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ADDITIONAL SAMPLING AND ESTIMATION DETAILS FOR URBAN FOREST INVENTORY AND ANALYSIS REPORTS
Version 2

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INTRODUCTION

This document is a supplement to some reports provided by the Urban Forest Inventory and Analysis (Urban FIA) program of the Forest Service, an agency of the U.S. Department of Agriculture. The reports can be found in the Treesearch collection of publications by searching for the keyword phrase "urban forest inventory". This version 2 is a supplement to reports written for the inventory years of 2020 to 2022. Both versions of the supplement can be found in the Understory collection of documents.

Additional details about the Urban FIA program, including resources and data tools, are available on the Urban FIA website.

UNDERSTANDING SAMPLING

In most cases, it is not feasible to count every element of a population. This limitation is particularly true in a **forest**[1] inventory because tallying every tree is prohibitively expensive and time consuming. As such, sampling is used to estimate attributes of interest for the population (e.g., number of trees). Sample size, plot design, measurement procedures, and ecological modeling all impact the degree of uncertainty associated with the resulting estimates. It is critical to understand these influences and to consider the level of confidence in an estimate when using the data for decision making.

All estimates based on a sample of the population have a degree of uncertainty that is expressed numerically as either a standard error (SE) or a percent sampling error. Standard errors are commonly used to construct confidence intervals (CI), which are informally interpreted as a range of values within which the true population value resides with a defined probability. The range of values encompassed by the estimate ± 1 SE represents a roughly 68.0 percent confidence interval; similarly, the estimate ± 2 SE represents a 95.0 percent confidence, and the estimate ± 3 SE represents a 99.7 percent confidence interval. For example, if a population estimate is 1,000 trees with an SE of 100 trees, there is a 68.0 percent probability that the true total number of trees in the population is between 900 and 1,100; a 95.0 percent probability the true population total is between 800 and 1,200 trees; and 99.7 percent probability the true population total is between 700 and 1,300 (Fig. S1). The smaller the SE, the narrower the interval will be for a given level of confidence.

In the Urban FIA city reports, we provide the estimate and SE in tables and estimates with 68 percent confidence intervals (± 1 SE) in figures. For example, the estimate above would be reported as 1,000 trees ± 100 trees. A smaller SE and associated narrower CI means that the population attributed is estimated more precisely (i.e., contained in a narrower range). The SE and percent sampling error associated with an estimate are primarily influenced by the number of plots, the plot size, and the population variability of the attribute being estimated. As an example of population variability, consider that tree densities can vary significantly throughout a city, ranging from a sparsely treed downtown to much denser tree populations within park or recreation areas. Figure S2 shows three examples of different samples that could be obtained from the same landscape to estimate total trees. Typically, true population parameters are unknown because measuring all trees within a landscape is not feasible. Each random sample yields an estimate that is close, but not exact, to the true population total. Increasing the number of plots increases the level of precision (reduces SE) of the estimate, but this also increases the cost and time associated with data collection. Urban FIA aims to sample approximately 200 plots in each city. Evidence suggests that sampling on 200 plots maximizes the trade-off between logistical and financial feasibility and precision of resulting estimates (Nowak et al. 2008b).

[1] See glossary in main report for definition of bolded terms.

The Urban FIA program estimates attributes of the urban forest using a hexagonal grid-based systematic sampling with random plot placement within each grid cell. Plots consist of a 1/6 acre circle with a radius of 48.0 feet. Each plot contains four nested microplots, each 1/300 acre in size with a radius of 6.8 feet and offset 12 feet horizontally in the four cardinal directions from the plot center (Fig. S3).

Various data are collected from either the entire plot or from within the smaller microplots. Using this random sample, population estimates can be divided into smaller divisions (e.g., land use classes). Subdivisions allow for a better understanding of the differences among subclasses, but the uncertainty in the estimates may be higher because there tends to be larger population variability within the subclasses.

In Urban FIA, trees less than 5.0 inches in **diameter** are measured on the four microplots, the combined area of which covers approximately 1/12 the area of the full 1/6 acre Urban FIA plot (Fig. S3). Estimates from data collected on microplots tend to display greater variability due to the smaller plot size, which results in larger standard errors and wider confidence intervals compared to estimates for variables measured across the full plot. Standard error will also increase for estimates that express subsets of attributes such as number of trees for a certain species or diameter class. In general, the more information that is available about an attribute, the smaller the standard error and percent sampling error and the more reliable the estimate.

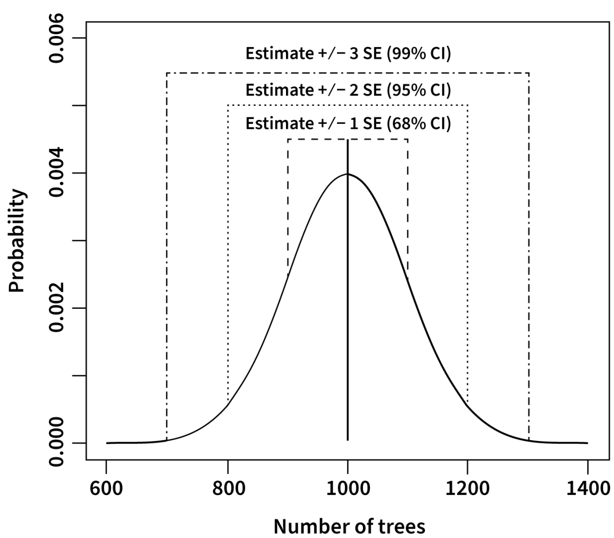
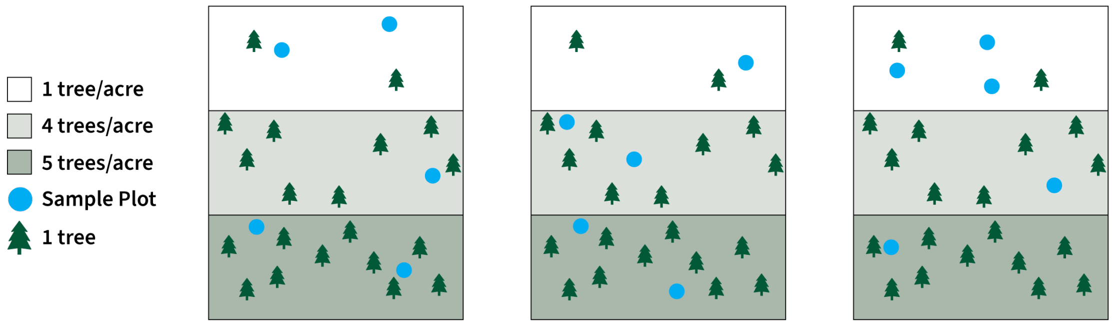


Figure S1.—An example of a normal distribution of the estimated number of trees in a population with a sample-based population estimate of 1,000 trees (black line) and a standard error (SE) of 100 trees. Confidence intervals (CI) corresponding to roughly 68 percent confidence (dashed line), 95 percent confidence (dotted line), and 99 percent confidence (dashed and dotted line) are also shown.



Sample Estimate #1

$$\frac{(1+1+4+5+5)\,\frac{\text{trees}}{\text{acre}}}{5\text{ plots}} = 3.2\,\frac{\text{trees}}{\text{acre}}$$

$$3.2\,\frac{\text{trees}}{\text{acre}} \times 6\text{ acres} = 19.2\text{ trees}$$

Sample Estimate #2

$$\frac{(1+4+4+5+5)\,\frac{\text{trees}}{\text{acre}}}{5\text{ plots}} = 3.8\,\frac{\text{trees}}{\text{acre}}$$

$$3.8\,\frac{\text{trees}}{\text{acre}} \times 6\text{ acres} = 22.8\text{ trees}$$

Sample Estimate #3

$$\frac{(1+1+1+4+5)\,\frac{\text{trees}}{\text{acre}}}{5\text{ plots}} = 2.4\,\frac{\text{trees}}{\text{acre}}$$

$$2.4\,\frac{\text{trees}}{\text{acre}} \times 6\text{ acres} = 14.4\text{ trees}$$

Figure S2.—Examples of random sampling of plots and resulting population estimates for total number of trees in a 6-acre urban forest. The example landscape includes areas where trees are sparse and areas where trees are abundant, shown as light and darker shades of green. On average, there are 3.3 trees/acre for this population [(1+4+5)/3] on the 6 acres, for 20 total trees. But typically, true population parameters are unknown because measuring all trees within a landscape is not feasible. For each plot, the number of trees per acre is calculated and then averaged across all plots to calculate mean trees/acre. The mean trees/acre is then multiplied by the area (6 acres) to calculate the sample estimate for total trees. As shown, random samples yield an estimate that is close, but not exact, to the true population total.

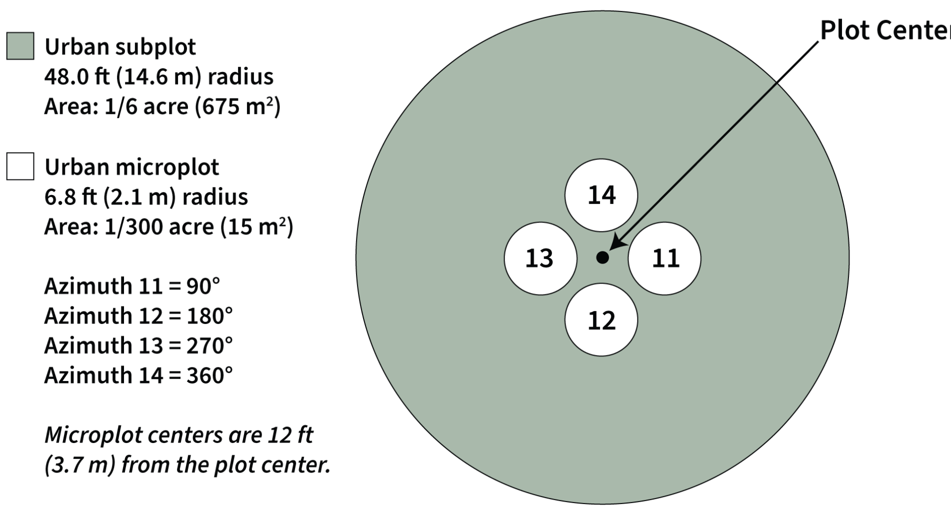


Figure S3.—Urban Forest Inventory and Analysis plot diagram (adapted from USDA Forest Service 2017).

The results of the inventory of a city's forest resources presented in an Urban FIA report should be approached with the understanding that, as with all estimates, there is some level of uncertainty. For example, because of a scarcity of models specific to urban settings, many estimates are derived from models developed for forested settings. As a result, these forest-based modeled estimates may not reflect urban-specific conditions impacting urban trees. Increased data collection in urban forests may allow for the development of more urban-specific models in the future. Additionally, as discussed above, sampling involves inherent uncertainty. While it is well established that random sampling methods are statistically unbiased, some species or tree sizes might not be sampled even though they are present in the population. It is also possible that a species may be overrepresented within the sample. This outcome is due to the nature of sampling, and the results reflect the observations made at randomly selected plot locations within the boundary of the project. In general, however, the probability of an observation is proportional to how common it is within the population. The standard errors and confidence intervals associated with an estimate should be considered to help determine the confidence in the estimate.

When results are compared across reporting years, differences in the estimates will reflect various changes in the data. Obvious causes for these differences include visible physical changes such as tree growth, mortality, or the presence of new trees which have been established through planting or natural regeneration. Other differences when comparing results from one year to another can be caused by less intuitive changes. For example, the values calculated for ecosystem services depend on models in i-Tree, a software suite of urban and rural forestry analysis and benefits assessment tools, which include data such as regional rainfall and weather patterns, estimated energy pricing, and localized pollution levels. As these model input values change over the years, the resulting calculations of ecosystem services will differ. Differences in results between sampling years can also occur due to changes in the sample area itself. Although the intent is to continuously sample the same research plots, the sample area does change slightly from one measurement cycle to the next. For example, many plots are on private property, and a landowner may allow access to a plot during the first visit but not for the next visit. Another example is as city boundaries expand, additional plots may be added to the sample. In other cases, reporting may occur before all the research plots have been visited due to procedural constraints. When these types of changes in the sample occur, they frequently cause slight differences in the resulting estimates. Occasionally they may cause more noticeable differences such as when an uncommon species is abundant on a plot for which the landowner granted permission for the first visit, but not for the second. Awareness of these complexities is useful when reviewing the results in Urban FIA reports.

METHODOLOGY

Urban FIA Sample and Data Collection

The Urban FIA inventory sampling within cities consists of various measurements collected on a set of plots located randomly within evenly sized hexagonal cells covering the entirety of the sampling area for a city. This section provides a brief summary of the methodology and procedures data collectors follow when measuring attributes of field-visited plots. For complete field measurement protocols, refer to the citation in the main text of each Urban FIA report for the correct version of the field guide used within the region. Field crews identify the urban forest inventory sampling locations using Global Positioning System (GPS) units and aerial photographs. All field-visited plots are monumented by measuring distance and azimuth to witness objects. To maintain plot integrity through time, every effort is made to avoid damaging private property and exposing plot locations.

In the urban plot (Fig. S3), data are collected for all live and standing dead trees with a diameter at breast height (d.b.h.) or diameter at root collar (d.r.c.) of 5.0 inches or greater. In the microplots, data are collected on all live and standing dead trees with a d.b.h. or d.r.c. of 1.0 inch through 4.9 inches (i.e., saplings). In FIA, trees are defined based on a regional tree species list that includes exotic and ornamental trees not normally seen on rural forest land. Woody perennial plants not listed are considered shrubs. The complete tree species list for each city is available in the Urban FIA field guide used for the region and year of data collection. The appropriate field guide is cited in the main text of each Urban FIA report and is available, along with other data collection materials, on the Urban FIA website resources page or by contacting the first author of the report.

Generally, inventory crews measure the d.b.h. at 4.5 feet above the ground for each tree. However, for trees identified as **woodland species** on the regional tree species list, measurements are taken of the d.r.c. at the ground line or stem root collar, whichever is farthest from the ground. These d.b.h. and d.r.c. data are collectively referred to as diameter in the urban reports.

In addition to diameter data, inventory crews identify tree species, measure tree length (i.e., measurement of tree from ground level to treetop), and describe tree status, health, and presence of damages. Additional measurements and descriptions are collected for individual tree crowns to further assess crown health and leaf surface area. Crown variables recorded include crown ratio (as a percentage of total tree length), crown class (relative to the surrounding trees), crown light exposure, crown dieback, crown diameter, and the absence of foliage. Inventory crews also note whether each tree is within a maintained area (e.g., as evidenced by the presence of landscaping or maintenance activities) or riparian area, and whether it is a street tree (e.g., located within 8 feet of the edge of a maintained surface roadway) or a planted tree.

Additional data are collected for live and dead trees greater than 20 feet in height located within 60 feet of residential buildings. Measurements of distance and direction to building are used to estimate tree effect on building energy use. The building affected by the tree does not have to be located on the plot. Space-conditioned structures (heated or cooled) are classified as buildings to include if they are no more than three stories (two plus an attic) in height above ground level. i-Tree uses an algorithm for single standing structures no larger than 4,000 square feet in total inhabitable (heated or cooled) space, although single-family homes or duplexes are included regardless of size. Unheated detached garages, sheds, or other outbuildings are not included.

Data collection methods include the delineation of unique condition classes on the urban plot and the determination of condition type (e.g., forest land, nonforest land, water). Forested conditions are further delineated based on such things as forest type, stand classes, and reserve status as outlined in traditional FIA methods. Condition classes on nonforest land are established based on land use, ownership, and reserve status. For each condition on the plot, field crews estimate percentage covers for tree/saplings, shrub/seedlings, buildings, impervious surfaces, permeable surfaces, herbaceous vegetation, and water.

Whole Tree vs. Individual Stem Approach for FIA Reporting

Forest Inventory and Analysis classifies all tree species into either woodland or timber categories. Woodland species are typically small trees characterized by a multi-stemmed growth form. Timber species are generally characterized by the growth of a central stem. In some cases, the bole of a timber tree species will fork aboveground, and if certain criteria are met, the resulting stems are recorded as separate tally trees. Within this framework, FIA has traditionally used the term “tree” to refer to an individual record in the TREE table of the FIA database. If the record is for a woodland species, then the record represents the entire tree, including all the constituent stems. If the record is for a timber species, the record can represent either a whole single stemmed individual or a single stem of a forked tree.

In 2017, Urban FIA data collection methods and the Urban FIA database were changed as outlined in the "National Urban FIA Field Plot Guide Version 7.1" (USDA Forest Service 2017), so that the individual stems of a forked timber tree could be combined and evaluated together to represent the entire tree (mother tree). Most field data for forked trees are still collected at the stem-level, with some exceptions. Crown measurements needed for i-Tree Eco processing, including uncompacted live crown ratio, crown diameter measurements, foliage absent, crown light exposure, and crown dieback, are calculated by using the crowns of all boles, forks, and branches (including any boles or forks supported by the same stump that were not tallied) as a single unit. Other field measurements taken at the whole organism or mother tree level include building energy data and tree labels (e.g., maintained area tree, riparian tree, street tree, and planted tree).

Regardless of how the data are collected in the field, many inventory estimates can be reported at either the stem-level or whole organism (mother tree) level. For example, the number of trees can be reported at the stem-level using traditional FIA methodologies by counting qualifying stems as individual trees, or at the mother tree level by counting the whole organism as one tree unit. For some estimates, individual stem measurements can be collapsed or aggregated into a single organism (mother tree) estimate. For example, a single mother tree diameter can be calculated post-field sampling by taking the square root of the sum of squared diameters of each stem.

In the Urban FIA reports, estimates of species counts, species characteristics, structure (diameters, density, leaf area), species composition (abundance, importance values), energy consumption, carbon avoided, and tree health (damages) are reported for the mother tree. Modeled estimates of volume, biomass, and carbon are compiled using stem-level data, but when they are summarized by tree variables like diameter class, estimates are reported for the mother tree.

All volume estimates are calculated using data from individual stems, not from whole mother trees, because the volume models used are designed for the traditional FIA forest land inventory where stem-based inputs are the standard. Aboveground and belowground biomass estimates are also calculated using individual stem data. Although not presented in this supplement, Urban FIA data do include estimates of leaf biomass and total dry biomass based on mother tree data using i-Tree methodologies. These data are included in the Urban DataMart.

For more information on measurement protocols for stems that divide into two or more branches, refer to FIA forking rules and mother tree methodologies in sections 5.9.2 and 5.12.1 of the "National Urban FIA Field Guide Version 7.1" (USDA Forest Service 2017).

Estimation of Urban Forest Values

Urban FIA field data are analyzed using FIA methodologies and the i-Tree Eco modeling software (Nowak 2024, Nowak and Crane 2000, Nowak et al. 2008a). Both the field data and modeling outputs are incorporated into the Urban FIA database. Results include information about forest structure and associated ecosystem services and monetary values. Structure is a measure of various physical attributes of the urban forest, including tree species composition, number of trees, tree density, tree health, leaf area, biomass, and species diversity. Ecosystem services are determined by forest structure and include attributes such as air pollution removal and carbon storage and sequestration. Monetary values are an estimate of the economic worth of the various forest functions. Detailed methods on estimating urban forest effects are presented in Nowak (2024).

Air pollution removal

Air pollution removal estimates are calculated by the i-Tree Eco model for ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter less than 2.5 microns ($PM_{2.5}$), and carbon monoxide (CO). Estimates are derived from calculated hourly tree canopy resistances for O_3, SO_2, and NO_2 based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi 1988, Baldocchi et al. 1987). Removal rates for $PM_{2.5}$ and resuspension rates vary with wind speed and leaf area as detailed in Nowak et al. (2013).

Pollution removal value, an estimate of the economic value (i.e., cost of illness, willingness to pay, loss of wages, and the value of statistical life) associated with avoided human health impacts, is also calculated by i-Tree Eco. Outputs from the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP) are used to estimate the monetary value resulting from changes in NO_2, O_3, $PM_{2.5}$, and SO_2 concentrations due to pollution removal by trees. BenMAP is an open-source computer program that uses local pollution and population data to estimate the health impacts of human-exposure to changes in air quality and calculates the associated economic value of those changes (Nowak et al. 2014, U.S. EPA 2012).

Avoided runoff

Annual surface water runoff that was avoided (referred to as avoided surface runoff) is estimated by i-Tree Eco based on rainfall interception and evapotranspiration by vegetation and ground surface storage and infiltration or precipitation and is the difference between annual runoff with and without vegetation. The monetary value associated with avoided runoff is based on an estimated national average cost of stormwater control and treatment of $0.008936/gallon (Nowak 2024).

Carbon storage and sequestration

Carbon storage is the amount of carbon bound in the tissue of woody vegetation. Tree diameter and height measurements are used to calculate volume and biomass, which is then used to estimate the amount of carbon a tree stores and sequesters. Volume, biomass, and carbon calculations discussed in this supplement use the National Scale Volume and Biomass (NSVB) modeling system adopted by the Forest Inventory and Analysis program in 2023 (Westfall et al. 2024).

Aboveground carbon is calculated by multiplying the modeled aboveground dry-weight biomass of each component (i.e., bole, stump, and top) of trees at least 1.0 inch in diameter by a species-specific carbon fraction. Biomass of woodland species is not broken down by component but is based on volume for the entire aboveground portion of the tree. Belowground carbon is equal to half the dry-weight biomass of coarse roots, which is based on a modeled ratio estimate from the literature (Chow and Rolfe 1989). The values of aboveground and belowground carbon are summed to calculate a single whole tree carbon storage value as presented in the main report associated with this online supplement.

FIA methods are based on studies of modeled tree volume and biomass for trees grown in forest settings. No adjustments were made to account for the fact that these methods are being applied in urban, nonforest areas where tree roots might be restricted from growing as they would in a natural setting. New models that more closely characterize the appropriate values in urban settings may be developed as more data from urban trees becomes available.

Carbon sequestration is the amount of carbon removed from the atmosphere and turned into tissue by a tree in a single year. Average annual diameter growth and height growth is estimated using i-Tree Eco based on local climate, crown competition level, and tree condition. These values are then added to the existing tree measurements (in year x) to estimate tree diameter and height in year x +1. Carbon is calculated in year x +1 by using NSVB FIA methodologies and i-Tree Eco's predicted future tree diameter and height. The difference between the carbon data for year x and year x + 1 reflects the amount of carbon that has been sequestered.

Carbon storage and sequestration is also estimated in i-Tree Eco using methods described in "Understanding i-Tree" (Nowak 2024). Unlike the FIA methodologies, these model estimates include the carbon contribution of foliage for evergreen trees and apply an adjustment for trees in urban land uses. The i-Tree based carbon estimates are not reported here, but are available online at the Urban DataMart and within the Urban Forest Stats tool.

To estimate the monetary value of carbon storage and sequestration, tree carbon values are based on the estimated social costs of carbon which is a monetary value that encompasses the economic impact of the increased carbon emissions on factors such as agricultural productivity, human health, and property damage (Interagency Working Group on Social Cost of Carbon 2013, Intergovernmental Panel on Climate Change 2014).

Wood volume

In forestry, volume is a measure of the solid content of the tree stem, and this value is used to estimate wood quantity. Volume data presented in the Urban FIA reports is estimated using NSVB methodology adopted by FIA in 2023 (Westfall et al. 2024), which is based on volume equations developed for forest grown trees and includes net cubic-foot volume by diameter class and species and net **board-foot sawtimber volume** by species. As with estimates of belowground biomass, no consensus models exist to specifically estimate the wood volume of urban trees. Estimates in urban areas represent an attempt to characterize urban wood volume given the available tools, which may overestimate or underestimate actual wood volume of urban trees. Cubic foot volume was computed for the central stem from a 1-foot stump deduction to a minimum 4.0-inch top diameter outside of bark. Net cubic foot volume is not calculated for woodland species because they are not typically commercially utilized. Sawtimber volume is the gross volume of wood in the central stem of a commercial tree species of **sawtimber** size (minimum 9.0 inches in diameter for softwoods, minimum 11.0 inches in diameter for hardwoods) from a 1-foot stump to a minimum top diameter outside bark (d.o.b.; 7.0 inches for softwoods, 9.0 inches for hardwoods). The volume calculations make deductions for rot, roughness, and broken tops. Net cubic-foot volume is an estimate of the gross volume in cubic feet minus deductions for **rotten**, missing, and broken-top **cull**. Net board-foot sawtimber volume is an estimate of the gross volume in board feet of the sawlog portion of sawtimber minus deductions for total board-foot cull.

Energy conservation

The effect of trees on residential building energy use is calculated in i-Tree Eco using distance and direction of trees from residential structures, tree height, and tree condition data (McPherson and Simpson 1999). Savings in residential energy costs are calculated based on state average costs for natural gas, heating season fuel oil costs, residential electricity costs, and costs of wood.

Compensatory values

Compensatory values (Nowak et al. 2002) are estimated in i-Tree Eco based on valuation procedures of the Council of Tree and Landscape Appraisers (2000). Following these methods, adjustment factors are applied to each tree to account for the effects of tree species, diameter, tree condition, and land use based on state-level variation in perceived value for each tree species.

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