

Appendix B—Methodology and Procedures

This analysis combines results of a citywide inventory with benefit–cost modeling data to produce four types of information:

1. Resource structure (species composition, diversity, age distribution, condition, etc.)
2. Resource function (magnitude of environmental and aesthetic benefits)
3. Resource value (dollar value of benefits realized)
4. Resource management needs (sustainability, pruning, planting, and conflict mitigation)

This Appendix describes street tree sampling, tree growth modeling, and the model inputs and calculations used to derive the aforementioned outputs.

Growth Modeling

Tree growth models for the Northern Mountain and Prairie region were developed from data (McPherson et al. 2003) collected in Fort Collins, CO. Fort Collins serves as the reference city for this region, which includes other areas of the central and northern United States that share similar tree species, tree growth patterns, and environmental conditions. For the regional modeling, a stratified random sample of 847 street trees belonging to the 20 most abundant tree species in Fort Collins was measured to establish relations between tree age, size, leaf area and biomass.

Information spanning the life cycle of predominant tree species was collected. The inventory was stratified into nine DBH classes for sampling:

- 0–3 in (0–7.62 cm)
- 3–6 in (7.62–15.24 cm)
- 6–12 in (15.24–30.48 cm)
- 12–18 in (30.48–45.72 cm)
- 18–24 in (45.72–60.96 cm)
- 24–30 in (60.96–76.2 cm)
- 30–36 in (76.2–91.44 cm)
- 36–42 in (91.44–106.68 cm)
- >42 in (>106.68 cm)

Thirty-five to 70 trees of each species were randomly 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 bole height (to nearest 0.5 m by clinometer), 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 was determined using historical planting records. Fieldwork in Fort Collins was conducted in June and July 2002.

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 ($\pm 20\%$ of actual leaf area) in estimating crown volume and leaf area of open-grown trees (Peper and McPherson 2003).

Nonlinear regression was used to fit predictive models—with DBH as a function of age—for each of the 20 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).

The public trees of Boulder were fitted to the growth models for the Northern Mountain and Prairie climate region. The information used is based on the city’s tree inventory which began in 1986 for street trees and in 1988 for park trees; a reinventory was completed in 2002 and 2004 for street and park trees, respectively.

Identifying and Calculating Benefits

Annual benefits for Boulder’s municipal trees were estimated for the fiscal year 2004. 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. (Calculations of CO₂ released due to decomposition of wood from removed trees do consider average annual mortality.) This approach directly connects benefits with tree-size variables such as DBH and LSA (leaf surface area). Many functional benefits of trees are related to processes that involve interactions between leaves and the atmosphere (e.g., interception, transpiration, photosynthesis); therefore, benefits increase as tree canopy cover and leaf surface area increase.

For each of the modeled benefits, an annual resource unit was determined on a per-tree basis. Resource units are measured as kWh of electricity saved per tree; kBtu of natural gas conserved per tree; lbs of atmospheric CO₂ reduced per tree; lbs of NO₂, PM₁₀, and VOCs reduced per tree; ft³ of stormwater runoff reduced per tree; and ft² of leaf area added per tree to increase property values.

Prices were assigned to each resource unit (e.g., heating/cooling energy savings, air-pollution absorption, stormwater-runoff reduction) using economic indicators of 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 economics). 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 provides first-order approximations. It is 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 science-based platform for decision-making.

Energy Savings

Buildings and paving, along with little tree canopy cover and soil cover, increase the ambient temperatures within a city. Research shows that even in temperate climate zones temperatures in urban centers are steadily increasing by approximately

0.5°F per decade. Winter benefits of this warming do not compensate for the detrimental effects of increased summertime temperatures. Because the electricity demand of cities increases about 1–2% per 1°F increase in temperature, approximately 3–8% of the current electric demand for cooling is used to compensate for this urban heat island effect (Akbari et al. 1992).

Warmer temperatures in cities have other implications. Increases in CO₂ emissions from fossil-fuel power plants, increased municipal water demand, unhealthy ozone levels, and human discomfort and disease are all symptoms associated with urban heat islands. In Boulder, there are opportunities to ameliorate the problems associated with hardscape through strategic tree planting and stewardship of existing trees thereby creating street and park landscapes that reduce stormwater runoff, conserve energy and water, sequester CO₂, attract wildlife, and provide other aesthetic, social, and economic benefits.

For individual buildings, street trees can increase energy efficiency in summer and increase or decrease energy efficiency in winter, depending on their location. During the summer, the sun is low in the eastern and western sky for several hours each day. Tree shade to protect east—and especially west—walls helps keep buildings cool. In the winter, allowing the sun to strike the southern side of buildings can warm interior spaces.

Trees reduce air movement into buildings and conductive heat loss from buildings. The rates at which outside air moves into a building can increase substantially with wind speed. In cold, windy weather, the entire volume of air, even in newer or tightly sealed homes, 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). Decreasing wind speed reduces heat transfer through conductive materials as well. Cool winter winds, blowing against single-pane windows, can contribute significantly to the heating load of homes and buildings.

Calculating Electricity and Natural Gas Benefits

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 (Δ UECs) 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 each of the 20 tree species were simulated at three tree-to-building distances, for eight orientations and for nine tree sizes.

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 Boulder's climate based on consultation with forestry supervisors.

Average energy savings per tree were calculated as a function of distance and direction using tree location distribution data specific to Fort Collins (i.e.

frequency of trees located at different distances from buildings [setbacks] and tree orientation with respect to buildings). 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, independent of location. Location-weighted savings per tree were multiplied by the number of trees of each species and DBH class and then summed to find total savings for the city. Tree locations were based on the stratified random sample conducted in summer 2003.

Land use (single-family residential, multi-family residential, commercial/industrial, other) for right-of-way trees was based on the same tree sample. Park trees were distributed according to the predominant land use surrounding each park. A constant tree distribution was used for all land uses.

Three prototype buildings were used in the simulations to represent pre-1950, 1950–1980, and post-1980 construction practices (Ritschard et al. 1992). Building footprints were modeled as square, which was found to be reflective of 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. Summer thermostat settings were 78°F (25°C); winter settings were 68°F (20°C) during the day and 60°F (16°C) at night. Unit energy consumptions were adjusted to account for equipment saturations (percentage of structures with different types of heating and cooling equipment such as central air conditioners, room air conditioners, and evaporative coolers) (*Table B1*).

Weather data for a typical meteorological year (TMY2) from Denver International Airport were used (Marion and Urban 1995). Dollar values for energy savings were based on Boulder prices for the 2004 for electricity and natural gas prices of \$0.057/kWh and \$0.6312/therm, respectively.

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 modified the effects of shade and climate on heating and cooling loads:

$$\Delta UEC_x = \Delta UEC_{SFD}^{sh} \times F^{sh} + \Delta UEC_{SFD}^{cl} \times F^{cl} \quad \text{Equation 8}$$

where

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

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

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

Changes in energy use for higher density residential and commercial structures were calculated from single-family residential results adjusted by average potential shade factors (APSF) and potential climate factors (PCF); values were set to 1.0 for single family residential buildings.

Subscript x refers to residential structures with 1, 2–4 or ≥ 5 units, SFD to simulated single-family detached structures, sh to shade, and cl to climate effects.

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

$$\text{Total change} = N \times \Delta UEC_x \quad \text{Equation 9}$$

Estimated shade savings for all residential structures were 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; this value was used here ($F_{adjacent\ shade} = 1.15$). 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 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% was used here, equivalent to approximately three existing trees per residence.

In addition to localized shade effects, which were assumed to accrue only to street trees within 18–60 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 as a function of neighborhood canopy cover were estimated 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 0.4°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). A lot size of 10,000 ft² was assumed.

Cooling and heating effects were reduced based on the type and saturation of air conditioning (*Table B1*) or heating (*Table B2*) 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 ($F_{equipment}$). Building vintage distribution was combined with adjusted saturations to compute combined vintage/saturation factors for air conditioning (*Table B3*). Heating loads

28 **Table B1**—*Saturation adjustments for cooling (%)*.

	Single family detached			Mobile homes			Single-family attached			Multi-family 2-4 units			Multi-family 5+ units			Commercial/ industrial		Instit./ 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	
Cooling equipment factors																		
Central air/ heat pump	100	100	100	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	33	33	33
Wall/window unit	25	25	25	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	0	0	0
Cooling saturations																		
Central air/ heat pump	38	56	72	38	56	72	38	56	72	38	56	72	38	56	72	86	86	86
Evaporative cooler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wall/window unit	37	23	25	37	23	25	37	25	26	37	23	25	37	23	25	9	9	9
None	25	21	3	25	21	3	25	21	3	25	21	3	25	21	3	5	5	5
Adjusted cooling saturation	47	62	78	47	62	78	47	62	78	47	62	78	47	62	78	88	88	88

Table B2—Saturation adjustments for heating (%), except AFUE [fraction] and HSPF [kBtu/kWh].

	Single family detached			Mobile homes			Single-family attached			Multi-family 2-4 units			Multi-family 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	
Equipment efficiencies																		
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
HSPF	6.8	6.8	8	6.8	6.8	8	6.8	6.8	8	6.8	6.8	8	6.8	6.8	8	8	8	8
HSPF	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412
Electric heat saturations																		
Electric resistance	2.4	10.9	21.4	2.4	10.9	21.4	2.4	10.9	21.4	2.4	10.9	21.4	2.4	10.9	21.4	4.9	4.9	4.9
Heat pump	0.4	1.8	3.6	0.4	1.8	3.6	0.4	1.8	3.6	0.4	1.8	3.6	0.4	1.8	3.6	5.4	5.4	5.4
Adjusted electric heat saturations	0.4	1.7	2.9	0.4	1.7	2.9	0.4	1.7	3.9	0.4	1.7	2.9	0.4	1.7	2.9	0.4	1.7	2.9
Natural gas and other heating saturations																		
Natural gas	69	61	50	69	61	50	69	61	50	69	61	50	69	61	50	69	61	50
Oil	18	19	0	18	19	0	18	19	0	18	19	0	18	19	0	0	0	0
Other	10	8	25	10	8	25	10	8	25	10	8	25	10	8	25	0	0	0
NG heat saturations	97	87	75	97	87	75	97	87	75	97	87	75	97	87	75	90	90	90

54 **Table B3**—Building vintage distribution and combined vintage/saturation factors for heating and air conditioning.

	Single family detached			Mobile homes			Single-family attached			Multi-family 2-4 units			Multi-family 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	37	41	22	37	41	22	37	41	22	37	41	22	37	41	22	100	100	100
Tree distribution by vintage and building type	18.3	20.4	11.2	2.01	2.24	1.23	1.41	1.57	0.86	1.81	2.01	1.10	2.09	2.33	1.28	11.6	6.8	11.7
Combined vintage, equipment saturation factors for cooling																		
Cooling factor: shade	8.46	12.4	8.56	0.93	1.36	0.94	0.57	0.84	0.58	0.62	0.90	0.62	0.40	0.58	0.40	3.6	1.0	0.0
Cooling factor: climate	8.65	12.7	8.75	0.96	1.40	0.97	0.42	0.61	0.42	0.43	0.62	0.43	0.48	0.70	0.48	9.7	19.0	0.0
Combined vintage, equipment saturation for heating																		
Heating factor, natural gas: shade	17.4	17.4	8.22	1.91	1.91	0.90	1.18	1.18	0.56	1.27	1.27	0.60	0.82	0.82	0.38	3.6	1.1	0.0
Heating factor, electric: shade	0.06	0.33	0.32	0.01	0.04	0.03	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.02	0.01	0.07	0.02	0.00
Heating factor, natural gas: climate	17.8	17.8	8.40	0.87	0.87	0.41	1.02	1.02	0.48	0.74	0.74	0.35	0.54	0.54	0.25	8.2	16.1	0.0
Heating factor, electric: climate	0.07	0.34	0.33	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.01	0.01	0.16	0.31	0.0

were converted to fuel use based on efficiencies in *Table B2*. The “other” and “fuel oil” heating equipment types were assumed to be 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 B3*).

Multi-Family Residence Analysis

Unit energy consumptions (UECs) from single-family residential UECs were adjusted for multi-family residences (MFRs) to account for reduced shade resulting from common walls and multi-story construction. To do this, potential shade factors (PSFs) were calculated 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). A PSF of 1 indicates that all exterior walls and roof are exposed and could be shaded by a tree, while a PSF of 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 multi-family residences of 2–4 units and 0.41 for ≥ 5 units.

Unit energy consumptions were also adjusted to account for the reduced sensitivity of multi-family buildings with common walls to outdoor temperature changes. 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).

Commercial and Other Buildings

Reductions in 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 window 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-effect 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 (1992) and others who observed that commercial buildings are less sensitive to outdoor temperatures than houses.

The beneficial effects of shade on UECs tend 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 700–3,500 ft²) is often larger than the building surface areas being shaded. A point is reached, however, at which no additional area is shaded as surface area increases. At this point, Δ UECs will tend to level off as CFA increases. Since information on the precise relationships between change in UEC, CFA, and tree size is not available, it was conservatively assumed that Δ UECs in *Equation 9* did not change for C/I and I/T land uses.

Atmospheric Carbon Dioxide Reduction

Sequestration (net rate of CO₂ storage in above- and below-ground biomass over the course of one growing season) is calculated for each species using the tree-growth equations for DBH and height, described above, to calculate either tree volume or biomass. Equations from Pillsbury et. al (1998) are used to calculate volume. Fresh weight (kg/m³) and specific gravity ratios from Alden (1995, 1997) are then applied to convert volume to biomass. When volumetric equations for urban trees are unavailable, biomass equations derived from data collected

in rural forests are applied (Tritton and Hornbeck 1982; Ter-Mikaelian and Korzukhin 1997).

Carbon dioxide released through decomposition of dead woody biomass varies with characteristics of the wood itself, the 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 assumed 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 CO₂ 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 Boulder was 5.0% per year for the first five years after planting for street trees and 2.0% per year for the first five years for park trees and 0.85% every year thereafter for street trees and 0.57% for park trees (Bussi-Sottile and Alexander 2005). Finally, CO₂ released during tree maintenance was estimated to be 0.21 lb CO₂/in DBH based on annual fuel consumption of gasoline (3,020 gal) and diesel fuel (1,040 gal) (Bussi-Sottile and Alexander 2005).

Calculating Avoided CO₂ Emissions

Reducing building energy use reduces emissions of CO₂. Emissions were calculated as the product of energy use and CO₂ emission factors for electricity and heating. Heating fuel is largely natural gas and electricity in Boulder. The fuel mix for electrical generation included natural gas (14%) and coal (80%) (U.S. EPA 2003).

Emissions factors for electricity (lb/MWh) and natural gas (lb/MBtu) fuel mixes are given in Table B-4. The monetary value of avoided CO₂ was \$0.0075/lb based on average high and low estimates for emerging carbon trading markets (CO2e.com 2002) (Table B4).

Improving Air Quality

Calculating Other Avoided Emissions

Reductions in building energy use also result in reduced emissions of criteria air pollutants (those for which a national standard has been set by the EPA) from power plants and space-heating equipment. This analysis considered volatile organic hydrocarbons (VOCs) and nitrogen dioxide (NO₂)—both precursors of ozone (O₃) formation—as well as sulfur dioxide (SO₂) and particulate matter of <10 micron diameter (PM₁₀). Changes in average annual emissions and their monetary values were calculated in the same way as for CO₂, again using utility specific emission factors for electricity and heating fuels (U.S. Environmental Protection Agency 2002). The price of emissions savings were derived from models that calculate the marginal cost of controlling different pollutants to meet air quality standards (Wang and Santini 1995). Emissions concentrations (Table B4) were obtained from U.S. EPA (2004), and a population estimate of 103,216.

Calculating Deposition and Interception

Table B-4—Emissions factors and monetary implied values for CO₂ and criteria air pollutants.

	Emission factor		Implied value ¹ (\$/lb)
	Electricity (lb/MWh)	Natural gas (lb/MBtu)	
CO ₂	2,210	118.0	0.0075
NO ₂	3.650	0.0922	2.54
SO ₂	5.650	0.0006	0.90
PM ₁₀	0.903	0.0075	0.45
VOCs	0.861	0.0054	2.39

¹\$15/ton for CO₂ from CO2e.com (2001), values for all other pollutants are based on methods of Wang and Santini (1995) using emissions concentrations from U.S. EPA (1998) and population estimates from the U.S. Census Bureau (2003).

Trees also remove pollutants from the atmosphere. The hourly pollutant dry deposition per tree is expressed as the product of the deposition velocity $V_d = 1/(R_a + R_b + R_c)$, pollutant concentration (C), canopy projection (CP) area, and time step. Hourly deposition velocities for each pollutant were cal-

culated using estimates for the resistances R_a , R_b , and R_c estimated for each hour over a year using formulations described by Scott et al. (1998). Hourly concentrations for NO_2 , SO_2 , O_3 and PM_{10} and hourly meteorological data (i.e., air temperature, wind speed, solar radiation) for Boulder were obtained from the Colorado Department of Public Health and Environment (Hague 2003). The year 1999 was chosen because data were available and it closely approximated long-term, regional climate records.

Deposition was determined for deciduous species only when trees were in-leaf. A 50% re-suspension rate was applied to PM_{10} deposition. Methods described in the section “Calculating Avoided Emissions” were used to value emissions reductions; NO_2 prices were used for ozone since ozone control measures typically aim at reducing NO_2 .

Calculating BVOC Emissions

Emissions 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 in the form of isoprene and monoterpene are expressed as products of base emission factors and leaf biomass factors adjusted for sunlight and temperature (isoprene) or simply temperature (monoterpene). Annual dry foliar biomass was derived from field data collected in Fort Collins, CO, during summer 2002. The amount of foliar biomass present for each year of the simulated tree’s life was unique for each species. Hourly air temperature and solar radiation data for 1999 described in the pollutant uptake section were used as model inputs.

Hourly emissions were summed to get annual totals. This is a conservative approach, since the benefits associated with lowered summertime air temperatures and the resulting reduced hydrocarbon emissions from biogenic as well as anthropogenic sources were not accounted for. The cost of these emissions is based on control cost estimates and was valued at \$4.99/lb for Boulder (Table B-4).

Reducing Stormwater Runoff

Calculating Stormwater Runoff Reductions

A numerical simulation model was used to estimate annual rainfall interception (Xiao et al. 1998). The interception model accounts for rainwater intercepted by the tree, as well as throughfall and stem flow. Intercepted water is stored on canopy leaf and bark surfaces. Once the storage capacity of the tree canopy is exceeded, rainwater temporarily stored on the tree surface will drip from the leaf and stem surface or flow down the stem surface to the ground. Some of the stored water will evaporate. Tree canopy parameters related to stormwater-runoff reductions include species, leaf and stem surface area, shade coefficient (visual density of the crown), tree height, and foliage period. Wind speeds were estimated for different heights above the ground; from this, rates of evaporation were estimated.

The volume of water stored in the tree crown was calculated from crown-projection area (area under tree dripline), leaf area indices (LAI, the ratio of leaf surface area to crown projection area), and the depth of water captured by the canopy surface. Species-specific shading coefficient, foliage period, and tree surface saturation storage capacity influence the amount of projected throughfall. Tree surface saturation was 0.04 inches for all three trees. Hourly meteorological and rainfall data for 1998 from the Colorado Agricultural Meteorological Network (COAGMET) (Station: Fort Lupton; latitude 40°00'25"N, longitude 104°50'57"W) and from Boulder, Colorado NOAA station (ID: 05048) were used for this simulation. Annual precipitation during 1998 was 18.1 in (459.74 mm), close to the recent 50-year average annual precipitation of 19.1 in (485.14 mm). Storm events less than 0.1 in (2.5 mm) were assumed not to produce runoff and were dropped from the analysis. More complete descriptions of the interception model can be found in Xiao et al. (1998, 2000).

Boulder has constructed a number of detention ponds for stormwater retention/detention. Data on the construction and maintenance for nine ponds were analyzed to derive average costs citywide.

For a typical 6.5-acre basin, land costs total \$1.78 million (\$274,000/acre) and construction costs are \$1.6 million (\$253,000/acre) (Hunter 2005). The annual cost for operation and maintenance is \$3,000. Assuming a 20-year life before dredging and reconstruction, the total life-cycle cost is \$3.46 million. Assuming the pond adds one foot of depth due to runoff seven times a year, it will store 45 acre-ft of runoff annually over the course of a year. The annual cost of storage in the holding pond is \$0.0118/gal. This price is comparable to the average price for stormwater runoff reduction (\$0.01/gallon) reported in similar studies (McPherson and Xiao 2004).

Aesthetic, Property Value, Social, Economic and Other 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 for planting trees is beautification. Trees add color, texture, line, and form to the landscape softening 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). Consumer surveys have shown that preference ratings increase with the presence of trees in the commercial streetscape. In contrast to areas without trees, shoppers indicated that they shopped more often and longer in well-landscaped business districts, and were willing to pay more for goods and services (Wolf 1999). 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 can contribute to reduced levels of violence, as well as foster safer and more sociable neighborhood environments (Sullivan and Kuo 1996).

Well-maintained trees increase the “curb appeal” of properties. Research comparing sales prices of residential properties with different numbers and sizes of trees suggests that people are willing to

pay 3–7% more for properties with ample trees versus few or no trees. One of the most comprehensive studies on 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 average home sale prices, the value of this benefit can contribute significantly to cities’ property tax revenues.

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 and 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 in and near cities. The act of planting trees can have social value, for community bonds between people and local groups often result.

The presence of trees in cities provides public health benefits and improves the well being of those who live, work and play in cities. Physical and emotional stress has both short-term and long-term effects. Prolonged stress can compromise the human immune system. A series of studies on human stress caused by general urban conditions and city driving showed that views of nature reduce the stress response of both body and mind (Parsons et al. 1998). City nature also appears to have an “immunization effect,” in that people show less stress response if they have had a recent view of trees and vegetation. Hospitalized patients with views of nature and time spent outdoors need less medication, sleep better, have a better outlook, and re-

cover quicker 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).

Certain environmental benefits from trees are more difficult to quantify than those previously described, but can be just as important. Noise can reach unhealthy levels in cities. Trucks, trains, and planes can produce noise that exceeds 100 decibels, twice the level at which noise becomes a health risk. Thick strips of vegetation in conjunction with landforms or solid barriers can reduce highway 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).

Urban forests can be oases, containing more biological diversity than rural woodlands. Numerous types of wildlife inhabit cities and are generally highly valued by residents. For example, older parks, cemeteries, and botanical gardens often contain a rich assemblage of wildlife. Street tree corridors can connect a city to surrounding wetlands, parks, and other greenspace resources that provide habitats that conserve biodiversity (Platt et al. 1994).

Urban and community forestry can provide jobs for both skilled and unskilled labor. Public service programs and grassroots-led urban and community forestry programs provide horticultural training to volunteers across the United States. Also, urban and community forestry provides educational opportunities for residents who want to learn about nature through first-hand experience (McPherson and Mathis 1999). Local nonprofit tree groups, along with municipal volunteer programs, often provide educational materials, work with area schools, and offer hands-on training in the care of trees.

Calculating Changes in Aesthetic, Property Value, Social, Economic and Other Benefits

In an Athens, GA, study (Anderson and Cordell 1988), a large front-yard tree was found to be as-

sociated with an 0.88% increase in average home resale values. In our study, the annual increase in leaf surface area of a typical mature large tree (40-year-old hackberry, average leaf surface area 7,266 ft²) was the basis for valuing the capacity of trees to increase property value.

Assuming the 0.88% increase in property value held true for the city of Boulder, each large tree would be worth \$3,634 based on the 2004 median single-family-home resale price in Boulder (\$413,000) (Boulder County Assessor 2004). However, not all trees are as effective as front-yard trees in increasing property values. For example, trees adjacent to multifamily housing units will not increase the property value at the same rate as trees in front of single-family homes. Therefore, a city-wide street tree reduction factor (0.85) was applied to prorate trees' value based on the assumption that trees adjacent to different land-uses make different contributions to property sales prices. Reductions factors were based on distribution of trees by land use in Fort Collins: single-home residential (59%), multi-home residential (8%), commercial/industrial (12%), vacant/other (6%). The park tree reduction factor was 50% (McPherson et al. 2001).

Given these assumptions, a typical large street tree was estimated to increase property values by \$0.50/ft² of LSA. For example, assuming a single, street tree adds 100 ft² of LSA per year when growing in the DBH range of 12–18 inches, during this period of growth, it effectively adds \$50, annually, to the value of an adjacent home (100 ft² × \$0.50/ft² = \$50).

Estimating Magnitude of Benefits

Resource units describe the absolute value of the benefits of Boulder's street trees on a per-tree basis. They include kWh of electricity saved per tree, kBtu of natural gas conserved per tree, lbs of atmospheric CO₂ reduced per tree, lbs of NO₂, PM₁₀, and VOCs reduced per tree, ft³ of stormwater runoff reduced per tree, and ft² of leaf area added per tree to increase property values. A dollar value was assigned to each resource unit based on local costs.

Estimating the magnitude of the resource units produced by all street and park trees in Boulder required four procedures: (1) categorizing street trees by species and DBH based on the city's street tree inventory, (2) matching other significant species with those that were modeled, (3) grouping remaining "other" trees by type, and (4) applying resource units to each tree.

Categorizing Trees by DBH Class

The first step in accomplishing this task involved categorizing the total number of street trees by relative age (as a function of DBH class). The inventory was used to group trees into 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) 30–36 in
- 8) 36–42 in
- 9) >42 in

Next, the median value for each DBH class was determined and subsequently used as a single value to represent all trees in each class. For each DBH value and species, resource units were estimated using linear interpolation.

Applying Resource Units to Each Tree

The interpolated resource-unit values were used to calculate the total magnitude of benefits for each DBH class and species. For example, assume that there are 300 silver maples citywide in the 30–36 in DBH class. The interpolated electricity and natural gas resource unit values for the class midpoint (33 in) were 348 kWh and 578.1 kBtu per tree, respectively. Therefore, multiplying the resource units for the class by 300 trees equals the magnitude of annual heating and cooling benefits produced by this segment of the population: 54,984 kWh of electricity saved and 91,340 kBtu of natural gas saved.

Matching Significant Species with Modeled Species

To extrapolate from the 20 municipal species modeled for growth to the entire inventoried tree population, each species representing over 1% of the population was matched with the modeled species that it most closely resembled. Less abundant species that were not matched were then grouped into the "Other" categories described below.

Grouping Remaining "Other" Trees by Type

The species that were less than 1% of the population were labeled "other" and were categorized according into classes based on tree type (one of four life forms and three mature sizes):

- Broadleaf deciduous: large (BDL), medium (BDM), and small (BDS).
- Coniferous evergreen: large (CEL), medium (CEM), and small (CES).

Large, medium, and small trees were >40 ft, 25–40 ft, and <25 ft in mature height, respectively. A typical tree was chosen to represent each of the above 15 categories to obtain growth curves for "other" trees falling into each of the categories:

BDL Other = Green ash (*Fraxinus pennsylvanica*)

BDM Other = Norway maple (*Acer platanoides*)

BDS Other = Crabapple (*Malus* spp.)

CEL Other = Blue spruce (*Picea pungens*)

CEM Other = Austrian pine (*Pinus nigra*)

CES Other = Bolleana shore pine (*Pinus contorta*)

When local data did not exist for specific categories (CES), growth data from similar-sized species in a different region were used.

Calculating Net Benefits and Benefit–Cost Ratio

It is impossible to quantify all the benefits and costs produced by trees. For example, owners of property with large street trees can receive benefits from increased property values, but they 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, due to allergies and respiratory ailments related to pollen. The values 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 “property value and other benefits.” Other types of benefits we can only describe, such as the social, educational, and employment/training benefits associated with the city’s street tree resource. To some extent connecting people with their city trees reduces costs for health care, welfare, crime prevention, and other social service programs.

Boulder residents can obtain additional economic benefits from street trees depending on tree location and condition. For example, street trees can provide energy savings by lowering wind velocities and subsequent building infiltration, thereby reducing heating costs. This benefit can extend to the neighborhood, as the aggregate effect of many street trees reduces wind speed and reduces city-wide winter energy use. Neighborhood property values can be influenced by the extent of tree canopy cover on streets. The community benefits from cleaner air and water. Reductions in atmospheric CO₂ concentrations due to trees can have global benefits.

Net Benefits and Costs Methodology

To assess the total value of annual benefits (*B*) for each park and street tree (*i*) in each management area (*j*), benefits were summed:

$$B = \sum_1^n j \left(\sum_1^n i (e_{ij} + a_{ij} + c_{ij} + h_{ij} + p_{ij}) \right)$$

Equation 10

where

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

a = price of annual net air quality improvement = PM₁₀ interception + NO₂ and O₃ absorption + avoided power plant emissions – BVOC emissions

c = price of annual carbon dioxide reductions = CO₂ sequestered – releases + CO₂ avoided from reduced energy use

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

p = price of aesthetics = annual increase in property value

Total net expenditures were calculated based on all identifiable internal and external costs associated with the annual management of municipal trees citywide (Koch 2004). Annual costs for the municipality (*C*) were summed:

$$C = p + t + r + d + e + s + c + l + a + q$$

p = annual planting expenditure

t = annual pruning expenditure

r = annual tree and stump removal and disposal expenditure

d = annual pest and disease control expenditure

e = annual establishment/irrigation expenditure

s = annual price of repair/mitigation of infrastructure damage

c = annual price of litter/storm clean-up

l = average annual litigation and settlements expenditures due to tree-related claims

a = annual expenditure for program administration

q = annual expenditures for inspection/answer service requests

Total citywide annual net benefits as well as the benefit–cost ratio (BCR) were calculated using the sums of benefits and costs:

$$\text{Citywide Net Benefits} = B - C \quad \text{Equation 11}$$

$$\text{BCR} = B - C \quad \text{Equation 12}$$