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# Improved estimates of tree-shade effects on residential energy use

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**Abstract**

Tree-shade alters building cooling and heating loads by reducing incident solar radiation. Estimates of the magnitude of this effect, and how it is influenced by urban forest structure (e.g. tree size and location), are difficult due to the complexity inherent in tree–sun–building interactions. The objective of this paper is to present a simplified method for making these estimates appropriate for neighborhood and larger scales. The method uses tabulated energy use changes for a range of tree types (e.g. size, shape) and locations around buildings (lookup tables), combined with frequency of occurrence of trees at those locations. The results are average change in energy use for each tree type that are not explicitly dependent on tree location. The method was tested by comparison to detailed simulations of 178 residences and their associated trees in Sacramento, California. Energy use changes calculated using lookup tables matched those from detailed simulations within ±10%. The method lends itself to practical evaluation of these shading effects at neighborhood or larger scales, which is important for regional assessments of tree effects on energy use, and for development of tree selection and siting recommendations for proposed energy conserving planting programs.

*Keywords:* Tree shade; Building energy use; Simulation modeling

## 1. Introduction

The rapidly increasing pace of world-wide urbanization hastens the need for improved understanding of environmentally beneficial urban forestry practices. Urbanization, especially if haphazard, can result in increased urban temperature, energy use, carbon dioxide emissions from fossil fuel power plants, municipal water demand, ozone levels, and human discomfort and disease [5]. These problems are accentuated by global climate change, which may double the rate of urban warming [2]. The extent to which urban forestry can mitigate these effects depends in large part on development of better tools to quantify the cost-effectiveness of alternate strategies and demonstrate their potential benefits [6,16,22].

Urban forests modify climate and building energy use through (1) shading, which reduces the amount of radiant energy absorbed and stored by built surfaces; (2) evapotranspiration, which converts liquid water in plants to vapor, thereby cooling the air; and (3) wind speed reduction, which reduces infiltration of outside air, effectiveness of ventilation, and convective cooling of building surfaces [25]. Alterations in long-wave radiation between a building and its surroundings from addition of trees have small effects compared to those from shade [8]. The focus of this paper is an improved method for estimating amount and timing of building shading from trees and its effects on cooling and heating energy use. Simple characterization of shading effects is complicated by the many possible permutations of building type, building surface orientation, tree location with respect to each building surface, tree size, canopy density, solar angle (time of day), season and microclimate. Given the difficulties associated with a measurement program that includes all of these factors, simulation models have been a necessary and practical alternative for evaluating these effects.

### 1.1. Simulation models

Simulation models that account for tree configuration (species, age and location), building characteristics (e.g. window area, building orientation, level of insulation), and weather conditions can be used to estimate effects of tree-shade on heating and cooling energy use [7,8,15,27]. Their use on a large scale has been limited due to their complexity and data requirements. Buildings representative of a range of construction practices have been used to

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account for differences in building energy use characteristics; housing stock data for all regions of the US are available (e.g. [21]). Weather data, important model inputs, are available for most regions of the country [10,21].

### 1.2. Tree structure

Irradiance reductions are a function of extent and transmissivity of tree crowns. Tree-shade has been modeled as a uniform irradiance reduction constant over time [15], as a plane horizontal building shade uniformly distributed around a building [8], as a horizontal cylinder simulating a continuous row of trees [30], as rectangular solids placed strategically next to a building [8], and as three-dimensional solids of revolution: spheroids, paraboloids, cylinders, etc. [17,31]. Canopy transmissivity is accounted for using shade coefficients which typically range from 0.5 to 0.9 for leaf-on and from 0.1 to 0.3 for leaf-off periods [11], independent of the method used to describe extent of shade.

### 1.3. Tree size and location

Changing tree size (determined by species and age) or location (defined by tree–building distance and tree azimuth with respect to a building) results in dramatic variation in amount and timing of building shade [26]. Tree azimuth is true compass bearing of a tree relative to a building. Effects of mature, medium-sized, deciduous trees have most often been modeled [8,14,26,30]. McPherson [12] treats trees of 7.3, 11.0, and 15.2 m height. These sizes can be interpreted as corresponding roughly to tree ages of 20, 30 and 45 years, or mature trees of small, medium and large size. Species differences are accounted for primarily by assigning trees to mature size classes, and distinguishing between evergreen and deciduous leaf patterns. More precise information on species-dependent size and structural characteristics of urban tree crowns is becoming available [20].

Tree azimuth is most often accounted for by placing tree(s) in various combinations adjacent to frequently sunlit building walls, e.g. those facing east, south or west. Generally only a few azimuths are considered [8,12,14,30]; a full range of azimuths is less commonly treated [26]. Tree–building distances of 2–5 m are most common [8,14,30], where trees approach but do not overhang the roof. McPherson [12] treated distances of 3.6, 6.7 and 10.4 m for one scenario in Chicago. Jones and Stokes Associates Inc. [9] proposed savings inversely proportional to the square of the distance to the building, and proportional to the square of canopy diameter. In terms of real-world applications, there is little available information about tree location with respect to buildings of different types as a function of species and age. Ground surveys of selected properties [27] and interpretation of aerial photographs [13,18] have been used to tabulate frequency of occurrence of trees at various locations around residences in Sacramento, California.

### 1.4. Existing shade and tree overlap

The actual incremental shade on a building surface from addition of a tree as part of a planting program is in part determined by the amount of shade on that surface from existing trees, from other program trees, or from adjacent structures such as fences or nearby buildings. Simpson and McPherson [27] calculated shading from each tree and structure within 18 m. It is difficult in practice to explicitly account for all solar obstructions, especially those near the horizon, so that a global reduction in solar radiation that accounts for existing trees and structures is often used. While resulting effects on energy use are relatively insensitive to the exact value of the reduction factor used [25], failure to account for existing shade inflates the impact of proposed tree planting.

Energy use changes resulting from addition of trees will be diminished to the extent of coincident shading from pre-existing trees. Reductions from multiple trees have been accounted for implicitly in tabulated values (Jones and Stokes Associates Inc. [9]). The reduction factor is approximately 5% per tree, based on Simpson and McPherson's [27] observation that an added tree produced changes in energy use that were 20–30% less than that for the first tree (200 kWh per tree for cooling and 1.0 GJ for heating annually) when there were a total of three–six trees already present.

### 1.5. Measurements

While direct comparison of measured and simulated effects of tree-shade on building energy use are few, measurements generally tend to confirm the magnitude of simulation results. Meier [19] reviewed several studies where air-conditioning savings from landscaping were directly measured, concluding that savings of 25–50% are likely through use of trees in the landscape. Akbari et al. [1] compared air-conditioning energy use before and after positioning 16 containerized trees (8 were $\sim$6 m high, and 8 $\sim$2.5 m high) so as to shade the southeast and southwest exposures of two residences in Sacramento. Measured savings, determined by comparing energy use before and after the addition of shade trees, averaged about 30% for both sites. Simulated savings were conservative, underestimating measured usage on days with higher cooling loads by up to 50%, with better agreement for lower cooling loads. Simpson [24] found good short term agreement between measured and simulated energy use for 1/4-scale model buildings surrounded by turf and rock ground covers.

### 1.6. Scale effects

Planting trees throughout a city will lead to changes in the energy balance that effect the climate of the entire city, primarily air temperature, wind speed, and vapor pressure.

On balance, these large scale effects have been found to reduce building energy use [3,8,29]. Wind speed reductions were found to often lead to increases in cooling load, but these were much smaller than savings from either shade or reduced air temperature. Measurements made in and around 0.05–1.1 ha urban wooded sites [23], 25 ha park [4], and 10–40 ha residential areas [28] confirm air temperature reductions from trees that extend outside the treed area up to four times the width of the site. These measurements also showed that vapor pressure differences were small between treed and adjacent untreed locations.

## 2. Objectives

Despite the knowledge of tree-shade effects on building energy use accumulated over the past 20 years, practical methods for their estimation are lacking. Such methods should incorporate interactions between building construction and orientation, tree size and location, and changing solar position and climate, but without requiring detailed calculations. The objective here is to describe a practical, simplified method to quantify tree-shade effects on large numbers of buildings to account for these interactions that lends itself to scaling up to neighborhood or larger areas. This is accomplished by combining (1) tabulated energy savings for typical tree and building configurations (lookup tables) with (2) tree location by distance and direction from buildings (tree distributions). Performance of the method is evaluated by comparison with detailed simulations of 178 homes in Sacramento, California.

## 3. Methods

### 3.1. Model development

Tree-shade effects on building energy use are attributed to either tree configuration, building characteristics, or climate. Tree configuration includes tree type, age and distribution. The term tree type is used to aggregate species-related tree characteristics including mature size (crown height and width, height to live bole [bole height]), growth rate, crown shape, foliation period (for deciduous trees) and shade coefficient for leaf-on and leaf-off periods. Tree distribution is expressed as relative frequency of occurrence of each tree type at selected tree-to-building distances and azimuths (true compass bearing of tree relative to building) (e.g. Table 1). Building characteristics refer to construction practices that influence energy efficiency, such as window area and orientation, and amount of insulation. Orientation refers to the direction a wall or window faces referenced to true north.

Tree location is defined by eight azimuth and three tree–building distance classes (Fig. 1). Tree azimuth classes are defined with reference to building wall orientation. A wall is cardinally oriented if the normal to the wall is within ±45°E of a cardinal direction (N, S, E or W); otherwise, it is intercardinal (NE, SE, SW, NW). For a cardinally oriented building, tree azimuth is cardinal if a line can be drawn normal from the building wall to intersect the tree bole (i.e. the tree is opposite a wall), otherwise it is intercardinal (i.e. the tree is opposite a corner). Distance classes are 3–6, 6–12 and 12–18 m.

Simulating effects of tree-shade on building energy use, while accounting for all possible combinations of these

Table 1
Tree distribution (frequency of occurrence in percent) averaged over tree type, tree–building distance, tree azimuth with respect to buildings, and building vintage for post-1983 Sacramento residences

| Tree type | Tree–building distance (m) | Tree azimuth | | | | | | | | All azimuths | All azimuths and distances |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | NE | E | SE | S | SW | W | NW | | |
| Large/rapid | 0–7.6 | 1.0 | 1.9 | 1.0 | 1.0 | 3.2 | 2.7 | 3.6 | 2.5 | 16.8 | 29.7 |
| | 7.6–12.2 | 0.0 | 0.6 | 0.6 | 1.5 | 1.9 | 2.7 | 2.7 | 0.4 | 10.3 | |
| | 12.2–18.3 | 0.2 | 0.2 | 0.8 | 0.2 | 0.6 | 0.0 | 0.2 | 0.6 | 2.7 | |
| Large/moderate-slow | 0–7.6 | 0.4 | 1.0 | 1.9 | 1.5 | 2.9 | 2.5 | 3.0 | 1.0 | 14.1 | 19.2 |
| | 7.6–12.2 | 0.2 | 0.0 | 1.0 | 0.8 | 0.4 | 0.6 | 1.1 | 0.0 | 4.0 | |
| | 12.2–18.3 | 0.2 | 0.0 | 0.0 | 0.4 | 0.0 | 0.4 | 0.0 | 0.2 | 1.1 | |
| Medium/spreading | 0–7.6 | 0.0 | 0.4 | 2.1 | 1.0 | 1.1 | 1.1 | 1.3 | 0.6 | 7.6 | 12.6 |
| | 7.6–12.2 | 0.0 | 0.2 | 0.8 | 0.8 | 0.0 | 1.0 | 1.0 | 0.6 | 4.2 | |
| | 12.2–18.3 | 0.0 | 0.2 | 0.2 | 0.0 | 0.2 | 0.2 | 0.0 | 0.0 | 0.8 | |
| Medium/upright | 0–7.6 | 0.2 | 1.5 | 1.5 | 1.3 | 1.9 | 2.7 | 2.1 | 1.0 | 12.2 | 14.9 |
| | 7.6–12.2 | 0.2 | 0.0 | 0.6 | 0.4 | 0.6 | 0.2 | 0.4 | 0.2 | 2.5 | |
| | 12.2–18.3 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | |
| Small | 0–7.6 | 0.4 | 1.9 | 3.0 | 2.3 | 2.7 | 3.8 | 3.2 | 2.7 | 20.0 | 23.6 |
| | 7.6–12.2 | 0.8 | 0.2 | 0.2 | 0.4 | 0.8 | 0.2 | 0.6 | 0.4 | 3.4 | |
| | 12.2–18.3 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | |
| All tree types/distances | | 3.4 | 8.2 | 13.5 | 11.6 | 16.2 | 17.9 | 19.2 | 9.9 | 100.0 | 100.0 |

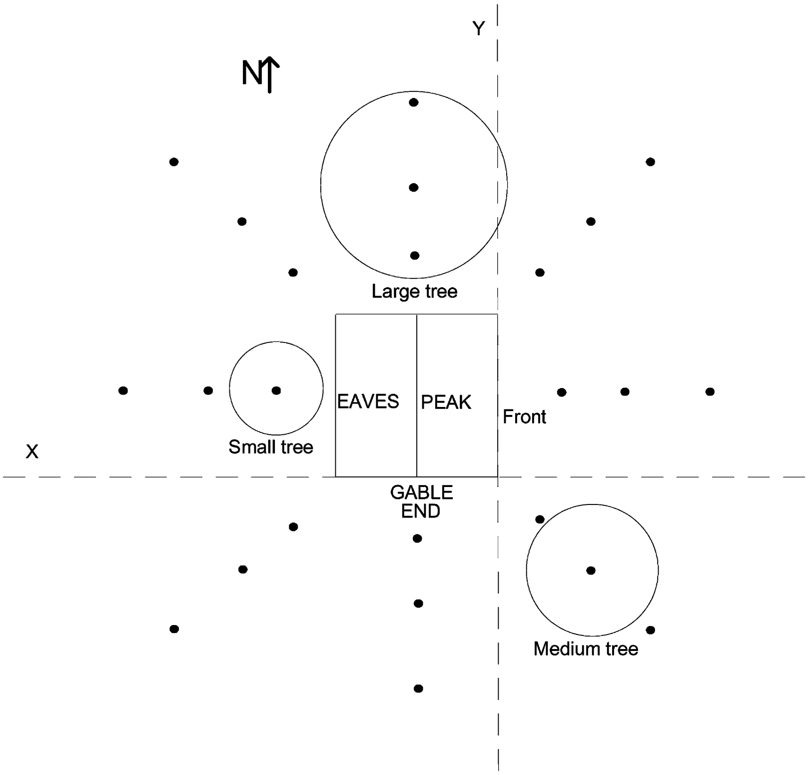

Fig. 1. Example tree locations with respect to a building. Crown projections of small, medium spreading and large, rapid growth trees are illustrated.

effects, is calculation intensive. Simply accounting for three tree types, five tree ages, three tree–building distances and eight azimuths for a single building and climate, for example, requires 360 simulations. Since calculations are performed hourly for a period of 1 year, over 3 million hourly simulations for each surface of each building being modeled are required. The method described here provides average effects of tree-shade on building energy use without "real-time" simulations of shade or building energy use, while still incorporating details about tree and building configuration.

Explicit dependence of changes in energy use on tree location is removed by weighting pre-calculated simulation results for single trees at discrete locations around a building (lookup tables) with tree distribution. Tree distributions for each vintage were constructed by assigning each tree within 18 m of the 178 single story residences described by Simpson and McPherson [27] to 1 of 24 locations described earlier. The difference between this weighted average energy use, with and without a tree, represents the average change in energy use due to shade from addition of a single tree at any location.

Results are adjusted for shade from existing trees and other solar obstructions, as well as addition of multiple trees per building. Multiple tree reduction factors were calculated as $1 + M_t(n-1)$, where $M_t$ is the fractional reduction in average cooling and heating energy use per tree from overlap of multiple program trees and $n$ is number of program trees. $M_t$ values were based on regression analysis of single story home data from Simpson and McPherson [27]. Energy use intensities (energy use per unit area) for both heating and cooling were grouped by vintage and number of trees, then averaged. These values were regressed against number of trees to form estimates of $M_t$. Intensities were used to account for effects of differing building size on the results.

A total of 360 sets of cooling and heating simulations (5 tree types × 24 locations × 3 building vintages) were conducted for single, mature (35-year-old) trees using methods, tree types and building vintages described by Simpson and McPherson [27]. The number of simulations were reduced by using symmetrical buildings, i.e. walls were of identical size and glazed area (see Appendix A to this article for details), with conditioned floor area equal to the average for each vintage. Resulting lookup tables can take a number of forms, and can include multiple tree types for a particular tree age, building type and climate region (Table 2). Total tree-shade impact on energy use for a given region is calculated as the sum of products of change in energy use with total number of trees for each tree type, tree age, and building type, adjusted for multiple trees based on average number of trees per building.

### 3.2. Model evaluation

Average annual changes in cooling and heating energy use per tree from individual simulations of 178 single-story residences in Sacramento, California [27] for each vintage (referred to subsequently as the simulation method), are compared to an analysis of the same data using lookup

Table 2
Lookup table for change in cooling energy use for mature trees and the post-1983 vintage[a]

| Tree type | Tree–building distance (m) | Tree azimuth | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | N | NE | E | SE | S | SW | W | NW |
| Change in site cooling energy use (kWh) | | | | | | | | | |
| Large/rapid | 0–7.6 | 14 | 100 | 276 | 180 | 258 | 183 | 391 | 126 |
| | 7.6–12.2 | 2 | 6 | 238 | 73 | 176 | 116 | 411 | 25 |
| | 12.2–18.3 | 0 | 2 | 136 | 31 | 51 | 66 | 338 | 20 |
| Large/moderate-slow | 0–7.6 | 13 | 79 | 245 | 149 | 246 | 146 | 347 | 95 |
| | 7.6–12.2 | 0 | 4 | 195 | 56 | 134 | 95 | 375 | 21 |
| | 12.2–18.3 | 0 | 1 | 96 | 21 | 29 | 50 | 274 | 15 |
| Medium/spreading | 0–7.6 | 13 | 62 | 229 | 131 | 225 | 139 | 364 | 96 |
| | 7.6–12.2 | 0 | 4 | 155 | 40 | 87 | 70 | 345 | 21 |
| | 12.2–18.3 | 0 | 1 | 49 | 10 | 4 | 26 | 207 | 16 |
| Medium/upright | 0–7.6 | 5 | 5 | 124 | 36 | 111 | 67 | 214 | 22 |
| | 7.6–12.2 | 0 | 2 | 65 | 15 | 24 | 41 | 185 | 13 |
| | 12.2–18.3 | 0 | 0 | 24 | 5 | 2 | 16 | 121 | 8 |
| Small | 0–7.6 | 10 | 5 | 149 | 65 | 146 | 99 | 261 | 28 |
| | 7.6–12.2 | 0 | 1 | 59 | 15 | 20 | 41 | 213 | 15 |
| | 12.2–18.3 | 0 | 0 | 15 | 3 | 0 | 13 | 113 | 8 |

[a] Tables for pre-1978 and 1978–1983 vintages, and heating table for the post-1983 vintage, are not shown.

tables. Effects of existing shade for the simulations were found as the difference between energy use with no shade, and with existing shade from trees, adjacent buildings and other obstructions. Size and location of pre-existing obstructions will not in general be available, so a global shade coefficient ($g$), where $1 - g$ is the constant fraction of solar radiation reduction on building surfaces, was used to account for existing shade in the lookup table method. Global shade coefficients of 0.78, 0.81, and 0.84 for pre-1978, 1978–1983 and post-1983 vintages, respectively, gave the best agreement between lookup tables and simulations (see Section 5.1 for a discussion of this approach).

Results are reported as annual energy use intensity in SI units of kWh/m$^2$ for cooling and MJ/m$^2$ for heating (1.055 MJ = 1.0 kBtu, and 1 m$^2$ = 10.76 ft$^2$).

## 4. Results

Approximately 70% of the 525 program trees planted at the 178 residences were within 7.6 m of buildings, 25% more than 7.6 but less than 12.2 m, and 5% from 12.2 to 18.3 m distant (Table 1). Average tree–building distances ± sample S.D. for these distance classes were 4.7 ± 0.3, 9.4 ± 0.1, and 15.0 ± 0.8 m. Approximately 49% of trees were large, 27% medium, and 24% small; larger trees tend to provide greater benefits.

Cooling and heating lookup tables for each vintage that result are illustrated here with changes in cooling for the post-1983 vintage (Table 2). Multiplying this table cell by cell with tree distribution (Table 1) results in weighted average savings of156 kWh per mature tree for that vintage. Totals for each vintage are calculated as simply the product with tree numbers (Table 3) and multiple tree reduction factor for each vintage. Changes in energy use can be broken out as a function of tree type, distance, or azimuth by simply recalculating the tree distribution. Tree age (size) effects, not explicitly addressed here, can be accounted for through the use of additional lookup tables, or reduction factors specific to tree type.

Total cooling and heating loads from lookup tables compared well with the simulation method (Table 4). Relative differences in energy use for all treatments were within 9% for cooling and 3% for heating (base case energy use is calculated with no shade). Changes in energy use from existing shade ranged from −21 to −24% for cooling, and from 9 to 11% for heating. Changes from addition of program shade referenced to existing shade ranged from −18 to −28% for cooling and from 4 to 7% for heating.

Lookup tables over-estimated changes in energy use for cooling and underestimated them for heating by up to 10% compared to the simulation method (Table 5). Cooling and heating reduction factors ($M_t$) were 6.1% and 4.7% per tree averaged over vintage, respectively, for each tree added after the first. Total reductions for multiple trees ranged 0.93–0.84

Table 3
Average conditioned floor area, building count and numbers of program trees by vintage

| Vintage | Conditioned floor area (m$^2$) | Building count | Program trees per building | Total program trees |
|---|---|---|---|---|
| Pre-1978 | 134 | 63 | 2.2 | 139 |
| 1978–1983 | 153 | 24 | 3.4 | 82 |
| Post-1983 | 151 | 91 | 3.3 | 304 |
| Average/total | 145 | 178 | 2.9 | 525 |

Table 4
Average annual cooling and heating energy use with no shade, existing shade, and existing shade + program trees for simulation method and lookup tables[a]

| Treatment | Simulation method | | | Lookup tables | | | Relative difference (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Pre-1978 | 1978–1983 | Post-1983 | Pre-1978 | 1978–1983 | Post-1983 | Pre-1978 | 1978–1983 | Post-1983 |
| Cooling (kWh) | | | | | | | | | |
| No shade (base case) | 3.993 | 2.802 | 2.080 | 3.913 | 2.714 | 2.015 | −2 | −3 | −3 |
| With existing shade | 3.043 | 2.162 | 1.665 | 2.973 | 2.052 | 1.589 | −2 | −5 | −5 |
| Program trees + existing shade | 2.525 | 1.684 | 1.252 | 2.432 | 1.527 | 1.149 | −4 | −9 | −8 |
| Heating (MJ) | | | | | | | | | |
| No shade (base case) | 56.2 | 35.9 | 26.4 | 55.8 | 35.0 | 26.2 | −1 | −3 | −1 |
| Existing shade | 60.1 | 39.0 | 28.3 | 60.6 | 38.7 | 28.9 | 1 | −1 | 2 |
| Program trees + existing shade | 62.6 | 41.7 | 30.6 | 62.8 | 41.2 | 31.0 | 0 | −1 | 1 |

[a] Relative difference = [(lookup − simulation)/simulation] × 100.

Table 5
Comparison of changes in cooling and heating energy use by vintage between lookup tables and simulation method[a]

| | Vintage | | |
|---|---|---|---|
| | Pre-1978 | 1978–1983 | Post-1983 |
| Cooling | | | |
| Cooling reduction per tree ($M_t$) (%) | −5.4 | −6.1 | −6.8 |
| Multiple tree reduction factor, cooling | 0.93 | 0.86 | 0.84 |
| ΔkWh per house, lookup tables | 541 | 525 | 440 |
| ΔkWh per house, simulation method | 518 | 478 | 412 |
| Relative difference (%) | 4 | 10 | 7 |
| Heating | | | |
| Heating reduction per tree ($M_t$) (%) | −3.8 | −4.7 | −5.7 |
| Multiple tree reduction factor, heating | 0.95 | 0.89 | 0.87 |
| ΔMJ per house, lookup tables | −2.10 | −2.34 | −2.03 |
| ΔMJ per house, simulation method | −2.33 | −2.56 | −2.26 |
| Relative difference (%) | −10 | −9 | −10 |

[a] Relative difference = [(lookup − simulation)/simulation] × 100.

for cooling and 0.95–0.87 for heating (Table 5). Larger corrections resulted for newer vintages that had more trees on average (Table 3).

## 5. Discussion

The level of agreement between the lookup tables and simulation methods (±10%) is promising given the complexity of the underlying calculations and the potential of the lookup tables to foster wider application of energy impacts of urban trees. The overestimate for cooling is well within the range of agreement between simulated and measured energy savings from trees that have been reported. The fact that the lookup table method overestimates cooling and underestimates heating changes suggest that factors which differentially affect heating and cooling are involved. One of these may be related to lower sun angles in winter which makes trees opposite south exposures more important, and tree–building distance less important (except for south trees), in determining heating impacts. Tree distance from buildings is more important in summer, when lower morning and afternoon sun angles favor east and west trees, and high midday sun angles lessen impact of south trees unless they are very close to buildings.

Cooling reduction factors per tree for cooling were smaller than those for heating (Table 5), which may be related to differences in shade coefficients between summer and winter. A tree crown and its resulting shade is much denser in summer (shade coefficients = 0.175, or 82.5% shade) than in winter (0.7, or 30% shade). Therefore in summer 82.5% of the area that could potentially be shaded by addition of an overlapping tree would already be shaded, so the increase in possible shading applies to only 17.5% of the overlap area. In winter, the possible increase applies to 70% of the overlap area. Consequently, the shading potential of an additional tree is reduced relatively more for cooling than for heating, by a factor on the order of 0.175/0.70 (−25%).

Energy savings do not scale linearly with distance. There is often a maximum impact on energy use for tree–building distances between 4.6 and 15 m, primarily for larger trees with west and east azimuths. Smaller relative impacts in these cases for trees close to buildings result in part from the solar beam striking building surfaces below the canopy at low sun angles. Due to this nonlinearity, energy use for a tree at the average distance from the building will not in general equal the average energy impacts for trees within a given distance range. In particular, our preliminary calculations indicate there may be overestimates on the order of 10% if the average distance used in the simulations is near that of maximum impact, because most trees in that range would actually result in smaller impacts. This phenomenon has been observed primarily for cooling, and it may help to explain the observed cooling overestimates relative to heating. These overestimates could be corrected by more judicious selection of, or use of additional, distance classes.

There is an apparently random component to computed energy use differences between methods (Table 5) in addition to the systematic differences just discussed. This may be in part due to the relatively small sample sizes in portions of the analysis. There were a total of 178 houses and 525 trees, which were divided according to vintage (Table 3). Trees were further subdivided by type and location to develop tree distributions, while houses were grouped by number of program trees to determine multiple tree effects. In the case of number of trees per vintage, tree type and location is not at issue in terms of sample size, since the lookup tables were constructed for the entire population of houses and trees. Successful application of the method would depend on how well the tree distribution used matched actual tree distribution for the building population being treated.

In the case of multiple tree effects, presenting results by number of program trees gave equal weight to energy changes regardless of number of trees. A potential weakness of this approach is that sample size and number of program trees had an inverse relationship. Samples contained as few as three or four homes in a number of cases, being most pronounced for the 1978–1983 vintage (24 total homes). However, the inverse relationship between group size and number of trees means more program trees per building in these cases, which tends to be a compensating effect. This is because the chances of shade being evenly distributed around a building increases in proportion to the number of trees present, so that the likelihood of extreme shading contrasts is reduced when there are more trees per building (for example, a house with trees only on the north compared to one with trees only on the south is much more likely to occur if there is only one tree per house than if there are six).

### *5.1. Constraints and limitations*

Results of application of lookup tables will only be as good as the fit of the lookup tables to the tree and building population being analyzed regardless of the sample size. For small sample sizes, there is an additional consideration, which is illustrated by example. Consider two identical houses with 10 $m^2$ of front and back glazing. One faces north with a shading tree to the north, while the other faces west with a shading tree to the west. The latter has cooling energy savings of 100 kWh, while the former 5 kWh, for an average of 52.5 kWh per house. The average house will have 5 $m^2$ glazing on all four walls. Assuming that energy savings is proportional to glazed area (an assumption that improves with increasing insulation of opaque surfaces), energy savings based on the average house will be 25 and 2.5 kWh for west and north trees, and average only 26 kWh per house. While this is an extreme case, it illustrates that caution must be used in applying lookup tables to small samples with large differences in building size or distribution of glazed area with orientation.

An empirical reduction factor (global shade coefficient) was used to account for effects of existing shade on building surfaces to develop lookup tables. This approach was taken because it was readily implemented. An improved method is needed to estimate effects of existing shade on heating and cooling energy use in order to establish a baseline from which to determine effects of added trees. Empirical reduction factors could potentially be derived based on estimates of existing tree cover, building density, or the relationship between utility estimates of energy use and simulations with no shade. The use of a reduction factor that is constant over time of day is not a problem conceptually, since the goal is to calculate changes averaged over many buildings. Average solar gain reduction for a group of buildings is likely to be much more uniform than that for any individual case, where shading will vary with time as a function of location and size of obstructions.

Because weather data and buildings used represent typical or average conditions, results are reflective of average long-term impacts for a large building population rather than impacts of extreme events on individual buildings. In addition, since results represent average conditions with respect to tree location, they should not be applied to estimate savings for a tree next to a particular building in a particular location except in the circumstance where average and actual conditions happen to be similar.

There are a number of other simplifications and assumptions which had small effects on the current analysis, but could have potentially larger impacts in other circumstances. For example, averaging tree distribution over building vintage had minimal effects here (7% or less); however situations could arise in which quite different planting patterns exist for different areas. Future application of the methods presented here could provide information necessary to account such circumstances and make necessary adjustments.

## 6. Conclusions

A simplified method that uses lookup tables and tree distributions to quantify regional effects of tree-shade on residential cooling and heating energy use is developed and tested. The method depends on use of a limited number of discrete tree locations to represent all possible tree azimuths and tree–building distances. Resulting lookup tables allow relatively simple computation of energy use changes while still representing effects of the complex interactions between trees, sun and buildings. Comparisons of lookup table results with a detailed analysis of 178 properties in Sacramento, California, yielded agreement between methods within 10%. Comparative data that do exist indicate that simulations tend to underestimate measured changes in energy use, and hence current results are considered conservative estimates of these changes.

The method is in itself valuable, separate from the issue of validation. It provides a conceptual framework in which to apply detailed, rigorously validated models to real-world problems, and so provide an improved accounting of the complex interactions between trees, sun, and building energy use in a simplified, usable manner. In addition, by providing a workable tool to apply results of detailed simulations of building energy use under a variety of conditions, it demonstrates their practical application, providing incentive for more fundamental research into the effects of urban vegetation on building energy use. Results provide a practical mechanism to scale up tree-shade effects to a neighborhood or larger scale, appropriate for state-wide or national assessments. Finally, the lookup table format lends itself to development of siting recommendations and guidelines designed to optimally select and locate shade trees to maximize energy benefits, important for evaluation of proposed tree planting programs, as well as evaluating the effectiveness of such programs over time. Questions that might be answered by the latter approach include in what locations, climates, and next to what type of buildings are large trees better than small trees, evergreens better than deciduous trees, or trees shading western exposures better than trees to the south.

## Appendix A. Simplified treatment of building orientation

One of the complications inherent in quantifying effects of tree-shade on building energy use is interaction of building dimensions with solar position, tree location, and building orientation. For example, shade has more effect on long or west-facing walls with large amounts of glazing than on short or north-facing walls with little glazing. To simplify these calculations, a method using buildings with square footprints is developed in this Appendix A. Our objective was to show that, on the average, energy use and changes in energy use due to a tree at a given azimuth would not vary with building orientation. This would greatly simplify the analysis since explicit representation of building aspect as a variable could be excluded.

Dimensions were calculated in two ways for each vintage. Average wall and glazing dimensions were first computed for each aspect, and second for each cardinal wall orientation (north, east, south, west). Building aspect is defined as either front, right, back or left with respect to the front facade. Right and left are defined relative to an observer standing outside a building facing its front elevation. Buildings with dimensions averaged over aspect had rectangular footprints, termed the ‘‘asymmetric’’ case, and those averaged over orientation had square building footprints, termed the ‘‘single-orientation’’ case. Wall and glazed areas were taken from Tables 6 and 7 for the asymmetric case, and Tables 9 and 10 for the asymmetrical case (i.e. 31 $m^2$ wall area and 6.7 $m^2$ glazed area for all aspects).

Table 6
Average building wall area by aspect

| Vintage | Glazed area ($m^2$) | | | | Length/width |
|---|---|---|---|---|---|
| | Front | Left | Back | Right | |
| Pre-1978 | 34 | 24 | 34 | 24 | 1.38 |
| 1978-1983 | 37 | 25 | 37 | 25 | 1.44 |
| Post-1983 | 37 | 25 | 37 | 25 | 1.51 |
| All | 36 | 25 | 36 | 25 | 1.45 |

Energy use and savings from single cardinal trees for asymmetric and single-orientation cases were calculated and compared. The post-1983 building was used with identical total wall and glazed areas for both cases. Cooling and heating energy use for five tree/building combinations were considered: no trees, and single trees opposite north, east, south and west walls. This required 20 simulations for the asymmetric case (5 tree per building combinations × 4 building orientations), and 5 simulations for the single-orientation case ( 5 tree per building combinations × 1 building orientation). Energy use for each tree azimuth in the single-orientation case was computed as an average weighted by the relative frequency of occurrence of each tree azimuth. In both cases, energy use without a tree provided a reference for calculating changes in energy use due to shade.

It was anticipated that areal distribution of walls and glazing would be nearly symmetrical, i.e. of equal area for all cardinal building orientations when averaged over a number of buildings. Consequently, the single-orientation case was further simplified so that distribution of wall and glazed area were the same on all walls, termed the ‘‘symmetrical’’ case. This is desirable, since it allows building dimensions to be derived from total glazed and conditioned floor area. Wall area common with garages (most buildings had attached garages) are not subject to solar gain. This was accounted for separately in the analysis by calculating

Table 7
Average glazed area by aspect

| Vintage | Glazed area ($m^2$) | | | | Back/sides | Front/sides |
|---|---|---|---|---|---|---|
| | Front | Left | Back | Right | | |
| Pre-1978 | 6.5 | 2.9 | 10.3 | 3.1 | 3.4 | 2.1 |
| 1978–1983 | 7.0 | 2.0 | 10.9 | 3.0 | 4.4 | 2.8 |
| Post-1983 | 6.5 | 3.3 | 12.3 | 4.5 | 3.2 | 1.7 |
| All | 6.6 | 3.0 | 11.4 | 3.8 | 3.4 | 1.9 |

average garage wall area by azimuth, and calculating heat transfer on this portion of the wall with no solar gain.

### A.1. Results

Front and back walls were 40–50% larger on average than side walls (Table 6). Front and back glazed areas were 2–3 and 3–4 times greater, respectively, than that of side walls (Table 7). This glazing distribution reflects the smaller size of side walls, as well as the common practice of placing more windows toward street and backyard areas. Garages, when present, were almost always attached to front walls, which reduced area in front available for glazing compared to the back. Conditioned floor areas calculated as products of wall lengths (based on areas in Table 6 and wall height of 2.4 m) are approximately 5% larger than those in Table 3, which results from garages being contained within the building envelope that have two common walls with the conditioned space.

Wall and glazed areas tend to be symmetrically distributed with respect to building orientation on average, despite being asymmetrically distributed with respect to building aspect. This is largely the result of building front orientation being approximately evenly distributed (Table 8), especially for the pre-1978 vintage, while favoring south for the 1978–1983 vintage and north or east for the post-1983 vintage. Distribution of wall area with orientation was nearly uniform for each vintage, differing at most 1–3% from the average for all vintages (Table 9). Average area of walls common with garages and hence receiving no solar gain are included in values in Table 9, and ranged from 7 to 17 m$^2$. Glazing was less uniform, but still nearly so, differing at most 8–10% by vintage from the average (Table 10).

Deviations from symmetry for wall area decreased with increased sample size. North and east front orientations were more common for the post-1983 vintage (Table 8), also evident in the distribution of glazed area for the post-1983 vintage favoring south and west (Table 10), a possible reflection of increased awareness of the desirability of solar access in the design of newer homes. Buildings with intercardinal orientations, 18% of the total, were treated as having cardinal orientations by evenly distributing them between bounding cardinal orientations. Including intercardinal buildings ensured that all buildings in the sample were represented in average values, and changed average wall area by less than 1%, average glazed area by less than 4%, and average energy use determined from lookup tables by less than 3%.

Table 8
Building front orientation distribution by vintage (%)

| Vintage | Building front orientation distribution (%) | | | |
|---|---|---|---|---|
| | N | E | S | W |
| Pre-1978 | 24 | 26 | 25 | 25 |
| 1978–1983 | 16 | 25 | 35 | 24 |
| Post-1983 | 36 | 30 | 17 | 16 |
| All | 29 | 28 | 22 | 20 |

Table 9
Average wall area facing cardinal orientations by vintage

| Building vintage | Wall area (m$^2$) | | | | |
|---|---|---|---|---|---|
| | N | E | S | W | All |
| Pre-1978 | 29 | 29 | 29 | 29 | 29 |
| 1978–1983 | 30 | 32 | 30 | 32 | 31 |
| Post-1983 | 31 | 31 | 31 | 31 | 31 |
| Average | 30 | 31 | 30 | 31 | 30 |

Table 10
Average glazed area facing cardinal orientations by vintage

| Building vintage | Wall area (m$^2$) | | | | |
|---|---|---|---|---|---|
| | N | E | S | W | All |
| Pre-1978 | 5.2 | 5.6 | 5.9 | 6.2 | 5.7 |
| 1978–1983 | 5.8 | 5.1 | 6.2 | 5.9 | 5.7 |
| Post-1983 | 6.1 | 6.2 | 7.2 | 7.2 | 6.7 |
| Average | 5.7 | 5.8 | 6.6 | 6.6 | 6.2 |

Differences in base case energy use and changes in cooling and heating energy use between symmetric and asymmetric cases averaged over tree azimuth and building orientation (Table 11, last column) were less than 2%. Maximum

Table 11
Changes in cooling and heating energy use for single trees, asymmetric and symmetric cases[a]

| Tree azimuth | Building orientation | | | | |
|---|---|---|---|---|---|
| | N | E | S | W | All |
| (a) Change in cooling (kWh) | | | | | |
| N | 7 | 5 | 12 | 5 | 7 |
| E | 168 | 239 | 162 | 323 | 214 |
| S | 293 | 99 | 182 | 100 | 184 |
| W | 249 | 420 | 238 | 337 | 314 |
| No trees | 1305 | 1639 | 1204 | 1544 | 1428 |
| (b) Change in cooling, symmetric case | | | | | |
| N | 8 | 8 | 8 | 8 | 8 |
| E | 221 | 226 | 221 | 226 | 224 |
| S | 173 | 166 | 173 | 166 | 170 |
| W | 310 | 315 | 310 | 315 | 312 |
| No trees | 1402 | 1414 | 1402 | 1414 | 1408 |
| (c) Change in heating, asymmetric case | | | | | |
| N | −0.002 | −0.000 | −0.003 | −0.001 | −0.001 |
| E | −0.367 | −0.552 | −0.426 | −0.782 | −0.501 |
| S | −1.524 | −0.405 | −1.140 | −0.416 | −0.938 |
| W | −0.323 | −0.625 | −0.378 | −0.468 | −0.448 |
| No trees | 27.1 | 28.8 | 29.3 | 28.5 | 28.2 |
| (d) Change in heating (MJ) | | | | | |
| N | −0.001 | −0.001 | −0.001 | −0.001 | −0.001 |
| E | −0.512 | −0.522 | −0.512 | −0.522 | −0.517 |
| S | −0.867 | −0.843 | −0.867 | −0.843 | −0.856 |
| W | −0.434 | −0.442 | −0.434 | −0.442 | −0.438 |
| No trees | 27.6 | 27.6 | 27.6 | 27.6 | 27.6 |

[a] Total annual energy use without trees (“no trees”) is included for comparison.

differences at a particular tree azimuth for changes in cooling and heating were 8 and 9%, respectively (maximum difference for north tree azimuth, where changes in energy use were negligible, was 11% for cooling). Symmetric buildings were simulated at all orientations (Table 11a and b) as a check of the method; results were not identical at each building orientation because there were doors at front and back, but not the sides. Given the nearly symmetrical distribution of wall and glazed area, as well as good agreement between energy use and changes due to tree-shade between symmetric and asymmetric cases here, symmetrical buildings (square footprint with glazed area divided equally between orientations) were used in lookup table development, avoiding explicit consideration of building orientation.

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