assigned based on taxonomic considerations (trees of the same genus were assigned the same value) or observed similarity to known species. Foliation periods for deciduous trees were obtained from the literature (McPherson 1984; Hammond et al. 1980) and adjusted for each climate zone based on consultation with forestry supervisors and local nursery representatives.

Estimated shade savings for all residential structures could be adjusted to account for shading of neighboring buildings and for overlapping shade from trees adjacent to one another. Homes adjacent to those with shade trees may benefit from the trees on the neighboring properties. For example, 23% of the trees planted for the Sacramento Shade program shaded neighboring homes, resulting in an additional estimated energy savings equal to 15% of that found for program participants, which gives $F_{adjacent\ shade} \approx 1.15$. 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 reductions in average cooling and heating energy use were approximately 6% and 5% percent per tree, respectively, for each tree added after the first. Simpson (1998) also found an average of 2.5–3.4 existing trees per residence in Sacramento. A multiple tree reduction factor of 85% is equivalent to approximately three existing trees per residence. Since these factors are difficult to assess and approximately compensating, it was assumed in the analysis that $F_{adjacent\ shade} \times F_{multiple\ tree} = 1.0$.

Climate Effects

In addition to localized shade effects, which are assumed to accrue only to trees within 60 ft of buildings, lowered air temperatures and wind speeds due to neighborhood 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 were estimated as a function of neighborhood canopy cover from published values following McPherson and Simpson (1999), then used as input for the building-energy-use simulations described earlier. Peak summer air temperatures were assumed to be reduced by 0.2°F for each percentage increase in canopy cover. Wind-speed reductions were based on the change in total tree plus building canopy cover resulting from the addition of the particular tree being simulated (Heisler 1990). An effective lot size (actual lot size plus a portion of adjacent street and other rights-of-way) of 10,000 ft^2 was assumed, and one tree on average was assumed per lot.

Upper Limit on Energy Conservation Benefits Attributed to Shade and Climate Effects

In certain climates, for example coastal southern California or the high Sierra, air temperatures can be at or below the typical air conditioner set point (e.g, 27 °C, 80 °F) when solar radiation loads are high. In these circumstances, solar loading can account for most of the air conditioning load. Strategic placement of a large tree to shade a building for large portions of the day under these circumstances could in fact reduce the cooling load by 50% or more. As noted above, typical savings are in the 10-30% range. To limit shade benefits to values reported in the literature an upper limit is set at 25% of the total cooling load. While larger savings are possible, total cooling loads and the kWh are generally small under the conditions that produce such large savings, so underestimation of savings due to this imposed upper limit is minimal.

Benefits resulting from climate effects are treated the same as shading benefits by imposing an upper limit at 25% of the total cooling load. Hence the total cooling energy benefit is the sum of shade and climate benefits, each individually limited to 25% of the total cooling load. This can be restated as:

$$\Delta\text{Cooling} = \text{minimum}(\Delta\text{shade effect}, 0.25*\text{Total Cooling Load}) + \text{minimum}(\Delta\text{Climate Effect}, 0.25*\text{Total Cooling Load})$$

Where:

- Δshade effect is the calculated change in energy use from shading,
- Δclimate effect is the calculated change in energy use from climate, and
- Total cooling load is the total calculated cooling load.

We account here for the effects of tree cover change on the scale of neighborhoods or larger, since little information is available relating the effect of individual trees on air temperature and wind speed. Since the calculations are done for individual properties, the aggregate canopy cover increase calculated for the individual properties must approximate the cover change for the neighborhood (or larger area) as a whole. The practical result of this is that the climate effect should only be calculated for a program that is clustering trees to create an appreciable increase in local tree canopy cover.

5. Initial Uncertainty Analysis

This initial uncertainty analysis estimates standard errors in CTCC's estimates of CO_2 emission reductions due to uncertainty in the emissions factor, interpolation, and energy analysis (σ_e, σ_f, and σ_E). While a complete analysis of these errors is not possible here, preliminary estimates are given based on the following analysis.

Greater uncertainty is involved with default emissions factors (σ_e) supplied by the CTCC than for locally derived values, since default factors are based on past data, and reflect only the largest utility service areas in the state. We assume a relative standard error (σ_e/e) of ±10% for default factors, and ±5% when locally derived data are utilized.

Uncertainty related to interpolation (σ_f) results from differences between the functional form used for interpolation here (linear) and the unknown form, a function of DBH or time. Empirical curve fitting could be used to reduce interpolation error, tested with additional between-class simulation runs. For now it is assumed based on the observed curve shapes that this relative error is ±10%. Overall uncertainty is relatively insensitive to the value selected.

Due to the many inputs and complexities of the building energy simulation modeling, which includes tree and building factors, σ_E is the most difficult standard error to quantify. Some of these factors, such as occupant behavior, are extremely difficult to quantify or verify. That being said, studies have been reported that deal with this issue, including one that compares actual measurements with simulated results.

We know of only one instance where simulations of energy savings effects of trees were compared to measurements. Akbari et al. (1997) made detailed measurements of two homes with and without 16 containerized trees ~2.4 to 6 m high shading south and west facing walls and windows. Measured savings were 47 and 26% over approximately 100 day summer measurement periods in Sacramento, California. Computer simulations were found to consistently underestimate the measured savings by a factor of two. Complete calibration of the model was not one of the objectives of the study, so the exact cause(s) of the discrepancies were not elucidated. Initial indications based on the limited data available are that simulated energy savings from shade trees may be conservative estimates of actual savings.

As a preliminary estimate of the relative error in the building energy simulation modeling we use the value from Hildebrandt and Sarkovich (1998) of ±25%, recognizing that additional analysis will be necessary for individual consideration of many factors involved.

These preliminary estimates of relative standard error of σ_e/e = 10%, σ_f/f = 10%, and σ_E/E = 25% were substituted into an equation to calculate an initial estimate of the error in reduced CO_2 emissions. This resulting error will depend on the relative size of terms in the equation, and particularly on the relative size of cooling savings compared to heating penalty. Typical errors appear to be ~30%, but can be larger if increased emissions from heating become similar in size to the reduced emissions from heating, e.g. $e_1E_{n,1} \approx e_2E_{n,2}$. Of course, in the latter case the net change in emissions becomes small, as does the magnitude of the error.

6. Frequently Asked Questions

- **Q: What is this product?**
  A: CTCC is the CUFR Tree Carbon Calculator and it is a tool that calculates the amount of biomass and carbon stored in a tree, as well as the amount sequestered annually. The CTCC also provides information on the effects of trees on residential heating and cooling energy use and associated greenhouse gas (GHG) emissions.

- **Q: What kind of software is it and what does it do?**
  A: The CTCC is programmed in an Excel spreadsheet and provides carbon-related information for a single tree located in one of six California climate zones. A web-based version with data for 16 US climate zones is under development.

- **Q: Does this software need any special computer requirements to work?**
  A: No. Only Microsoft Excel is necessary.

- **Q: What information do I need beforehand to fill out the CTCC?**
  A: Section 3.1 in the help file answers this question in detail. You need to know the region where the trees are located, the species you are measuring and the DBH or age of each tree. If you want to know effects on building energy use you need information about the heating and cooling equipment, the distance of each tree to the building, and its azimuth (compass bearing).

- **Q: Do I need any special equipment to measure input data?**
  A: A dbh tape and a compass will be enough.

- **Q: What do I do if my species is not in the corresponding list for my region?**
  A: There are 20-30 species in each climate zone. If you want to calculate carbon and energy results for a species not included in the list,

choose the species from the same climate zone with the most similar mature size and growth rate.

- **Q: Why do I receive errors about workbooks not opening when initializing CCTC main workbook?**
  A: Make sure to set macro security settings on "Low" to allow VBA application code to execute. To do so, click Tools-macro-security and choose 'Low'.

- **Q: How do I know if the calculator has loaded properly?**
  A: You should not see REF or N/A in any cell. If you do, it is incorrectly loaded and will not work properly. Check the security level of your macros and try again.

- **Q: Do I need to fill-in all three worksheets before the calculator will work?**
  A: No. The calculator only needs input data for the shaded cells in the main CTCC worksheet to work. The Data and Output templates are one possible way for you to keep track of the input data and results for each tree in your project.

- **Q: How many trees can I run in the calculator at a time?**
  A: Trees must be calculated one by one, and records of results can be kept in a different worksheet if wanted for later compilation of results.

- **Q: How will I know when the CTCC has finished calculating my input values?**
  A: The calculator provides results in the bottom table in the main CTCC worksheet. There will always be an instant result as long as all the shaded input cells are filled. To make sure that the values in the output table are correct, make sure that all the input cells match your collected information.

- **Q: Are energy and carbon dioxide sequestration results for the total life of the tree or just one year?**
  A: They are annual results, based on the amount of carbon dioxide sequestered and energy saved during a single year. Outputs for carbon dioxide stored and aboveground biomass are for the time from the tree's planting to its specified size or age.

- **Q: What does aboveground biomass include?**
  A: The calculator includes trunk, branches and stems in estimates of aboveground dry weight. Roots and foliage are not included.

- **Q: What is the difference between storage and sequestration?**
  A: Sequestration is an annual measure of the CO_2 stored as biomass, whereas storage accounts for the amount of CO_2 sequestered by the tree every year after it was planted.

- **Q: What kind of units are the results in?**
  A: Results are provided in both English and SI units. You can select the most convenient for you.

- **Q: How can the outputs be used?**
  A: CTCC outputs can be used to estimate GHG benefits for existing trees or to forecast future benefits.

- **Q: Can I obtain outputs for dead trees?**
  A: Yes. The carbon stored in dead trees can be reported when used for wood products or bioenergy projects, but will not be registered at this time. Only live trees, however, are eligible for energy conservation projects.

- **Q: How can I keep track of the results I obtain for each tree?**
  A: Some special steps are required to copy single tree results from the output table to an output template, where data are compiled for many trees. All cells on the 'CTCC' page of the workbook except the gray input section have been locked (using the Excel 'protect' feature) to prevent inadvertent user modification. To copy values from the Results section, this lock can be overridden by going to "Tools" in the main menu, clicking on "Protection", then selecting "Unprotect Sheet". This allows output cells to be selected and data to be copied. If data are to be pasted into another excel workbook, then the user should select "Edit" from the main menu, click on "Paste Special", then select "Values" in the dialog box (necessary since formulas actually populate these cells), and finally click on "OK". For example, cells C35:J35 can be copied from the 'CTCC' page and then pasted as values into successive rows in columns C:J of the 'Output Template' page to create a table

of results.

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