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**Shading coefficients of six tree species in Tucson and their impact on annual energy loads**


Dougherty, Eileen, M.L.Arch.

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U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

# SHADING COEFFICIENTS OF SIX TREE SPECIES IN TUCSON AND THEIR IMPACT ON ANNUAL ENERGY LOADS

by

Eileen Dougherty

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This thesis has been approved on the date shown below:

| | |
|---|---|
| E. Gregory McPherson<br>Dr. E. GREGORY MCPHERSON<br>Assistant Professor of<br>Renewable Natural Resources | 1/27/88<br>Date |
| William H Havens<br>Dr. WILLIAM H. HAVENS<br>Professor of<br>Renewable Natural Resources | 1-27-88<br>Date |
| James R. Simpson<br>JAMES R. SIMPSON<br>Assistant Professor of<br>Soil and Water Science | 1-27-88<br>Date |

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# ABSTRACT

This study determined winter and summer shading coefficients for six commonly used landscape trees in Tucson using a photographic dot-matrix method. Tree types were developed from this data reflecting canopy density, shape, and foliage periods, then applied to SPS and MICROPAS computer programs to model effects of tree shade on annual energy loads for three residential construction types.

Statistical analysis showed pruning to have a significant effect for 5 of the 6 species tested. Significant differences were also found among species and within species due to seasonal effects in foliage density.

Shading scenarios manipulated the number and location of tree types were modeled. Greatest net annual savings were from 3 African sumac trees located on the west side of a masonry house typical of the 1950s ($121). Shade from tree species found to have significantly different shading coefficients (10%) did not substantially increase energy savings ($5 - $12).

# CHAPTER 1

## INTRODUCTION

Tree shade falling on a building reduces solar radiation incident on building surfaces, thus reducing space cooling requirements during overheated periods. This reduction of transmitted solar radiation increases space heating costs during underheated periods. Substantial reductions in net annual energy costs for space heating and cooling may be achieved through strategic placement of tree species exhibiting appropriate solar traits. Appropriate solar traits include the canopy density of the tree, leaf-out, and leaf-drop periods.

The net effect of tree shade is correlated to the canopy density of the tree: the denser the tree shade, the greater the savings achieved in cooling, or adversely, the greater the cost in heating. Canopy density figures are used in existing computer models to predict energy costs and savings in space conditioning resulting from adjacent trees. The reliability of the models' results depend in part on the accuracy of these canopy density figures. Currently, no canopy density figures exist for tree species commonly used in southwest desert landscapes. Similarly, no studies have examined the effects of tree shade on housing construction types typical of the southwest desert region.

Designing landscapes to reduce annual energy costs in Tucson requires accurate canopy density figures for local tree species. With this information, it is then possible to simulate the effects of various trees on building energy performance. Thus, this study was undertaken in two parts. The first part measured six commonly used landscape tree species in Tucson for winter and summer canopy densities, and statistically determined whether a significant difference in canopy densities existed within a species due to seasonal influences.

The second part of this study utilized computer models to simulate the effect of these canopy shading densities on residential energy consumption in Tucson. Three residential construction types were modeled: a wood and a masonry structure typical of the 1980s, and a masonry structure typical of the 1950s.

Trees and shrubs also mitigate the microclimates of buildings by reducing the impact of wind and through the evapotranspiration process of the plant (Heisler 1977, Buffington 1987, McPherson 1987, Parker 1987). Effects of evapotranspiration and wind were not examined in this study.

# CHAPTER 2

# LITERATURE REVIEW

This chapter discusses the reduction of solar radiation through tree canopies and the effect of this irradiance reduction on residential heating and cooling loads as reported in the literature. Studies concerned with measuring solar radiation through tree canopies commonly use radiation-measuring instrumentation or photographic images to determine canopy densities. These methods measure slightly different portions of the solar spectrum and have been tested by only two authors (Wagar, Heisler, and Atkinson-Adams 1986, Yates 1987). Additionally, many researchers have based their results on a less than statistically-sound sample size.

To estimate the effect of tree shade on residential heating and cooling loads, researchers have used field studies, models, and computer simulations. Results show that both savings and increased costs can be attributed to tree shade.

## Solar Radiation Through Trees

Solar radiation strikes the earth as direct or diffuse light. Upon striking foliage, solar radiation is either absorbed by the plant, reflected by the plant, or transmitted through the plant. The fraction of available solar radiation transmitted through the plant is defined as the plant's shading coefficient. The term shading coefficient (SC) was first used by engineers to define the fraction of solar radiation transmitted through building materials (ASHRAE 1981). A SC of 1.0 is equivalent to full transmission and a SC of 0.0 is equivalent to full shade. More recently the term has been adapted by arborists and landscape architects to describe the fraction of solar radiation transmitted through tree canopies. The major difference between solar radiation transmitted through building materials as opposed to trees, is that trees are dynamic and the SC varies with wind, season, growth, and species.

The SC of a tree depends on the 1) location of the sun, 2) inclination, shape, and thickness of leaves, and 3) density of foliage and woody parts. Seasonal factors effecting SCs are the distribution of fruit, flower, and leaf coverage.

## Measurement Methods of Radiation Through Tree Canopies

Measurement of radiation through tree canopies falls into two categories: closed-forest canopy measures and open-grown tree canopy measures. Methods used for each approach are described below.

Closed-Forest Canopy Measures. Light penetration through closed-forest canopies is studied to determine the solar radiation available for forest-floor plant growth. Anderson (1964) developed a method using hemispherical photographs overlaid with a circular grid to estimate the amount of direct and diffuse light intercepted by forest canopies. Although photographic methods do not allow for transmission of light through leaves, Anderson concluded that hemispherical photography proved to be an accurate measure of direct and diffuse radiation (.01 - .05 level) when compared to measurements recorded from actinographs. Reifsnyder, Furnival, and Horowitz (1970) measured direct and diffuse radiation on the forest floor using pyranometers in a grid pattern. They found diffuse light under the canopy to be uniformly distributed. The ratio of below-to-above canopy was the same for sunny and cloudy days. The study of solar radiation through forest canopies is complex, involves labor intensive and time consuming measurement methods, and provides information based on the structure of closed-forests. Studies involving open-grown trees are similar in that they are concerned with solar radiation through tree canopies, but the structure of a closed-forest canopy is different from that of an open-grown tree. In residential landscapes, trees are most often isolated, therefore this study is concerned with open-grown tree canopy measures.

Open-Grown Canopy Measures. Two methods of measuring open-grown canopies commonly described in the literature are the use of: pyranometers sensitive to the entire solar spectrum (380 nm - 4500 nm), or photographic methods that capture the tree image from which canopy density calculations are derived. Photographs are sensitive solar energy in the visible portion of the spectrum (400 nm - 700 nm).

Pyranometers have been used to measure SCs by taking readings above and below the tree canopy to determine the amount of solar radiation available and the amount of solar radiation within the tree's shadow. While pyranometers measure direct, diffuse, transmitted, and reflected radiation, numerous readings must be taken below the tree canopy to adequately reflect the tree's SC. Too few readings will result in a sampling error due to the random distribution of sun and shade beneath the canopy. Several researchers (Heisler, Halverson, and Zisa 1981, Heisler 1982, Gardner 1982, Gardner and Sydnor 1984) utilized pyranometers at fixed horizontal and vertical locations, in the center of tree shade, taking readings at regular intervals. Zanetto and Thayer (1983) used pyranometers located along a transect in the center of the tree shadow. Other researchers have taken systematic readings at one foot grid intervals (McPherson 1981), or automated pyranometers on tracks taking 63 readings at 4.3 feet intervals (Youngberg 1983). Locations and number of readings beneath the tree canopy varied with researchers.

Photographic methods require that a free standing image of the tree, without obstructions, be photographed at a constant elevation angle from the ground. Elevation angles vary with researchers (30 - 63 degrees). Researchers also photograph various portions of the crown. Wagar et al. (1986) used three overlapping photographs encompassing most of the tree crown, and compensated for the "missed edge" mathematically. Thayer (1984) suggested positioning the camera so that the tree crown is directly inside the slide frame and Yates (1987) used a single photograph of the entire tree crown. To calculate SCs, the tree image is projected over a dot-grid matrix. A plant's shading density is the ratio of crown matter falling on intersections to crown area. The shading density subtracted from 100% is the plant's SC. This method was developed by Heisler (1982), and has since been used by Heisler (1986a), Wagar et al. (1986), and Yates (1987).

Video scanners or densitometers have also been used to analyze tree canopy images (Westergaard 1982, Thayer

1984, Wagar, et al. 1986). By assigning values of gray tones, the scanner distinguishes tree material from background material by a pre-established cut-off value. The SC is the ratio of dark to light values. Video scanners are an alternative to the dot-matrix procedure but are difficult to use because the method requires the branches of trees to be silhouetted against the sky without obstructions. This can be very difficult to accomplish due to terrain or other background matter.

Two studies (Wagar et al. 1986, Yates 1987) have compared radiation sensitive instruments with photographic procedures for trees out of leaf. Both studies achieve similar conclusions, although they measured slightly different components of the solar spectrum. Wagar et al. (1986) used pyranometers which measure direct and diffuse radiation. Yates (1987) used measurements from a luminance photometer to compare photographic results. The luminance photometer measures the visible portion of the solar spectrum (400 nm - 700 nm) and pyranometers measure visible, near infrared, and portions of the ultra violet solar spectrum (350 nm - 4500 nm). Although luminance photometers and pyranometers have different spectral responses, these studies had similar results. Photographs taken from different azimuths did not affect density measures.

Different elevation angles, however, did affect density measures. Wagar et al. (1986) found a 3.7% decrease in density when comparing a 45 degree camera angle to a 33 degree camera angle. The ranking of tree species was held constant in both cases. Yates noted a 3% lower density when moving the camera further away from the tree, lowering the elevation angle from 25 - 8.8 degrees. Yates suggests that these variations in canopy densities reflect the difference in path length through the tree canopy with the different camera elevations, and that path lengths will vary depending on canopy shape and size (Fig. 1). In both these studies, different camera angles resulted in a 3 - 3.7% difference in canopy density figures. The conclusion of these researchers is that photographic methods which hold the camera elevation constant, offer a valid method for determining canopy densities for trees out of leaf.

Two concerns arise when photographing trees in leaf. The first concern is the reflectivity of the leaves. As solar radiation passes through the canopy, leaves selectively filter solar radiation resulting in a larger percentage of long wave radiation under the tree canopy (700 nm - 1100 nm). Photographs and photometers do not measure the long wave portion of the solar spectrum. Anderson (1964), Reifsnyder and Lull (1965), and Woodward and Sheey (1983), however, report that this reflection is very low because solar radiation penetrates the top of the crown and reflection is repeated through the crown, each time diminishing its value. Also, reflection of leaves vary with wavelength, species, age, upper and lower leaf surface, angle, distribution, aridity of site, soil fertility, and season. Anderson (1964) concludes that the amount of reflection would be less than the expected measurement error using photographs or photometers.

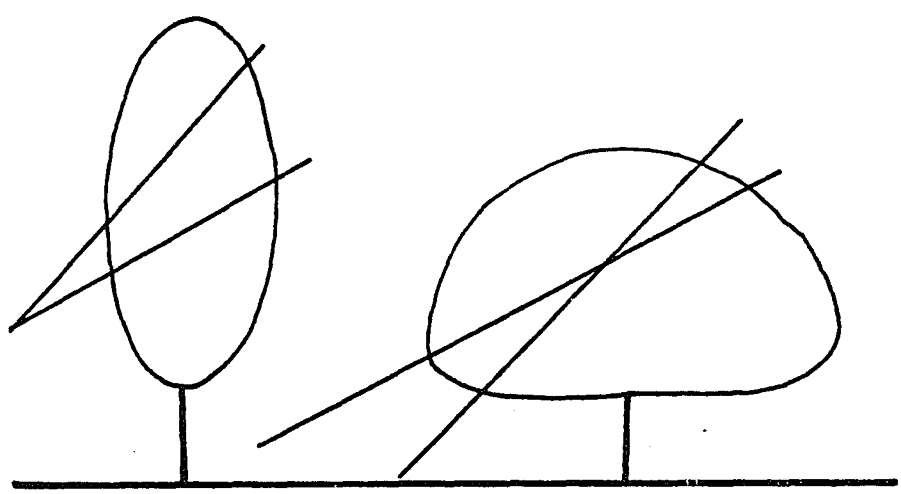


Fig. 1 Path Lengths Resulting from Different Camera Elevations for Ellipsoid and Paraboloid Tree Shapes

The second concern when photographing trees in leaf is the angle of the leaf as it relates to camera or sun elevation angles. As the leaf angle changes the amount of radiation absorbed and transmitted through the crown will vary. As the camera angle changes, the amount of solar radiation visible through the canopy varies. In an attempt to quantify the amount of solar absorption with leaf angle, Reifsnyder and Lull (1965) calculated the amount of incoming radiation expected for two leaves. The leaf perpendicular to the sun received incoming radiation at 1.2 ly/min. and the leaf parallel to the sun received .30 ly/min. of incoming solar radiation. They conclude that leaves will intercept radiation as a function of their angle, but that values change rapidly with wind. No studies describe leaf angles on landscape trees.

Tree species vary in their ability to reduce solar radiation. This variation may be attributed to genetic differences among species, size, age, season, climate, and growing conditions. Gardner and Sydnor (1984) measured five tree species using pyranometers positioned to reflect the changing angle of the noon sun, at four points, vertically along the tree crown. When comparing SCs, they found significantly different SCs in leaf ($p = .05$) for <u>Pyrus calleryana</u> (Ornamental pear 'Chanticleer')

.25 and _Gleditsia triacanthos inermis_ (Honey Locust) .44. _Acer rubrum_ (Scarlet Maple) .31, _Zelkova serrata_ (Sawtooth zelkova) .39, and _Gymnocladus dioica_ (Kentucky coffee tree) .40 were not significantly different from each other in leaf ($p = .05$). Out of leaf the significance pattern of SCs differed. _Pyrus_ .62, _Zelkova_ .78, and _Gynmocladus_ .90 were significantly different ($p = .05$). The sample contained 4 trees of each species, which is insufficient for strong conclusions.

Gardner and Sydnor (1984) also found that height influenced SCs, though age was not tested because the twenty trees sampled averaged 15 - 20 years. Likewise, Wagar, et al (1986) measured three tree species (20 - 25 trees of each species) out of leaf for canopy density and found that SCs tended to increase as the tree size increased, but that this pattern varied with species. _Gymnocladus dioica_ (Kentucky coffee tree) and _Platanus x acerifolia_ (London plane tree) showed a positive relationship with SCs and crown spread. _Fraxinus velutina_ 'Modesto' (Modesto ash) showed a minimal SC at 10m (32'), while larger and smaller trees had lower SCs. This study did not include measurements for the trees in leaf.

In examining seasonal influences on SCs, Gardner and Sydnor (1984) found that winter and summer SCs of deciduous trees were not correlated inferring that trees providing heavy shade in the summer do not necessarily provide heavy shade in the winter. Heisler (1986b) also looked for a winter to summer density relationship using reported canopy density (amount of blockage) figures for 21 tree species. His interest was in identifying species that provided dense shade during the cooling season, but allowed maximum solar access during the heating season. Winter to summer ratios of canopy density ranged from .36 - .69. Only five species had winter to summer ratios lower than .40 (Fraxinus pennsylvanica, Acer saccharum, Liquidambar styraciflua, Quercus rubra, and Zelkova serrata). Again, data for many of these species were based on limited sampling.

McPherson (1984) lists winter and summer SCs for evergreen and deciduous trees from numerous studies. Summer SCs for selected species ranged from .07 - .38 and winter SCs ranged from .27 - .89. SCs varied for the same tree species with different researchers. For example, SCs for the tree species Gleditsia triacanthos inermis (honey locust) varied as much as .37 out of leaf (Erley and Jaffee 1979, Hammond, Zanetto, Adams 1980), and in this case researchers used the same measuring instrument (light meter). McPherson attributes this variation to genetics, environmental influences, and/or different measurement methods. SC values listed are not consistently mean values from a statistically sound sample, but rather some were recorded to compare measurement methods, at times measuring only one or two trees. Consequently, designers cannot always be confident that SCs reported in the literature are representative of trees in the landscape. Desert tree species were not represented in any of the studies listed.

Summary. Shading coefficients vary among species and within species due to genetics, size, season, climate, environmental conditions, and measurement methods. SCs for some tree species in temperate climates have been determined, although studies often use a less-than statistically-sound sample size. Also, SCs have not been determined for tree species in desert regions where shade is expected to have the greatest benefit.

Light sensitive instrumentation and a photographic dot-matrix method are the methods generally utilized to determine the shading coefficient of open-grown trees. Although these methods measure somewhat different components of solar radiation, they provide similar estimates of light transmittance through the tree crown. The method chosen for this study was the photographic dot-matrix because it provides a relatively quick, and cost efficient method to reliably estimate tree SCs. Six tree species frequently used for shade in southwest landscapes were measured. Sample size for each species ranged from 14 to 32 trees.

## Solar Radiation on Small Buildings

Although many factors affect the interior temperatures of buildings, solar radiation is a significant factor in building heat gain. The effect of solar radiation on a building depends on the thermodynamics of the structure, and the nature, intensity, and amount of solar radiation falling on the building.

Studies concerned with the effect of tree shade on buildings have focused on the amount and density of the shade (Deering 1956, Schiler 1979, McPherson 1981, Rundie and Dewers 1984) or the location of the shade (Parker 1983, McPherson 1984, Wagar 1984, Heisler 1986a). Other studies hold tree shade factors constant to compare the effect of landscape designs, housing types, and/or climatic regions (Buffington 1978, 1979, Thayer, Zanetto, and Maeda 1983, Thayer and Maeda 1985, McPherson 1987). Given their various focuses and climatic regions, these studies report that tree shade can:

1. reduce indoor temperatures up to 20 degrees F;

2. reduce daily cooling requirements up to 6 hours a day;
3. eliminate the need for cooling systems in cold and temperate climates;
4. reduce the peak demand of energy for communities thereby reducing the number of power stations needed to accommodate peak loads;
5. block up to 40 - 50% of winter solar radiation and increase heating demands when leafless.

Although these conclusions vary somewhat with climate and housing construction type, researchers agree that tree shade is most beneficial on the roof, west wall, and east wall, respectively, and designs combining these locations result in greater savings (McPherson, Herrington, and Heisler in press). To avoid increases in heating demands, avoid planting trees on the south side of buildings.

The amount of possible savings varies with the type of housing structure. Buffington (1981) ran computer simulations for a wood frame and a concrete block house in Miami. Two shading scenarios were simulated. The first, an energy-conserving design, provided the house with well placed shade to reduce energy loads. The second scenario located shade to increase energy loads. The energy-conserving design for the wood frame house resulted in a savings of $193, and a savings of $209 for the masonry house.

Other results (McPherson 1987) clearly illustrate that the greatest potential for energy savings is in hot climates where cooling loads represent the largest portion of the energy budget. Annual energy savings for Tucson 35% ($200) and Miami 38% ($186) were more substantial than for Salt Lake City 19% ($148) and Madison 13% ($98).

Three methods of determining the effect of tree shade on building energy performance are field studies, models, and computer simulations.

<u>Field studies</u>. One type of field study involved mobile homes or small scale replicas of houses used to quantify the effect of tree shade on space conditioning. The scale models were calibrated to each other, and designed or altered to mirror the thermodynamics of standard houses. Researchers located houses in full sun, partial and full shade, recording inside and outside temperatures (Deering 1956, McPherson 1981, DeWalle and Heisler 1983, Parker 1983). This type of study provides reliable results and allows the effect of tree shade alone to be assessed, yet they are extremely time

consuming and costly.

The second type of field study, performed by Rudie and Dewers (1984) involved surveying 113 occupied houses. Their criteria stated that the houses have similar designs, orientations, and were built in the same time period to reflect similar building standards. Houses were categorized into five shade classes representing different levels of shade. Electrical data in kilowatt hours were recorded and converted to a value per square foot to correct for the varying sizes of living area. Results demonstrated that tree shade was the most highly significant variable for cooling, followed by light colored walls, and light colored roofs. The drawback of this method is that the variety of residents' lifestyles affecting energy use was not separated from space conditioning demands.

Models. Heisler (1986a) used a physical model of a tree to simulate shadow patterns on a house. This process enabled him to determine the optimal location for tree placement. Irradiance reductions were then calculated with regression equations based on previous tree density studies. Results showed a 20 - 25% reduction of energy costs with optimal shading.

Computer Simulations. Computer simulations offer a quick, reliable method to assess the impact of tree shade on buildings. The user is able to hold certain factors constant while manipulating other factors such as the area, location, and density of shade, housing type, and local climate.

Buffington (1978, 1979, 1981) developed a computer simulation model based on heat gains and cooling loads which calculates hourly transfer functions for wall and roof construction. SCs were assigned to the entire wall to simulate light, heavy, and full tree shade. Tree shape was not modeled. This approach allowed simulation of different climates and building materials.

Schiler (1979) developed a computer program to simulate the effects of foliage on building energy loads. The user locates trees and manipulates size. The energy load of the proposed landscape plan is then assessed. This system, however, is not currently utilized because the hardware it requires is now obsolete.

Thayer et al. (1983) and Thayer and Maeda (1985) used a program called SOLEST to compare the effects of shade from rows of street trees on solar, solar retrofit, and conventional houses. SC values from another study were used. With this program the user inputs the building dimensions, thermal parameters, occupant behavior, utility rates, climate data, and radiation data. The program computes the thermodynamics of the house assigning average monthly SCs for walls, windows, roof pitch, and solar collectors according to the spatial geometry (tree form) of the trees to be simulated. The program utilizes a degree day method which is less reliable than hourly simulation methods due to continual weather fluctuations.

A fourth approach interfaces the Shadow Pattern Simulator (SPS) with MICROPAS to model the effect of tree shade on building energy loads (McPherson 1986). The user inputs canopy height and width, bole height, location, and SC values for trees to be modeled. With this information, SPS calculates the pattern and percent of irradiance reductions from tree shade at three, half hour intervals. These half hour intervals are averaged and input to MICROPAS (a building energy analysis program) which simulates the response of energy demands to tree shade. This half hour averaging allows for the movement of shade within the hour. MICROPAS assigns hourly shading coefficients to glazed surfaces, and incorporates SPS values for opaque surfaces as well. Estimates of building energy use are based on a building's thermal characteristics, occupant behavior, and specific weather data. Both opaque and glazed surfaces are considered in the analysis. With these programs McPherson simulated the effect of irradiance reductions on houses in Tucson, Madison, Miami, and Salt Lake City. "Optimal" SCs rather than actual SCs and foliage seasons were modeled to provide the best possible savings available with tree shade.

McPherson (1987) tested the SPS program for accuracy of shadow projections. He also tested SCs as single trees and overlapping trees by comparing SPS hourly SCs with manual calculations. SPS projections and hourly SC were found to be correct. The interaction of MICROPAS with the SPS was tested and found satisfactory, although this aspect was difficult to test due to the lack of quantitative data. It is currently begin tested further.

Another area examined in this study was difference between photographic estimates of tree crown profile areas and formula-based estimates of tree crown profiles for five geometric solids (cone, vertical ellipsoid, horizontal ellipsoid, paraboloid, and sphere). No significant differences resulted at the $p = .05$ level. The conclusion was that geometric shapes can be used for simulation purposes without loss of accuracy.

Summary of Solar Radiation on Buildings. Solar radiation falling on buildings is a significant factor in energy performance. Reduction of solar radiation on small buildings by trees reduces the amount of energy required for cooling. The amount of energy saved varies with the housing type, location of shade, density of shade, leaf-out and leaf-drop periods, and climatic location. A review of the literature indicates that in regions where cooling represents the largest energy load, shade will have the greatest impact.

Models exist to accurately simulate the effect of tree shading on heating and cooling loads. SPS and MICROPAS programs rely on accurate SCs. SPS and MICROPAS systems were used in this study, and incorporated SCs determined through the photographic dot-matrix method described earlier.

## Conclusions

SCs vary with species, size, season, climate, and environmental conditions, and can have a substantial impact on building energy performance. Accurate SCs are needed to model the impact of tree shade on space conditioning. Presently, there is limited information available on solar radiation transmittance through open-grown tree canopies based on statistically-sound data. Also, no data exist for SCs of southwest landscape trees, where shade is expected to have the greatest impact.

Computer simulation models exist to accurately simulate the effect of tree shade on the heating and cooling loads of buildings. Two of the computer simulation models mentioned earlier used SCs that reflected light, heavy, and full shade, or "optimal" shade and did not model SCs from actual tree species. Reliable SCs are required for models that simulate effects of trees in different landscape situations. Further research is needed to determine statistically-sound SCs for desert tree species and to apply these SCs to simulate their effect on heating and cooling loads. Therefore, this study measured SCs for six desert tree species, based on a large sample, and modeled their effects on residential buildings located in Tucson's desert climate.

# CHAPTER 3

# METHODS

This chapter describes the materials and process used to test the following hypotheses:

## Hypotheses

1. Shading coefficients vary significantly among species, therefore, accurate shading coefficients for each species are required to accurately simulate their shading effects.

2. Shading coefficients vary significantly between winter and summer within a species, therefore, shading coefficients must be changed in simulations to reflect seasonal influences.

3. Shading in Tucson has a substantial impact on annual energy loads.

Hypotheses 1 and 2 were tested in the first half of this study. Summer and winter shading coefficients (SC) were derived for six tree species: *Cercidium microphyllum*, *Eucalyptus polyanthemos*, *Morus alba*, *Olea europaea*, *Prosopis velutina*, and *Rhus lancea*. Hypothesis 3 was tested in the second half of the study using SPS and MICROPAS systems to simulate the effect of tree shade and residential energy use in Tucson.

## Measuring Shading Coefficients

Shading coefficients were determined for six tree species commonly used in the Tucson area through the photographic dot-matrix method. Testing hypotheses 1 and 2 required that summer and winter shading coefficients for each species be determined.

### Sample Selection

The six tree species selected represent commonly used landscape trees in Tucson. The sample trees were located in June 1986 in an opportunistic, rather than random, process. Trees selected for this study were based on the six criteria described below. Trees were required to:

1) Represent a variety of sizes for each species.
2) Reflect typical growth patterns of the species without severe distortion from pruning or disease.
3) Exhibit open growth not constricted due to buildings or other trees.
4) Be easily photographable and not obstructed by objects.
5) Receive regular irrigation.
6) Remain unpruned between photographing sessions.

The six tree species in this study were chosen because they are commonly planted in Tucson, and an adequate sample size could be located. Trees were located on golf courses or city parks, with a small portion of the sample on landscaped business frontages. A total of 250 trees were photographed and measured in January and June 1987. Fifty-five trees were discarded from the sample due to irregular irrigation and pruning between photograph sessions. The remaining sample consisted of 144 trees. Winter and summer photographs of each were taken. A brief description of the six species' characteristics (Duffield and Jones 1981, personal communication, Ralph McPheeters, Catalina Heights Nursery, December 1987) follows. Sample statistics are summarized in Table 1.

1. Cercidium microphyllum (Foothill palo verde) This is a drought deciduous, low water use tree. It is not easily available from nurseries due to its slow growth, but is often retained on sites when possible. Foothill palo verde is a native species but is planted less frequently than Cercidium floridum and Parkinsonia aculeata, which are readily available in nurseries. This tree typically grows 10 - 12 feet tall, but will reach 25 feet with ample irrigation. Its form is rounded with trunks dividing close to the ground. Bark is yellow-green, and leaflets are small and round. In late spring the tree is covered with yellow flowers. Twenty trees

were sampled with height ranging from 12 - 21 feet. Average crown diameter was 13 - 27 feet.

2. Eucalyptus polyanthemos 'Polydan' (Polydan eucalyptus). This tree was started from a selection of wide-leaf seedlings that reverted from Eucalyptus polyanthemos. Polydan was heavily planted in Tucson 30 to 50 years ago but is not often planted now as more drought tolerant varieties are available. Polydan is an evergreen tree that requires regular irrigation and is susceptible to chlorosis. Tree form is oblong with gray-green leaves and mottled bark. Thirty-two trees were sampled with height ranging from 22 - 59 feet. The average crown diameter range was 13 - 37 feet.

3. Morus alba (Mulberry). Morus alba 'Kingan' is a selected male seedling, and was heavily planted until recently, when the county banned its planting due to a high pollen content. Other less popular cultivars are 'Fruitless', 'Stribling', and 'Chaparral'. Mulberrys represent a large portion of existing residential trees. This is a fast-growing deciduous tree requiring ample to moderate irrigation. Tree form is erect with a dome shaped crown and deep green foliage. Average mature height is 35 - 40 feet with a wider crown spread. Leaf-drop is early December, and leaf-out is March. Fourteen trees were photographed with height ranging from 17 - 24

feet. Average crown diameter ranged from 20 - 40 feet.

4. Olea europaea (Olive). Olive trees were commonly planted until recently when they also were banned for their pollen content. The planting ban is expected to be modified to accept the variety 'Swan Hill', which has a low pollen content. Olive trees represent a large portion of residential trees. They are evergreen, slow growing, and reach 15 - 30 feet tall with a crown almost as wide. Olea europaea was the most commonly planted variety, and 'Manzanillo' was planted more rarely. Tree form is rounded with medium gray-green leaves and a gray trunk. Olive accepts drought to ample irrigation. Thirty-two trees were photographed. Height ranged from 10 - 24 feet with the average crown diameter ranging 10 - 34 feet.

5. Prosopis velutina (Native mesquite). This is a cold and drought deciduous tree that grows rapidly to 30 - 40 feet tall with irrigation. Form is often twisted and multiple trunked with fine, green foliage and rough bark. Native mesquites are low water use trees and similar in appearance to Chilean mesquites. Native and Chilean mesquites were considered weed trees and not frequently planted until after World War II. Native mesquites occasionally hybridize with South American mesquites. This may be reflected by higher within-

species canopy density variability in the sample. Leaf-drop varied among the trees sampled in this study, with some retaining their leaves through January. For those trees that dropped their leaves, leaf-out period was late June. Varieties available presently are Chilean, Velvet, Argentine, and Texas mesquites. Twenty-three mesquite trees were sampled. Height ranged from 11 - 25 feet. Average crown diameter ranged from 17 - 51 feet.

6. Rhus lancea (African sumac). An evergreen tree that accepts little to moderate water, but grows rapidly with ample irrigation. Mature trees form a dome shaped crown of dark green foliage reaching 30 feet wide. Height averages 20 feet. This tree was popular in the 1930s, and has no known cultivars. Twenty-three trees were sampled. Height ranged 10 - 29 feet. Average crown diameter ranged from 7 - 44 feet.

## Measurements

Each tree was measured in the same manner for height and average crown diameter. Tree height was measured using an Abney level. Average crown diameter measurements were recorded with a meter tape four times from the center of the tree trunk to the edge of the tree canopy. Measurements were taken once to the north, south, east, and west, then divided by 2, to obtain the average crown diameter.

Table 1
Sample Description

| Species | Number in Sample | Height Range | Average Crown Diameter Range |
|---|---|---|---|
| Palo verde | 20 | 12.1'-21.2' | 13.5'-26.9' |
| Polydan | 32 | 22.2'-55.9' | 13.5'-37.1' |
| Mulberry | 14 | 16.9'-24.6' | 20.0'-40.4' |
| Olive | 32 | 10.1'-33.7' | 10.1'-33.7' |
| Mesquite | 23 | 11.8'-25.3' | 16.9'-50.6' |
| African sumac | 23 | 10.1'-43.8' | 6.7'-43.8' |
| Total | 144 | | |

Location, irrigation, pruning, and photographic quality were noted at the site. Irrigation quantities were later confirmed by the individuals responsible for maintenance. All trees received suplementary irrigation on a regular basis. Pruning was classified into three categories representing the visible effect that pruning had on the crown density:

1) Neutral: pruning that had no visible effect on the canopy form or density.
2) Open: pruned or missing branches where pruning has left obvious, unnatural gaps in the canopy.
3) Dense: evidence of earlier pruning that has resulted in unusually dense twig growth.

<u>Pretesting</u>. Three trees were photographed at three different camera elevations: 20, 30, and 50 degrees (from the ground), and different azimuths. The 30 degree elevation offered the best solution for maintaining a constant elevation while encompassing various sizes of tree crowns within the slide frame. Photographs were taken at a variety of distances from the tree in order to capture the entire crown in the slide.

Image Acquisition

Photographs were taken with a 35 mm, single lens reflex camera with a 28 mm wide-angle lens. Shutter speed was maintained at 1/1000 of a second, and Ektachrome slide film, (100 ASA) was used. The entire tree crown filled the slide frame as completely as possible while maintaining a 30 degree elevation angle. The camera was mounted on a tripod and an Abney level was used to adjust lense elevation to 30 degrees above horizontal. Azimuth angles varied. Every effort was made to keep obstructions out of the tree crown.

In-leaf and leaf-less photographs were taken from the same location for each tree. Summer and winter slides of each tree were compared to assure proper camera location. Two time periods were photographed to represent leaf-drop and leaf-out periods: January 8 to January 29 1987, and June 9 to July 7 1987, respectively.

The winter season (November - March) was typical for

Tucson with slightly above normal temperatures in November, and near normal temperatures for January. (Normal daytime temperatures are 65 degrees F, and nighttime temperatures average 38 degrees F.) Daytime temperatures ranged from 60 - 65 degrees F, while nights were in mid 30s F. Nightly hard freezes occurred once in December, and frequently in January during the photograph session (Fig. 2). Four inches of snow fell in late January followed by a hard freeze. The summer season (May-September) was hot, breaking all records of recorded temperatures (Fig. 3). There were 71 days with temperatures exceeding 100 degrees F. Normally, Tucson experiences fourty-six days of 100 degrees F. (personal communication, The National Weather Service, Tucson, September 1987).

Dot-matrix Method

The dot-matrix method used in this study was developed by Heisler (1981) to determine the shading densities of open-grown trees. This method was altered slightly based on pretesting and conversations with Heisler.

A 3 x 2 foot foam core board was marked with 425 intersections, at 1 1/2 inch intervals. The board was pinned vertically on the wall and covered with trace paper.

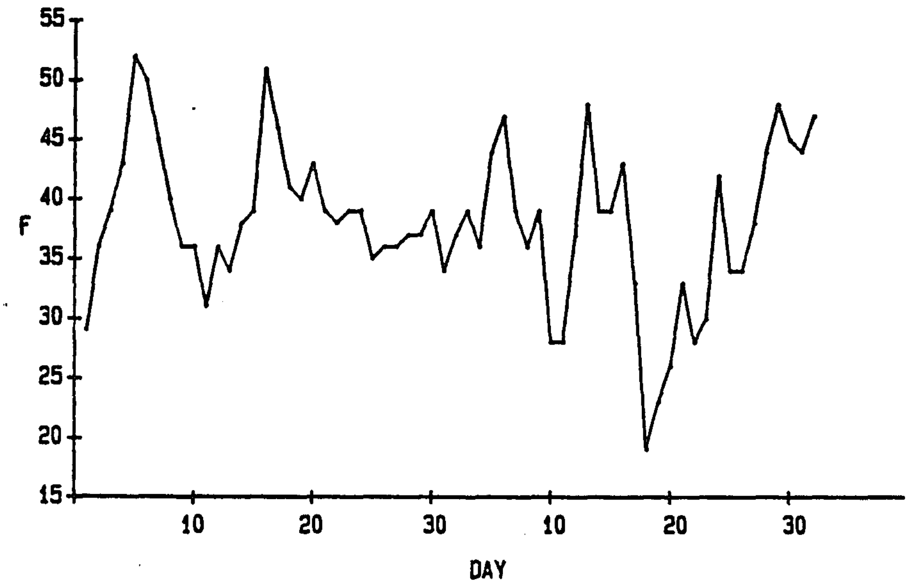



Fig. 2 Minimum Temperatures for
December 1986 and January 1987

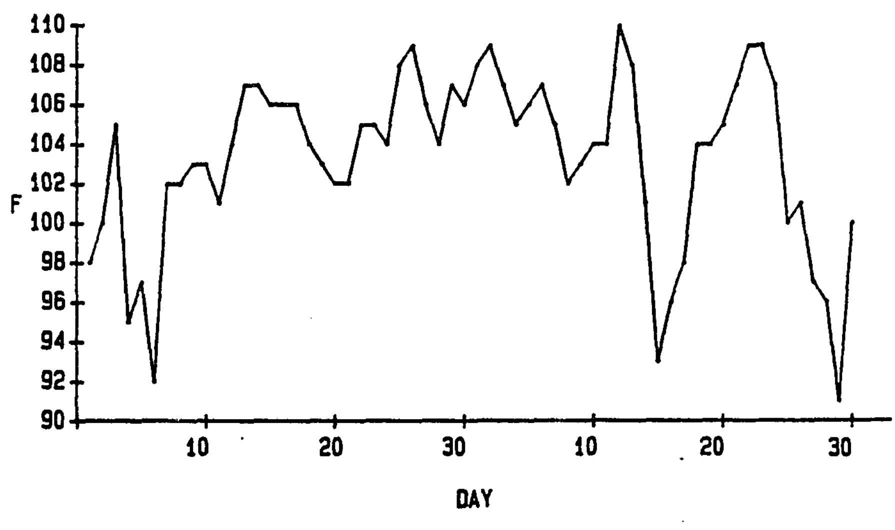



Fig. 3 Maximum Temperatures for
June and July 1987

The tree canopy image was projected onto the board, centered, and adjusted to encompass as much of the board as possible. The crown was defined by connecting a line, branch-tip to branch-tip around the silhouette of the tree on the trace paper.

In order to increase consistency and reduce the arbitrary nature of defining the tree crown boundary, the "1/4 crown rule" was developed. The "1/4 crown rule" defines the furthest distance two outlying branch-tips can be connected to form the crown (personal communication, Gordon Heisler, August 1986). The "1/4 crown rule" establishes the crown boundary by measuring the crown diameter of the projected canopy image, and multiplying the measurement by .25. The resulting measure is the maximum distance between two branch-tips that can be spanned to define the crown. If the distance between two branch-tips is greater than this measurement, the next, most outlying branch-tip between the two and within the 1/4 crown measure is connected (Figure 4). Once the tree crown was defined, the number of intersections that fell on leaf, twig, or branch were counted as "hits" and marked with a slash. The number of intersections not falling on plant matter were counted as "misses" and circled, and the number of intersections that were indistinguishable as "hits" or "misses" were counted as "questions" and marked. The "hits", "misses", and "questions" were added to determine the area of the tree crown. "Hits" plus half of the "questions" were divided by the crown area to arrive at a percent shading density for the tree.

$$\frac{\text{"hits"} + 1/2 \text{ "?s"}}{\text{tree crown area}} = \text{crown density}$$

This percent density was subtracted from 100% to provide the percent transmissivity or SC of the tree. SCs were determined in this manner for all trees, summer and winter.

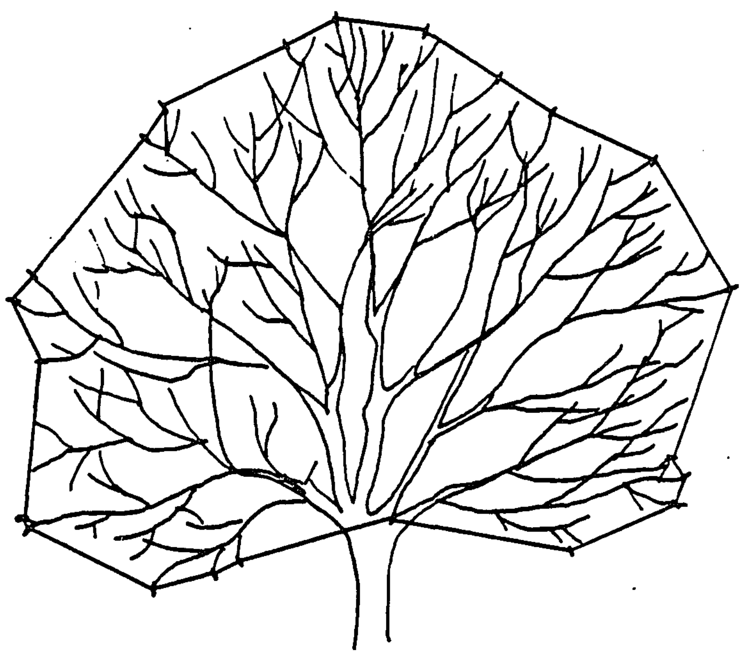


Fig. 4 Example of a Tree Canopy
Defined by the 1/4 Crown Rule

Analysis

An analysis of variance using SPSS-X (1986), was calculated to test between-subjects and within-subjects effects of species, seasonal SC, and pruning effects using transformed data. Data were transformed to stabilize the variance that resulted from an uneven number of cases in each treatment cell of the ANOVA matrix. All conclusions were drawn from transformed data, but are reported in untransformed data to enhance interpretation. Data were transformed by taking the square root of each datum and arcsining the result. The degrees of freedom in this ANOVA were 126 which makes the test sensitive to any slight interactions, therefore species, seasonal SC, and pruning effects were further tested using the following equation:

$$\bar{y}1 - \bar{y}2 \pm t(1 - \alpha/2;\ df)\ \frac{MSE}{r1} + \frac{MSE}{r2}$$

where:

$\bar{y}1$ = the mean of treatment 1

$\bar{y}2$ = the mean of treatment 2

$t$ = student's t value for $p = .01$

$\frac{MSE}{r1}$ = the mean square error for replications in treatment 1

$\frac{MSE}{r2}$ = the mean square error for replications in treatment 2

This equation tested the difference between pruning treatments within a species, within a season, using the worse case scenario: Mulberry, summer SCs, pruning neutral and pruning open (transformed data). Confidence intervals were used to determine which species were significantly different from other species, and which species showed seasonal differences.

## Computer Simulations

Hypothesis 3 was tested in the second half of this study using SPS and MICROPAS programs. Hypothesis 3 states: Shading in Tucson has a substantial impact on annual energy loads. A more specific set of questions were developed to guide research design:

1) Do different SCs have an effect on energy performance?
2) Do different tree shapes have an effect on energy performance?
3) Do east and west shade have an effect on energy performance?
4) Do increasing number of trees have an effect on energy performance?
5) Do different construction types have an effect on energy performance?

SPS and MICROPAS systems were used to determine the annual space conditioning requirements for three residential constructon types in Túcson: a masonry and a wood frame house typical of construction used in the 1980's, and a masonry house typical of construction built in the 1950's with some energy conserving modifications. These houses were modeled with one, two, and three trees on the east or west side of the house to determine the impact of various shading scenarios. Four tree types were modeled using SC data collected earlier in this study. Shading scenarios and housing types are described after a description of SPS and MICORPAS programs.

SPS and MICROPAS Systems

SPS calculates and projects shadow patterns and irradiance reductions from tree shade onto buildings. The user describes size, roof angle, and orientation of the building, as well as the location, size, shape, and seasonal SCs of tree(s) to be modeled. The user also inputs the latitude and longitude of the location, time zone, and simulation day, month, and year of season to be modeled. These data are used to calculate sun angles.

Seven seasons were modeled in this study to simulate a full year: winter, winter-spring, spring-summer, summer, summer-fall, fall-winter, and peak-cooling. Seven seasons were necessary to reflect the annual sun path plus a peak cooling season to provide information for the most extreme climatic period in Tucson.

Tree shade was modeled for each building surface as cells of a grid. Shaded grids are filled with the plant's shading coefficient, at three half-hour intervals. The three values are averaged to derive one value for each grid cell for each hour. This averaging improves the accuracy of the MICROPAS simulation by considering the movement of the shadow during the hour.

MICROPAS estimates building energy use on an hour-by-hour basis. The user inputs thermal characteristics of the house, efficiency of heating and cooling systems, occupant behavior, and specific weather data. The program provides information on annual energy performance summaries, seasonal loads, and peak conditions in British Thermal Units (BTUs) and dollars.

MICROPAS simulations were run for the three residential construction types without trees to provide base data for each house, then with trees to compare the effect of tree shade on the energy performance of three residential construction types.

## Residential Construction Types

Residential construction types were designed to reflect three available housing construction types in Tucson. The three residential construction types are described below. Table 2 follows and shows thermal specifications for each construction type.

Masonry 80: Reflects a typical masonry house of the 1980s with energy saving qualities. The structure is built of 6 inch reinforced block walls with board insulation (R-8), R-30 insulation in the attic, and double pane glass on all windows (Figures 5 and 6).

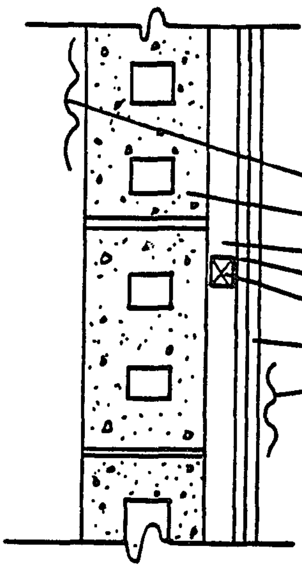
<u>Wood 80</u>: Reflects a typical wood frame house of the 1980s. Construction is wood frame walls with drywall, insulation and sheathing (R-15), R-30 insulation in the attic, and double pane glass windows (Figure 7).

<u>Masonry 50</u>: Reflects houses built in the 1950s with energy efficient modifications homeowners most likely have added (personal communication, John Guenther, Tucson Electric Power, Energy Management, September 1987). Energy efficient modifications are better quality insulation in the attic and weather stripping to reduce air infiltration. The house is a double-brick, stucco-frame structure (R-3), with R-11 insulation in attic and single pane glass windows (Figures 8 and 9).

Most housing characteristics were held constant to reduce the number of factors responsible for different amounts of energy use. The factors held constant were:

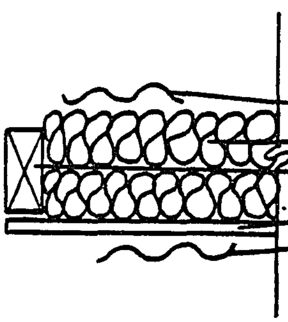
1) Orientation: long axis running north and south to expose the largest opaque and glazed surfaces to the east and west sun.

2) Size, shape, and color: single story, ranch style building, rectangular shape, 36 x 41 feet (1476 square feet), painted gray.



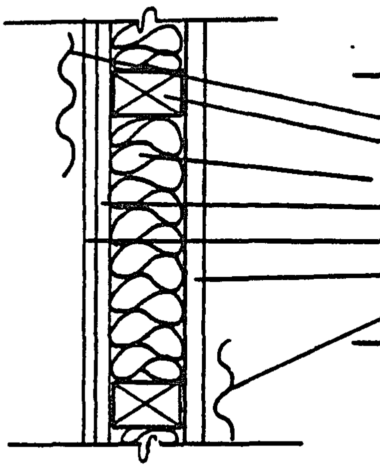
| FRAMING (25%) | | CAVITY (75%) |
|---|---|---|
| .17 | outside air film | .17 |
| .96 | block | .98 |
| -- | air space | .98 |
| 5.26 | board insulation | 5.26 |
| .94 | 2"x 2" wood strips | -- |
| .45 | 1/2" gympsum board | .45 |
| .68 | inside air film | .68 |
| 8.46 | Total Resistance | 8.50 |
| | Composite Resistance | 8.49 |
| | Composite U-value | .117 |

Fig. 5 Masonry 80
6" Reinforced Block Wall



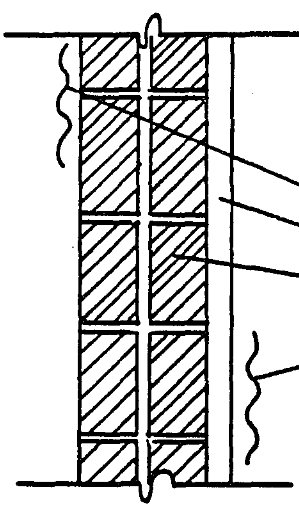
| WITHOUT JOIST (90%) | | WITH JOIST (10%) |
|---|---|---|
| 1.46 | attic | 1.46 |
| 30.00 | R-30 insulation | -- |
| -- | 2"x 6" joists 24" o.c. | 6.87 |
| .45 | 1/2" drywall | .45 |
| .77 | inside air film | .77 |
| 32.68 | Total Resistance | 9.55 |
| | Composite Resistance | 30.89 |
| | Composite U-value | .032 |

Fig. 6 1980 Ceiling Construction



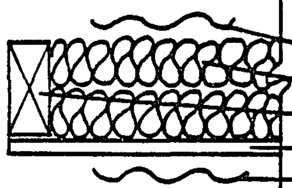
| WITHOUT STUD (75%) | | WITH STUD (25%) |
|---|---|---|
| .17 | outside air film | .17 |
| -- | 2" x 4" stud 16" o.c. | 4.37 |
| 15.00 | R-15 insulation | -- |
| 1.22 | 1/2" seathing | 1.22 |
| .61 | 1/8" siding | .61 |
| .45 | 1/2" dry wall | .45 |
| .68 | inside air surface | .68 |
| 18.13 | Total Resistance | 7.50 |
| | Composite Resistance | 15.47 |
| | Composite U-value | .065 |

Fig. 7 Wood 80
Wood Frame Wall



| | Wall |
|---|---|
| outside air film | .17 |
| stucco | .20 |
| double brick | 1.95 |
| inside air film | .68 |
| Resistance | 3.00 |
| U-value | .333 |

Fig. 8 Masonry 50
Double Brick Stucco



| WITHOUT JOIST (90%) | | WITH JOIST (10%) |
|---|---|---|
| 1.46 | attic | 1.46 |
| 11.00 | R-11 insulation | -- |
| 6.87 | 2"x 6" joists 24" o.c. | 6.87 |
| .45 | 1/2" drywall | .45 |
| .77 | inside air film | .77 |
| 13.68 | Total Resistance | 9.55 |
| | Composite Resistance | 13.27 |
| | Composite U-value | .075 |

Fig. 9 1950 Ceiling Construction

3) Location and amount of glazing and opaque surfaces (Figure 10, 11, and 12). Glazed surface is 14% of floor area.

4) Slab foundation (Figure 13), shingled roof (Figure 14), roof pitch (18 degree angle), and 2 foot overhangs on east and west sides (Figure 15).

5) Internal gains: heat sources inside structure from lighting, appliances, people, and atmospheric humidity (68,262 btu/day). Occupancy is 3.2 people with highest loads at breakfast and dinner hours, and lowest loads at night. Seasonal variations in internal loads are minimal.

6) Ventilation: natural window ventilation was used for cooling whenever the outside air provided a cooling effect inside. Ventilation temperature setting was 70 degrees F. When natural cooling could not keep inside temperatures below degrees 78 F, the ventilation system closed and the cooling system came on.

Space conditioning systems were the same for the 1980's and 1950's house though their efficiency rating changed. The 1950's furnance was a gas unit with a free standing pilot. The efficiency rating was 65%. The 1980's furnace did not have a free standing pilot. The efficiency rating was 76.4% (personal communication, Jack Leonard, Heating and Cooling Wholesale, September 1987).

The Seasonal Energy Efficiency (SEER) of the air

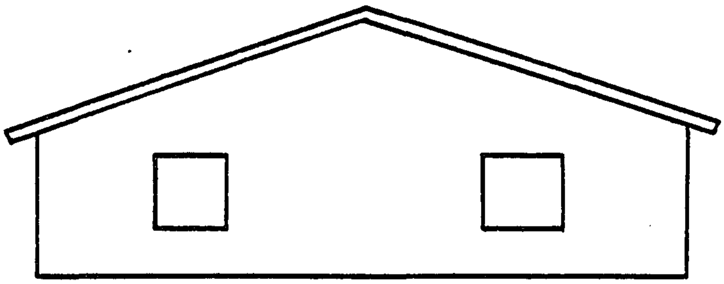


Fig. 10 North and South Elevations

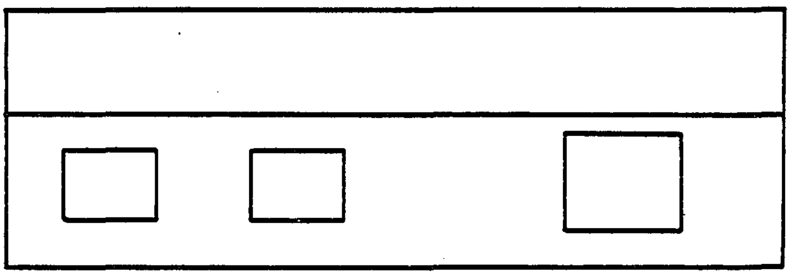


Fig. 11 East Elevation

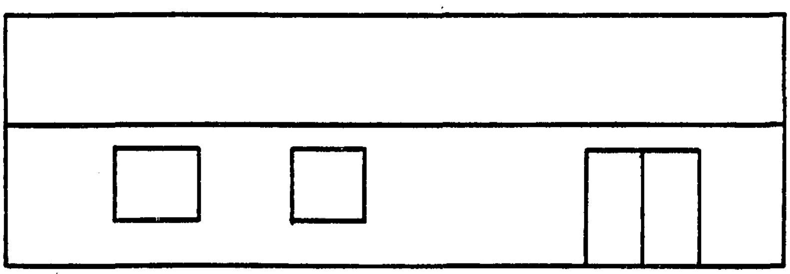


Fig. 12 West Elevation

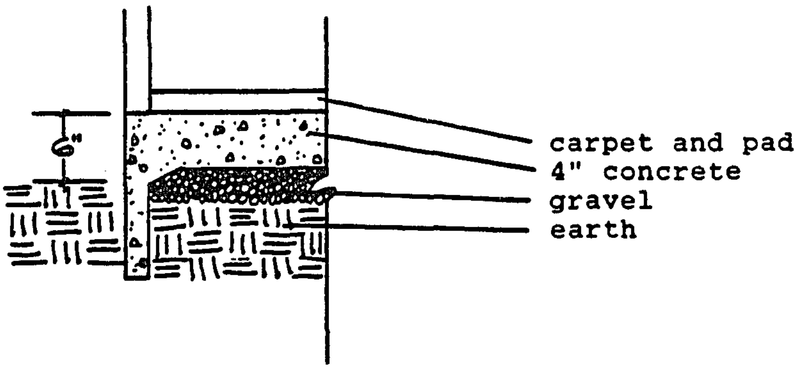
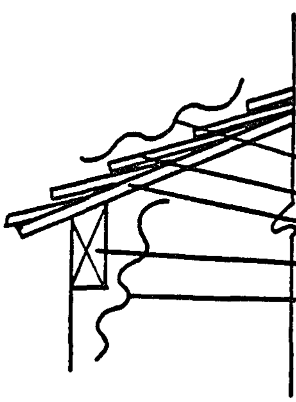



Fig. 13 Slab-on Grade Foundation



| WITHOUT JOIST (90%) | | WITH JOIST (10%) |
|---|---|---|
| .17 | outside air film | .17 |
| .44 | 1/4" asphalt shingle | .44 |
| .62 | 1/2" plywood | .62 |
| -- | 2" x 6" rafters 24" o.c. | -- |
| 1.42 | inside air film | 1.46 |
| 2.69 | Resistance | 2.69 |
| | U-value | .372 |

Fig. 14 Roof Construction

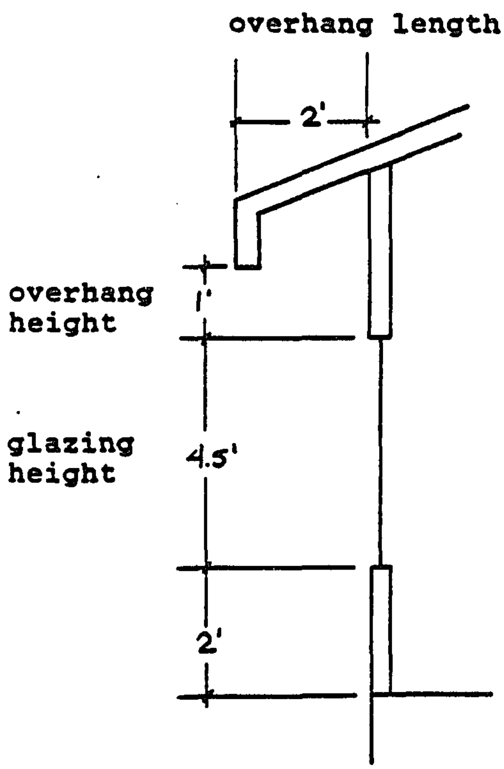



Fig. 15 Overhang Dimentions
for East and West

Table 2
Thermal and Energy Specifications for
Wood 80, Masonry 80, and Masonry 50

| | |
|---|---|
| FLOOR AREA | 1476 sq ft |
| FLOOR DIMENSIONS | 41' X 36' |
| WINDOW AREA | |
| Total | 214 sq ft |
| North and South | 32 sq ft |
| East and west | 75 sq ft |
| WINDOW SHADING COEFFICIENT | 0.63 sum. 0.80 win. |
| WALL AREA | |
| Total | 1170 total |
| North and South | 332 sq ft |
| East and West | 253 sq ft |
| SOLAR ABSORPTIVITY | |
| Walls | 0.70 |
| Roof | 0.40 |
| INSULATION | |
| Roof | R-2.69 |
| Ceiling | |
| 1980 | R-30.89 |
| 1950 | R-13.27 |
| Walls | |
| WOOD 80 | R-15.47 |
| MASONRY 80 | R-8.49 |
| MASONRY 50 | R-3.0 |
| Slab edge | R-1 |
| Windows | |
| 1980 | R-1.8 |
| 1950 | R-1.1 |
| THERMAL MASS | |
| Carpeted slab | 1476 sq ft 68,865 lbs. |
| INFILTRATION RATE | medium |
| VENTILATION RATE | variable |
| WIND CORRECTION FACTOR | 0.33 |
| GAS FURNACE EFFICIENCY | |
| 1980 | 0.76 |
| 1950 | 0.65 |
| AIR CONDITIONING EFFICIENCY | |
| 1980 | 9.0 SEER |
| 1950 | 6.5 SEER |
| THERMOSTAT SETTINGS | 70 F low, 78 F high |
| INTERNAL SENSIBLE & LATENT HEAT GAIN | 68262 Btu/day |
| ENERGY COSTS | |
| Natural Gas (Heating) | 0.50/therm |
| Electricity (Cooling) | 0.08/therm |
| HEATING COSTS (1 million Btu) | $7.14 |
| COOLING COSTS (1 million Btu) | $8.70 |

conditioning units were 6.5 SEER for the 1950's model, and 9.0 SEER for the 1980's model (personal communication, J. Leonard, September 1987).

## Shading Scenarios

Shading scenarios were developed to answer five questions stated earlier:

1) Do different SCs have an effect on energy performance?
2) Do different tree shapes have an effect on energy performance?
3) Do east and west shade have an effect on energy performance?
4) Do increasing number of trees have an effect on energy performance?
5) Do different construction types have an effect on energy performance?

To answer the first two questions, the six tree species measured in the first part of the study were categorized by seasonal SCs, shape, and expected size after a 5 year period, assuming they were transplanted from 15 gallon containers. SCs simulated were the mean SC for each representative species before separation into pruning classes. These SCs reflect all pruning effects. Four tree types resulted and are referred to as Mulberry, Mesquite, Sumac, and Polydan. Data for each category, are listed in Table 3. Canopies were assumed to be pruned up to 7.0 feet to allow people to pass underneath and for views out windows shaded by the tree. Tree shapes modeled were paraboloid and vertical ellipsoid.

To answer questions 3 and 4, tree types were simulated on the east and west side of the house singularly, and in groups of two and three. Trees were located 12.5 feet from the house so that they did not overhang the roof. They were positioned to shade as much of the east and west surfaces as possible without shading the south wall (Figures 16 and 17).

To address the final question, tree types and locations were simulated for three residential construction types: Masonry 80, Wood 80, and Masonry 50, described earlier.

To summarize, four tree types reflecting various SCs and shapes were simulated to determine the effect of crown density and crown shape on space conditioning loads. One, two, and three trees were simulated to determine the impact resulting from the addition of one more tree. Tree shade was simulated on east and west surfaces for three different residential construction types. Previous studies show that largest savings result from summer shade on these surfaces, and that savings vary with construction type.

Table 3
Tree Types

| SPECIES | SHAPE | FOLIATION | HEIGHT | CROWN DIA. | BOLE HT. | WINTER SC | SUMMER SC |
|---|---|---|---|---|---|---|---|
| Mulberry | Paraboloid | June-Dec. | 18.0' | 25.0' | 7.0' | .43 | .26 |
| Mesquite/ Palo Verde | Paraboloid | Evergreen | 18.0' | 25.0' | 7.0' | .25 | .25 |
| African Sumac/ Olive | Paraboloid | Evergreen | 18.0' | 25.0' | 7.0' | .15 | .15 |
| Polydan | Ellipsoid | Evergreen | 21.0' | 13.0' | 7.0' | .16 | .16 |

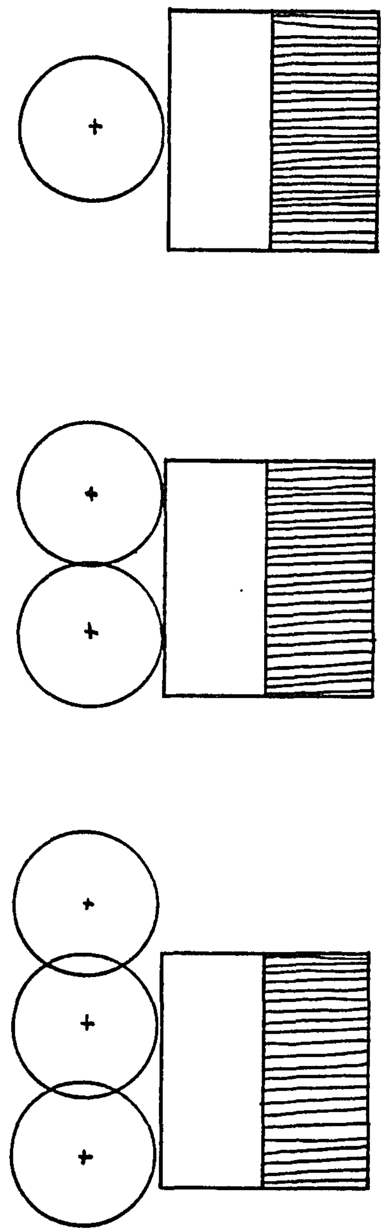


Fig. 16 West Side Location
for Paraboloid Tree Type

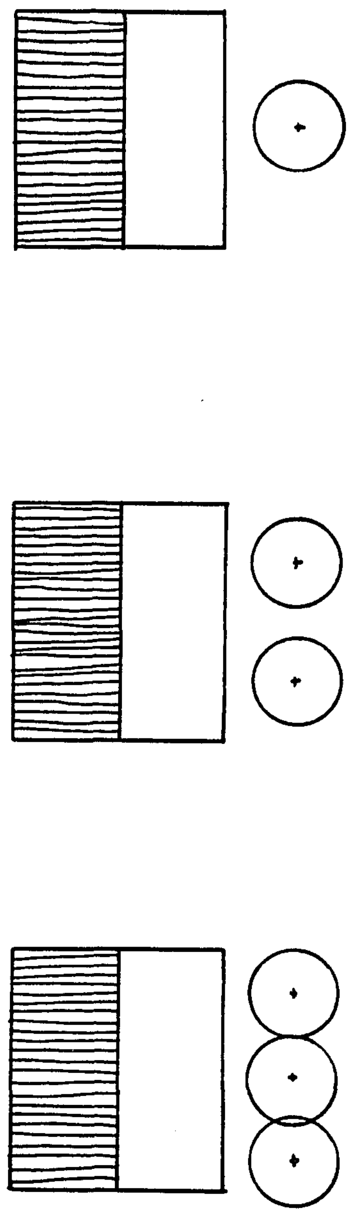


Fig. 17 East Side Location
for Ellipsoid Tree Type

# CHAPTER 3

## RESULTS AND DISCUSSION

Hypotheses 1 and 2 were tested in the first part of the study using the photographic dot-matrix method to determine SCs. Data collected in the first part of the study were used to develop shading scenarios to test Hypothesis 3. SPS and MICROPAS systems were run to determine the effect of these shading scenarios on energy performance. Results are presented here with related hypotheses.

### PRUNING

Analysis of variance demonstrated an interaction of pruning x species x seasonal shading coefficient (SC) at .05 level (Table 4). Given the interaction of pruning with species and season found in this study, it is surprising other studies do not consider it as a variable. Pruning is not discussed by Gardnor and Sydnor (1984) who used trees from a shade tree evaluation plot. We can expect that trees in their study had similar care and similar pruning treatments. Wagar, Heilser, and Atkinson-Adams (1986) measured trees around Berkeley and Davis, CA opportunistically (as in this study). They mentioned locating trees on golf courses, and in residential areas but did not mention pruning differences, which we can expect varied with the individuals responsible for maintenance. Pruning affected SCs reported in this study.

Table 4
Analysis of Variance

| Within-subject effect Source of Variation | SS | DF | MS | F | Sig. of F |
|---|---|---|---|---|---|
| Within cells | .37 | 126 | .00 | | |
| Season | .08 | 1 | .08 | 26.36 | .000 |
| Pruning by Season | .00 | 2 | .00 | .04 | .962 |
| Species by Season | .13 | 5 | .03 | 9.27 | .000 |
| Species by Season by Pruning | .07 | 10 | .01 | 2.38 | .013 |

This study opportunistically sampled trees wherever they could be photographed and met the criteria described previously in chapter 3. Large portions of the sample were located on golf courses or city maintained property, thus reducing the number of tree managers. In residential settings, each homeowner acts as a tree manager and we can expect pruning to have an even greater effect on SCs than in this study. A sample of randomly selected trees, with similar maintenance practices would reduce the number of variables affecting canopy density, such as pruning, fertilizing, irrigation, soil conditions, varieties and cultivars. Established tree study plots, municipal park systems, or other large tracts of land under a single management regime are possible locations to find large samples of similarly maintained trees. This would provide SCs representative of a species rather than representative of numerous maintenance factors.

Further testing of the differences between pruning classes for a species, within a season proved to be significant (p = .01) for 5 of the 6 species (Table 5), therefore all data are reported within pruning classes. Mean SCs reflected pruning treatment in most cases (Table 6). For example, Polydan summer SCs were neutral .15, open .19, and dense .09. However, Palo verde (winter), Sumac (winter, summer), and Mesquite (summer) have denser SC in the neutral category than in the open category. Mulberry (summer) has a more open SC in the dense pruning category than the neutral category. For species Palo verde, Sumac, and Mulberry, these pruning classes were not significantly different (Table 5). Pruning classes neutral and open for Mesquite (summer) were significantly different and the open category SC is .03 denser than the neutral category. Looking at the images did not provide an explanation for this, as the canopy densities appeared similar in the open category, but there was much more apparent variation in the neutral category.

Although pruning has a significant effect on seasonal SCs, a greater variation exists among species than among pruning classes. The greatest mean variations among species, within a pruning class, within a season were .37 (for winter, Mulberry and Sumac, pruning open) and .26 (for summer, Mulberry and Sumac, pruning open). The greatest variation within a species, among pruning classes was .17 (Mulberry, summer, pruning neutral and open).

Table 5
Significance of Pruning Class
($p = .01$)

| Species | Pruning Class | Summer | Winter |
|---|---|---|---|
| Mulberry | neutral-open | yes | yes |
| | open-dense | no | yes |
| | neutral-dense | no | no |
| Palo verde | neutral-open | no | no |
| | open-dense | no | no |
| | neutral-dense | yes | yes |
| Mesquite | neutral-open | yes | no |
| | open-dense | no | no |
| | neutral-dense | no | yes |
| Polydan | neutral-open | no | no |
| | open-dense | yes | yes |
| | neutral-dense | yes | yes |
| Olive | neutral-open | yes | yes |
| | open-dense | yes | yes |
| | neutral-dense | yes | no |
| Sumac | neutral-open | no | no |
| | open-dense | no | no |
| | neutral-open | no | no |

Table 6
Mean Seasonal Shading Coefficients by Pruning Class
(p = .01)

Pruning Neutral

| Species | Winter | | | Summer | | | S.D.* |
|---|---|---|---|---|---|---|---|
| Mulberry (9*) | .40 | a | (.48-.31) | .22 | a | (.31-.15) | yes |
| Palo Verde (5) | .27 | b | (.34-.21) | .25 | ab | (.31-.23) | no |
| Mesquite (10) | .27 | b | (.34-.20) | .26 | b | (.40-.20) | no |
| Olive (9) | .16 | c | (.28-.08) | .17 | c | (.25-.12) | no |
| Polydan (17) | .17 | c | (.20-.13) | .15 | c | (.18-.13) | no |
| Sumac (11) | .17 | c | (.31-.10) | .15 | c | (.23-.02) | no |
| Total 61 | | | | | | | |

Pruning Open

| Species | Winter | | | Summer | | | S.D.* |
|---|---|---|---|---|---|---|---|
| Mulberry (3) | .53 | a | (..55-.49) | .39 | a | (.50-.27) | no |
| Palo Verde (4) | .23 | c | (.25-.20) | .29 | ab | (.34-.21) | no |
| Mesquite (8) | .33 | b | (.48-.23) | .23 | bc | (.32-.06) | yes |
| Olive (18) | .19 | c | (.26-.15) | .18 | cd | (.28-.12) | no |
| Polydan (8) | .18 | c | (.23-.16) | .19 | cd | (.23-.05) | no |
| Sumac (3) | .16 | c | (.21-.12) | .13 | d | (.15-.13) | no |
| Total 44 | | | | | | | |

Pruning Dense

| Species | Winter | | | Summer | | | S.D.* |
|---|---|---|---|---|---|---|---|
| Mulberry (2) | .39 | ** | (.39-.39) | .28 | ** | (.28-.27) | ** |
| Palo Verde (11) | .26 | a | (.26-.12) | .25 | a | (.30-.16) | no |
| Mesquite (5) | .20 | b | (.37-.19) | .19 | b | (.25-.15) | yes |
| Olive (5) | .12 | c | (.14-.10) | .13 | c | (.16-.07) | no |
| Polydan (7) | .12 | c | (.23-.13) | .09 | c | (.26-.05) | no |
| Sumac (9) | .14 | c | (.20-.10) | .12 | c | (.17-.09) | no |
| Total 39 | | | | | | | |

Species followed by the same letter are not significantly different from each other.
(Range)
S.D.* = Seasonal Difference
* Number in sample. Total = 144
** Confidence interval too wide, due to a small sample size.

## Hypothesis 1

Hypothesis 1 states: SCs vary significantly among species, therefore, accurate shading coefficients are required to accurately simulate their shading effects.

The six tree species measured fell into 3 groups, each group having a significantly different SC from the others (p = .01). Three tree groups reflecting seasonal densities and degree of deciduousness are shown in Table 7.

Differences among species varied with pruning class. Findings are reported below for the neutral pruning class at the .01 level. Mean seasonal SCs for all species, within pruning classes are listed in Table 4.

Within the winter season, three tree groups with significant differences resulted. Ranked from lowest or most dense SC to highest or most open SC are 1) Olive (.16), Afican sumac (.17), and Polydan (.17), 2) Mesquite (.27) and Palo verde (.27), and 3) Mulberry (.40). Within the summer season, significant tree groups from most dense SC to most open are 1) African sumac (.15), Polydan (.15), and Olive (.17), 2) Mulberry (.22) and Palo verde (.25), and 3) Palo verde (.25) and Mesquite (.26). Maximum mean SC differences among species were .37 for winter, and .26 for summer (all pruning classes).

Table 7
Three Significant Tree Groups

| Species | Deciduousness | Seasonal Density | Average SC |
|---|---|---|---|
| Olive/ Polydan/ Sumac | evergreen | dense summer<br>dense winter | .15<br>.15 |
| Palo verde/ Mesquite | drought deciduous | medium summer<br>medium winter | .25<br>.25 |
| Mulberry | deciduous | medium summer<br>open winter | .26<br>.43 |

Winter ranking of SCs represented the degree of deciduousness as expected. The most dense species were evergreen: Olive, African sumac, and Polydan. The next most dense species were drought deciduous: Mesquite and Palo verde. Among-species differences changed with pruning class. The least dense species was Mulberry.

Summer ranking of SCs again reflected the species' degree of deciduousness, however the Mulberry, Mesquite, and Palo verde order varied since their deciduousness were more closely related. Mulberry, Mesquite, and Palo verde were not as dense as the evergreen species. Olive, Polydan, and African sumac species were not significantly different from each other in any of the pruning classes, which was expected since all three species are dense evergreen trees.

It was surprising to find that Mulberry had a relatively higher summer SC than several other species because it is often planted for its dense shade. It is likely that the stressed appearance of many of the Mulberry trees are reflected by the higher SCs (apparently typical of Tucson). The higher SCs may also reflect an enlarged canopy boundary created by new branch growth not yet filled with twig and leaf growth. Both conditions are visible in the slide samples.

## Hypothesis 2

Hypothesis 2 states: SCs vary significantly between winter and summer within a species, therefore, SCs must be changed in simulations to reflect seasonal influences.

Significant within-species variation were found for Mulberry (pruning neutral) and Mesquite (pruning open and pruning dense) species at .01 level (see Table 4). Mulberry showed a significant difference between seasons with pruning neutral (winter SC .40, summer SC .22) but not pruning open (winter SC .53, summer SC .39) or pruning dense (winter .39, and summer .28). The lack of seasonal difference for the pruning open and dense is most likely a problem with the sample size of these classes. Both classes had less than 4 samples, resulting in a wide confidence interval. Figures 18 - 20 show seasonal trends within pruning classes.

Mesquite was significantly different between seasons for pruning open (winter SC .33, summer SC .23) and pruning dense (winter SC .20, summer SC .19) but not pruning neutral (winter SC .27, summer SC .28). The lack of significant seasonal-differences in pruning neutral appears to reflect the greater variability of the species' seasonal SCs. This variability most likely reflects the various leaf-drop periods and durations of the Mesquite species.

Palo verde, Olive, Polydan, and African sumac were not significantly different between seasons for any pruning category. Olive, Polydan, and African sumac are evergreen trees and were not expected to reflect seasonal differences. Palo verde is a drought deciduous tree and seasonal variations were not expected.

SC trends for each species by season, in relation to crown size are discussed below. Trends are not based on statistical results because sample sizes within pruning classes were too small for statistical analysis. Rather, trends are inferred from graphs plotting seasonal SCs with average crown diameter using all data because pruning classes appear to support overall species trends.

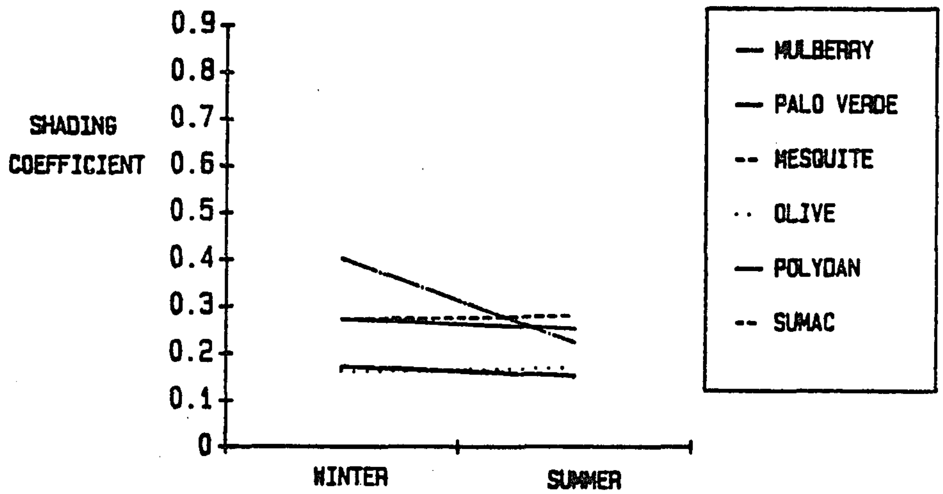



Fig. 18 Species' Seasonal Trends for Pruning Neutral

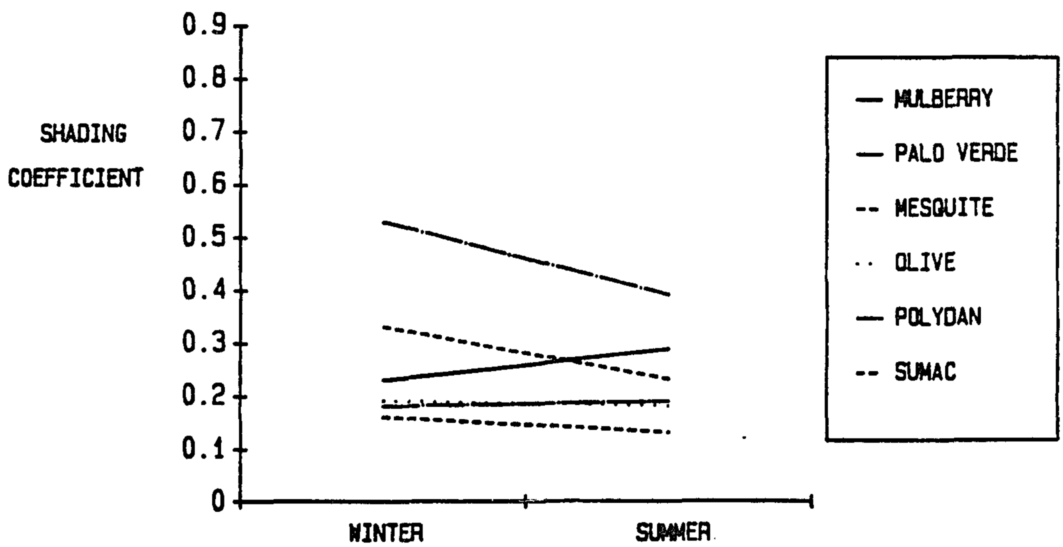



Fig. 19 Species' Seasonal Trends for Pruning Open

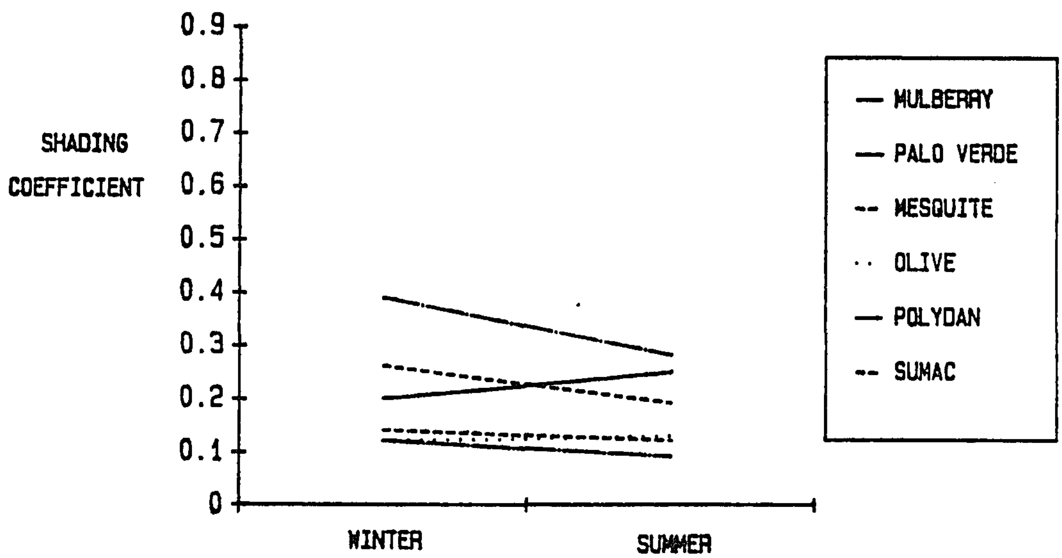



Fig. 20 Species' Seasonal Trends for Pruning Dense

Mulberry and Mesquite summer and winter SCs decreased as average crown diameter reached 30 feet, then increased with size (Figure 21 and 22). Olive and African sumac, summer and winter SCs also tended to decrease with increasing crown diameter (Figure 23 and 24). This seems to indicate that canopy density increases as these species reach mature sizes, then decreases as the tree declines with age.

The general trend for the Palo verde was for summer SCs to increase with average crown diameter and winter SCs to decrease with average crown diameter (Figure 25). Palo verde seem to develop denser winter canopies with

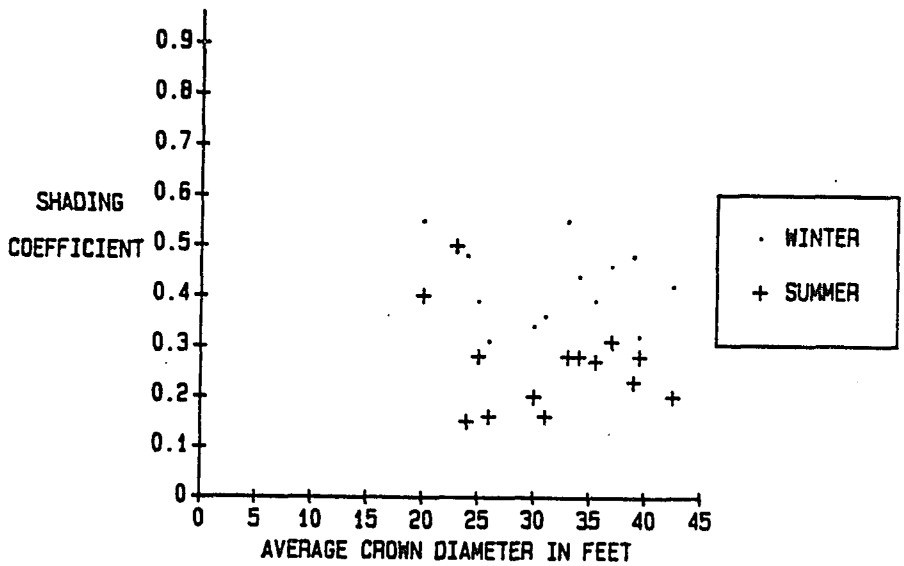



Fig. 21 Seasonal SC Trends for Mulberry

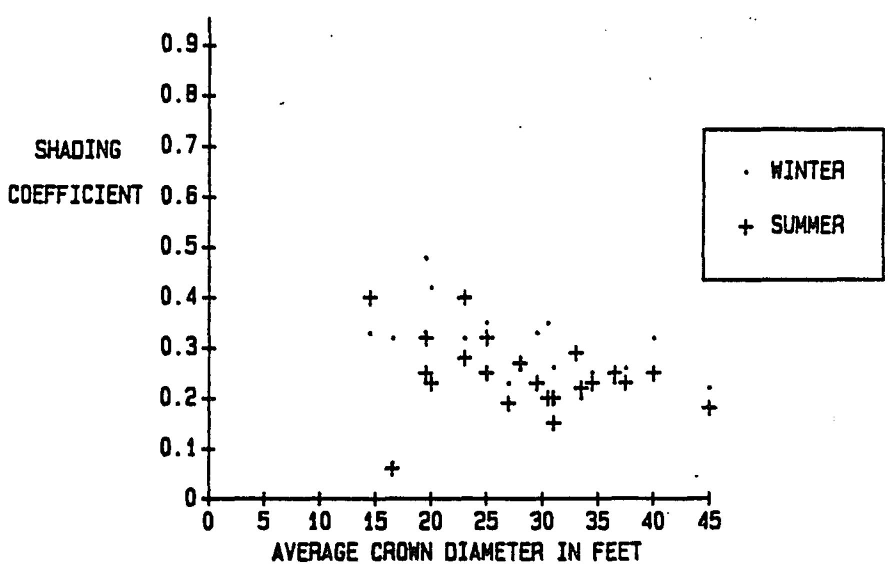



Fig. 22 Seasonal SC Trends for Mesquite

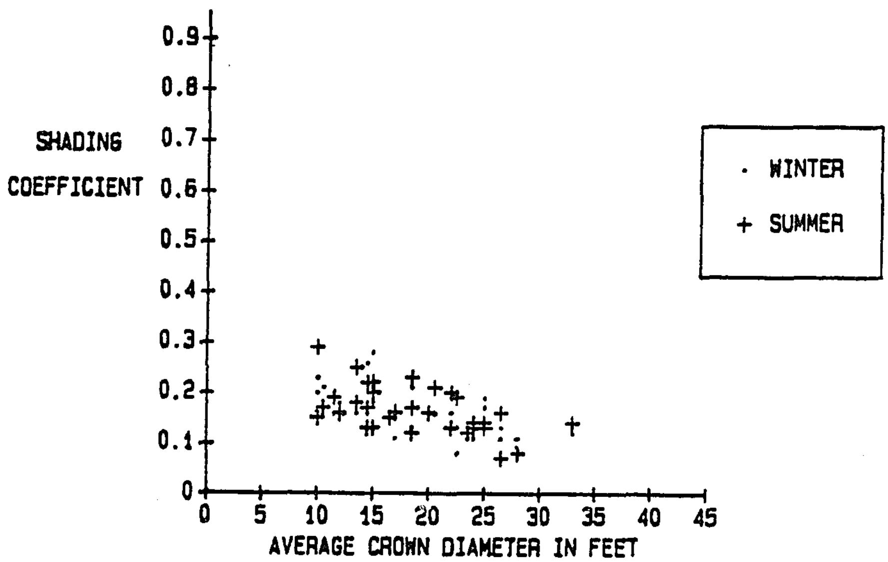



Fig. 23 Seasonal SC Trends for Olive

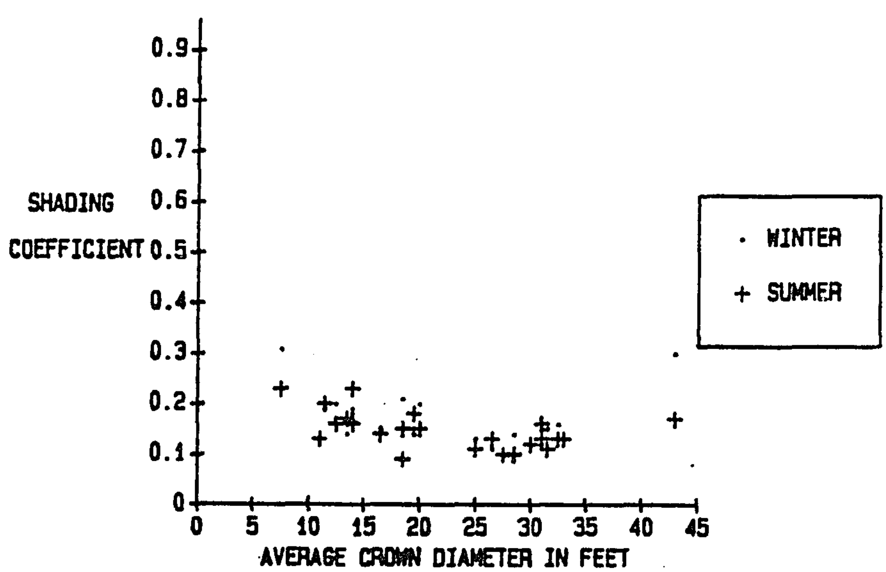



Fig. 24 Seasonal SC Trends for African Sumac

size, while reducing summer canopy density with size. Polydan SCs ranged from .05 - .26, varying without relationship to canopy diameter (Figure 26).

In an attempt to determine trees with desirable solar traits, Heisler (1986b) calculated winter to summer canopy density (amount blockage) ratios from studies in the literature. Trees that were expected to have a low winter to summer ratio did not. A tree canopy with a low winter canopy density and a high summer canopy density would result in a low winter to summer ratio. (Winter canopy density divided by summer canopy density = seasonal canopy density ratio). Heisler considered .40 to be a ratio reflecting a species with desirable solar traits. Winter to summer ratios within pruning class from this study are shown in Table 8.

Tree species considered here have high winter to summer ratios. High ratios were expected for the evergreen trees: Mesquite, Palo Verde, African Sumac, Polydan, and Olive. In some cases, the winter to summer ratio is greater than 1.00 indicating an decrease of canopy density from winter to summer. Although Mulberry showed significant seasonal differences, those differences were not great enough for the species to be considered a tree with appropriate solar traits by Heisler's (1986b) standards.

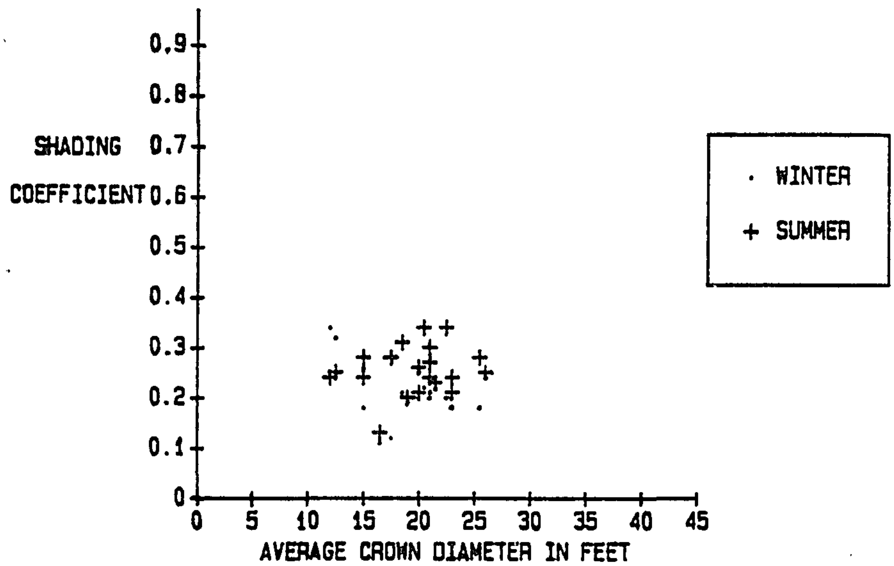



Fig. 25 Seasonal SC Trends for Palo Verde

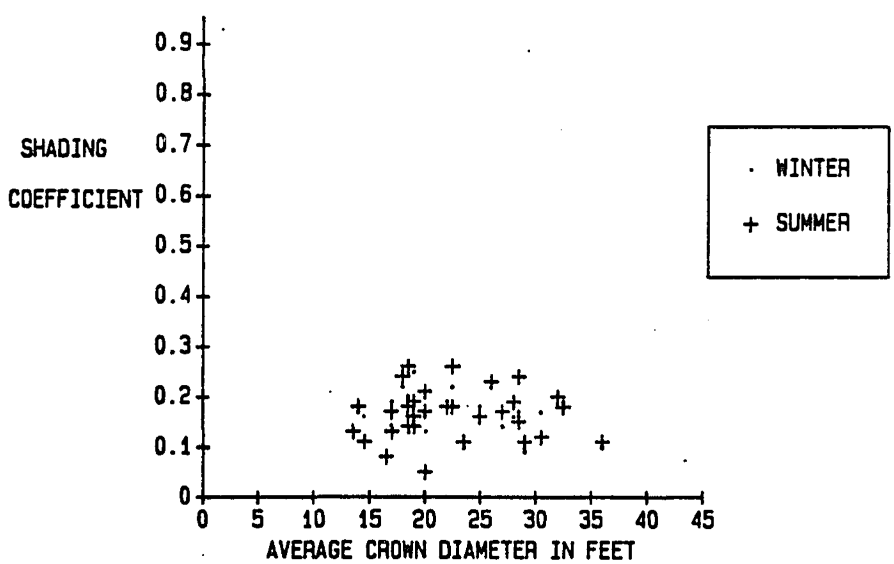



Fig. 26 Seasonal SC Trends for Polydan

Table 8
Winter To Summer Canopy Density Ratios

| Species | Pruning Neutral | Pruning Open | Pruning Dense |
|---|---|---|---|
| Mulberry | .76 | .77 | .85 |
| Mesquite | .98 | .88 | .99 |
| Palo verde | .97 | 1.08 | .98 |
| African sumac | .97 | .96 | .97 |
| Polydan | .97 | 1.01 | .97 |
| Olive | 1.01 | .98 | 1.01 |

In summary, significant differences were found for SCs within species and among species. The six species measured fell into three significant tree groups based on the species' seasonal SCs. In the following section, these tree groups are simulated to quantify their impact on energy loads.

## Hypothesis 3

Hypothesis 3 states that shading in Tucson has a substantial impact on annual energy loads. To test this hypothesis, MICROPAS simulations were run for each residential construction type without trees to provide a control for comparison with shaded residences. Annual energy costs for the 1950 control were more than twice the costs for the 1980 homes (Table 9). The Wood 80 home was slightly more efficient than the Masonry 80 house.

Table 9
Annual Energy Costs
Wood 80, Masonry 80, and Masonry 50 Controls ($)

| Construction Type | Heating | Cooling | Total |
|---|---|---|---|
| Wood 80 | 68 (13%) | 449 (87%) | 517 |
| Masonry 80 | 88 (15%) | 505 (85%) | 593 |
| Masonry 50 | 273 (20%) | 1,120 (80%) | 1,393 |

(percentages are of total costs)

Various shading scenarios were modeled using SPS and MICROPAS programs to compare the effects of tree shade densities and locations on residential construction types with and without tree shade. General effects of tree shade are presented first as they relate to hypothesis 3, and then as they answer the following questions:

1) Do different SCs have an effect on energy performance?
2) Do different tree shapes have an effect on energy performance?
3) Do east and west shade have an effect on energy performance?
4) Do increasing number of trees have an effect on energy performance?
5) Do different construction types have an effect on energy performance?

## Effects of Tree Shade on Annual Energy Loads

Annual energy savings resulting from tree shade were greatest when 3 African sumac trees were located on the west side of house. This shading scenario provided the lowest SC, largest area of shade, and located the shade on the most significant surface (west wall) thereby reducing solar radiation reaching the house more effectively than other shading scenarios. Savings from this shading scenario were $55 (12%) for Wood 80, $64 (12%) for Masonry 80, and $121 (10%) for Masonry 50 (Figure 27, 28, and 29).

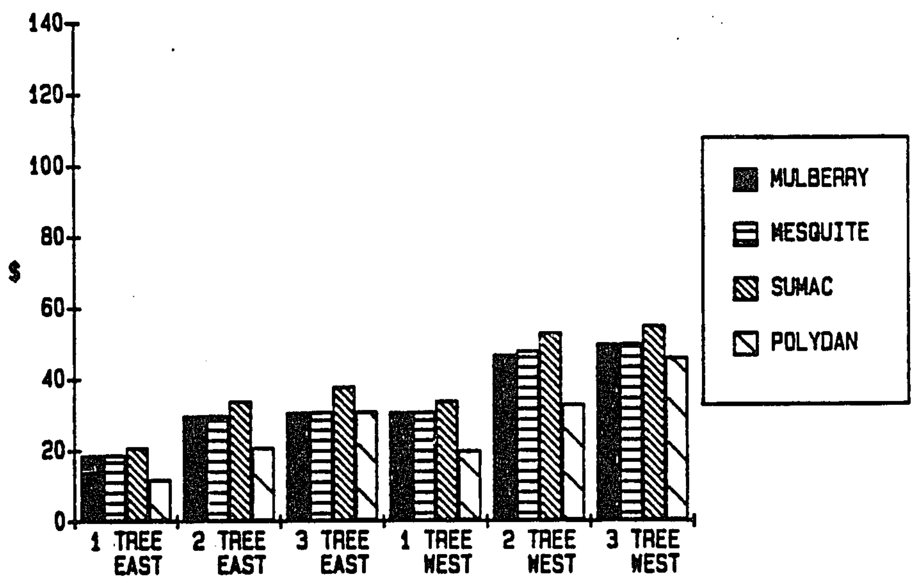



Fig. 27 Annual Energy Savings for Wood 80

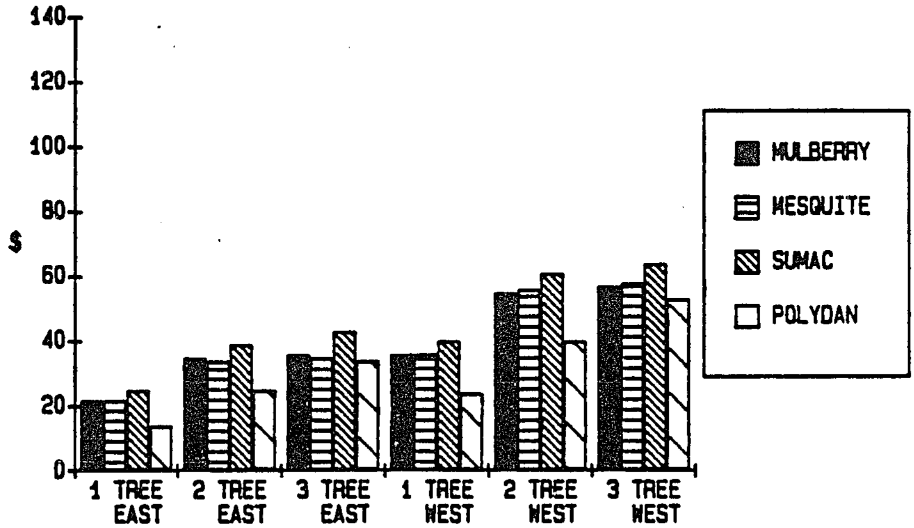



Fig. 28 Annual Energy Savings for Masonry 80

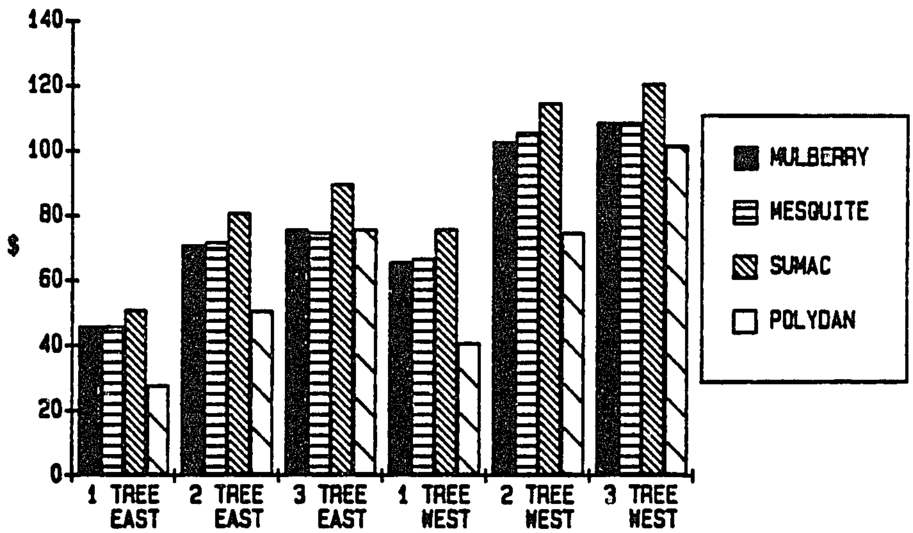



Fig. 29 Annual Energy Savings for Masonry 50

The next greatest savings was a result of 2 African sumac trees located on the west side of the house. The SC was lower than all other shading scenarios (.15), although the area of shade was less than shade from three trees. Savings resulting from this scenario were $53 (12%) for Wood 80, $61 (12%) for Masonry 80, and $115 (9%) for Masonry 50.

The shading scenario offering the least amount of savings was 1 Polydan located on the east side of the house. This scenario offered a low SC (.16) but limited the area and location of shade provided by that tree (this was the smallest of the tree types modeled). Because the area of shade was so much less than other scenarios, and the east wall is less important for reducing cooling loads than the west wall, the resulting savings were small: Wood 80 $14 or 2%, Masonry 80 $12 or 2%, Masonry 50 $28 or 2%. Results demonstrate that tree shade in Tucson does have an impact on annual energy consumption. Annual energy savings ranged from $12 - $121 depending on the SC and shape of the tree, location of the shade (east or west), number of trees, and the residential construction type shaded by the tree.

Effects of Different SCs on Energy Performance

Mesquite (SC .25) and African sumac (SC .15) differed in their ability to reduce energy demands.

Simulations modeling these tree types held tree shape, location, and residential construction type constant but increased SCs by .10. A greater savings of $5 - $12 (1%) for all construction types resulted with the lower SC of the African sumac (Table 10). The ability of different trees to provide different savings is supported in a study (McPherson 1987) where a SC of .10 provided a $24 (6%) savings in cooling costs over a SC of .40 for equal areas of shade on the west wall of a Tucson house.

Tree species determined through statistics to be significantly different did not provide a substantially greater reduction in energy use.

Table 10
Comparison of Annual Energy Savings ($)
from 3 Mesquite and Sumac Tree Types
Located on the West Side

| | Wood 80 | Masonry 80 | Masonry 50 |
|---|---|---|---|
| <u>Mesquite</u> (SC .25) | 50 (10%) | 58 (11.%) | 109 (8%) |
| <u>Sumac</u> (SC .15) | 55 (12%) | 64 (12%) | 121 (10%) |

(percentages are of total costs)

Tree types with SCs exhibiting seasonal differences did not result in a substantially greater savings. Mulberry and Palo verde tree types were simulated to compare the effects of a deciduous tree with an evergreen tree of similar summer SCs (.26 and .25 respectively), but different winter SCs (.46 and .25 respectively). For all housing types, and all shading scenarios incorporating these tree types, resulting annual savings were the same or within $3 of each other for all construction types. Table 11 shows cooling savings and heating costs for Mulberry and Palo verde tree types, with 2 trees located on the east side. Seasonal SC differences in Tucson for east and west walls have a negligible difference in reducing energy performance. These results suggest that evergreen or deciduous trees can be located to shade east or west walls in Tucson without adversely effecting annual energy costs.

Table 11
Comparison of Energy Savings and Costs ($)
from 2 Palo Verde and Mulberry Tree Types
on the East Side

| | Wood 80 | Masonry 80 | Masonry 50 |
|---|---|---|---|
| <u>Palo verde</u> | | | |
| (summer and winter SC .25) | | | |
| cooling savings | 33 (6%) | 37 (7%) | 81 (7%) |
| heating costs | 3 (.6%) | 3 (.5%) | 9 (7%) |
| <u>Mulberry</u> | | | |
| (summer SC .26 and winter SC .43) | | | |
| cooling savings | 30 (7%) | 37 (7%) | 79 (6%) |
| heating costs | 3 (.4%) | 2 (.4%) | 7 (.5%) |

(percentages are of total costs)

In locations where heating constitutes the majority of the energy budget, the effect of seasonal SCs is greater. Evergreen shade (SC .10) increased annual energy costs $71, while deciduous shade (SC .30 and .80) reduced annual energy costs $16 in Madison, with all surfaces shaded (McPherson 1987). The difference in annual savings was $87. In Pennsylvania deciduous trees provided a 7% greater savings than evergreen trees (DeWalle, Jacobs, and Heisler 1983). In colder climates the seasonal SC difference can result in more substantial savings.

Effects of Tree Shape on Annual Energy Loads

Tree shape and size influenced the amount of shade provided by a tree, thus affecting building energy use. Paraboloid and vertical ellipsoid tree shapes were modeled. The ellipsoid tree type, Polydan, showed the least amount of savings of any tree type, although its SC (.16) was only slightly higher than African sumac (.15). Table 12 compares savings from ellipsoid and paraboloid tree types from 2 trees located on the west. The paraboloid trees (24 foot crown diameter) were wider than ellipsoid trees (13 foot crown diameter) due to their growth rate and provided more shade on the walls than the ellipsoid, although the ellipsoid shape, which was 3 feet taller, shaded portions of the roof while the paraboloid did not. The impact of shade on the walls was greater than the impact of shade on the roof due to a higher R-value of insulation in the ceiling and ventilation in the attic, limiting the impact of solar radiation.

Table 12
Comparison of Annual Energy Savings ($) for Paraboloid and Ellipsoid Tree Shapes from 2 Trees on the West Side

| | Wood 80 | Masonry 80 | Masonry 50 |
|---|---|---|---|
| African sumac (SC .15) (Paraboloid) | 53 (11%) | 61 (11%) | 115 (9%) |
| Polydan (SC .16) (Ellipsoid) | 33 (7%) | 40 (7%) | 75 (6%) |

(percentages are of total costs)

Effects of East and West Shade on Annual Energy Loads

Trees on west side of the house had a greater effect on reducing annual energy loads than trees on the east. West shade reduced energy costs from $8 - $48 more than east shade (Table 13). The impact of 1 tree located to shade the west wall provided similar savings to 2 trees located to shade the east wall (Fig. 30). The greater savings from shade on the west is due to the impact of summer sun being greatest on the west side of the house. The west side impact is greatest because buildings are slow to warm up after cooling off at night due to their mass. They do not reach peak heat until mid-afternoon, compounding the effect of solar radiation. When the summer sun is prevented from reaching the west walls, cooling loads are reduced, in this study by as much as $121 (10%).

Table 13
Comparison of East and West Cooling Savings ($)
from 1, 2, and 3, Sumac Tree Types

| | Wood 80 | Masonry 80 | Masonry 05 |
|---|---|---|---|
| East Shade | | | |
| 1 Tree | 23 (5%) | 27 (5%) | 57 (4%) |
| 2 Tree | 37 (8%) | 42 (8%) | 91 (7%) |
| 3 Tree | 41 (9%) | 46 (8%) | 101 (8%) |
| West Shade | | | |
| 1 Tree | 35 (7%) | 40 (7%) | 77 (6%) |
| 2 Tree | 54 (12%) | 62 (12%) | 117 (9%) |
| 3 Tree | 57 (12%) | 65 (12%) | 124 (10%) |

(percentages are of total costs)

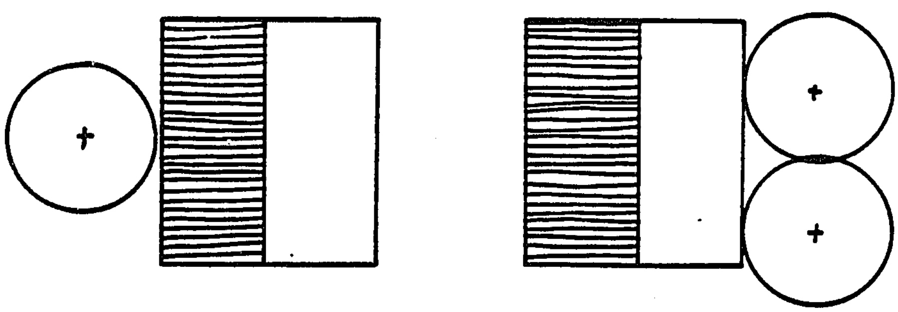


Fig. 30 Location of 1 Paraboloid Tree on the West and 2 Paraboloid Trees on the East

Trees on the east side of the houses increased heating costs $1 - $11 and trees on the west side increased heating costs 0 - $3 for all construction types. Savings from cooling outweighed heating costs in all scenarios. These results are similar to McPherson's (1987) study where heating cost on east walls in Tucson resulted in $1 - $8 increases.

It is not possible to aggregate the effect of tree shade from these simulations on both east and west walls with the MICROPAS system (McPherson 1987). This is due to a nonlinear relationship between shading factors, and heating and cooling loads, as the amount of surfaces shaded increased. However, we do know from previous research that there will be additional savings when trees are located to shade both east and west walls and roofs. Simulations combining east and west shade will be run in a future study.

Effects of Increasing Numbers of Trees on Annual Energy Loads

One, two, and three trees were simulated for east and west sides of the house and for all tree types. In all scenarios, three trees offered the greatest savings although the amount of savings received from adding one more tree varied with tree type. For the paraboloid trees, the marginal value of three trees over two trees are minimal, $1 - $9 (savings varied with housing and tree type). The addition of two trees over one tree offered a $4 - $39 additional savings (again varying with housing and tree type). A greater savings was achieved by adding a second tree rather than a third tree. Shade from the third paraboloid tree fell only partially on the west wall due to the tree's location (Fig. 16).

Ellipsoidal trees were located closer together due to their smaller crown diameter. They were evenly spaced running the length of the walls, without extending past the north or south wall boundaries (Figure 17). Two trees offered an additional savings of $9 - $34 (savings varied with housing type) over one tree, and three trees offered an additional savings of $9 - $27, over two trees. In all cases, the addition of one more tree was almost equal to the amount of savings offered by the first tree. This was due to the location of the trees. Each additional tree offered approximately the same additional amount of shade. Table 14 shows annual energy savings from locating one more paraboloid or ellipsoid tree.

## Effects of Tree Shade on the Energy Performance of Different Construction Types

The 1980s houses are more energy-efficient resulting in less savings than the Masonry 50 house, although the percentage of savings were similar for all houses (Figure 31). Solar radiation on the walls is responsible for most of the summer heat gain. The Masonry 50 construction type more readily absorbed and conducted solar radiation heat gain through the walls due to a lower R-value (Masonry 50 R-3., Masonry 80 R-8.49, and Wood 80 R-15.27), and therefore, provided greater savings when tree shade limited the amount of solar radiation on the walls. Simple weatherizing modifications were incorporated into the Masonry 50 house before simulations were run (upgraded insulation in the attic). Therefore, two feasible options exist for increasing the energy-efficiency of this construction type. The first is to paint the exterior walls a white or near white color rather than the gray simulated. White or near white colors have been found to reduce cooling loads 11% in Miami (Buffington 1978). A similar effect may be found in Tucson. Or, the second option is to provide tree shade on east or west walls to reduce cooling loads 6% and 10% ($90 - $121) respectively, as demonstrated in this study. Locating trees or shrubs on the east and west sides combined will offer even greater savings, although the effect was not tested in this study.

Table 14
Annual Energy Savings ($)
from 1, 2, and 3 Trees
Located on the West Side

| | Wood 80 | Masonry 80 | Masonry 50 |
|---|---|---|---|
| African sumac | | | |
| SC .15 | | | |
| (paraboloid) | | | |
| 1 Tree | 34 (7%) | 40 (7%) | 76 (6%) |
| 2 Trees | 53 (11%) | 61 (11%) | 115 (9%) |
| 3 Trees | 55 (12%) | 64 (12%) | 121 (10%) |
| Polydan | | | |
| SC .16 | | | |
| (ellipsoid) | | | |
| 1 Tree | 20 (4%) | 24 (4%) | 41 (3%) |
| 2 Trees | 33 (7%) | 40 (7%) | 75 (6%) |
| 3 Trees | 46 (10%) | 53 (10%) | 102 (8%) |

(percentages are of total costs)

Masonry 80 and Wood 80 are more energy-efficient due to their construction and resulting savings are less than that of the Masonry 50 construction type. However, energy savings of $55 - $64 can be achieved from locating trees on west sides.

## Considerations of this Study

The following section considers limitations associated with the photographic dot-matrix method and simulation designs, as well as implications of this study.

### Photographic Dot-matrix Method

Several limitations exist when using photographs to

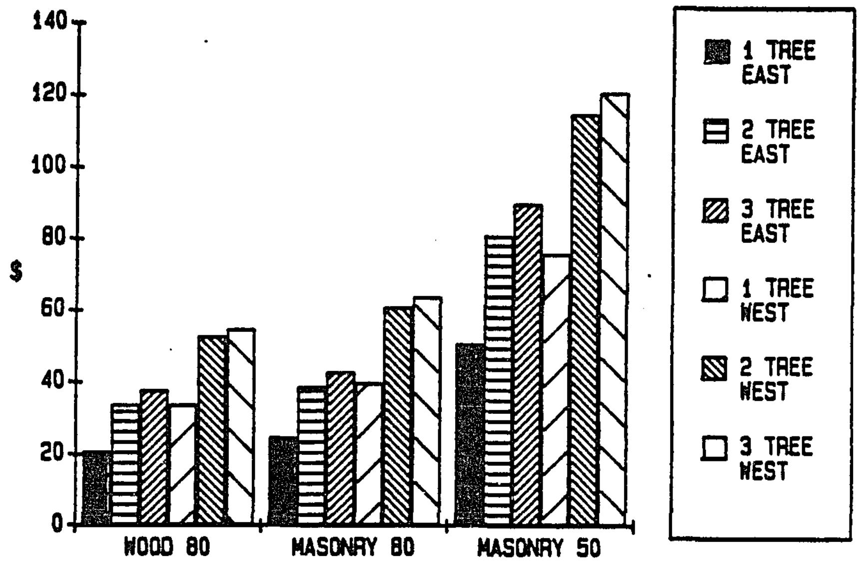



Fig. 31 Annual Energy Savings
for Wood 80, Masonry 80, and Masonry 50

estimate SCs. First, are limitations associated with the reflectance of leaves, the angle of leaves within the canopy, and the elevation angle of the camera as it determines the path length through the tree canopy. Second, are problems associated with capturing a clear image of the canopy, such as wind, obstructions in the crown, and distortion created with a wide angle lens. Considering these limitations, the resulting SCs reflect a particular camera or sun angle, and canopy configuration at a point in time.

It is likely that the 1/4 crown rule will have an effect on how these results compare to other studies. If a smaller measure had been used to determine the canopy boundary, SCs would have been lower, and if a larger measure had been used, resulting SCs would have been higher. Wagar et al. (1986) connected branch-tip to branch-tip without indentations to define canopy boundaries. Their method, compared to the 1/4 crown method should result in a higher SC. Yates (1987) and Gardnor (1982) do not discuss defining canopy boundary in either of their studies.

Computer Modeling.

The orientation of residential construction types exposed most of glazing on east and west sides of the house to model the greatest impact of tree shade. With a more sensitive orientation that locates glazed surfaces away from summer sun, savings from tree shade would be reduced. Buffington (1978) found that a more sensitive orientation reduced cooling loads by 10% in Miami. Orientation may have a greater impact in Tucson because the heat gain from solar radiation is greater than in Miami, and a more sensitive orientation will reduce the impact of solar radiation.

The savings provided by one tree located to shade a glazed area is underestimated in this study because the MICROPAS program averages the glazed and opaque surfaces over an entire wall. Solar radiation falling on glazed surfaces has a greater impact on heat gain than solar radiation falling on opaque surfaces. Therefore, savings achieved by locating one tree to shade a glazed area should be greater than this study reports, and savings achieved by locating two trees along a wall could be slightly overestimated. A more sophisticated program that models shade on glazed and opaque surfaces independently would provide better estimates of energy savings from tree shade.

The simulations modeled tree types that assumed five years of growth and characterized a range of similar trees in the landscape. This provides a basis for designers to select trees reflecting the tree types simulated, substitute them in designs, and have an understanding of their effect on energy loads. Table 15 lists the tree types simulated with local species exhibiting similar traits that could be substituted in designs.

Several researchers have modeled the effect of tree shade on housing energy loads and examined the savings gained from energy conserving landscapes. Projections of the costs of purchasing and maintaining the landscape over time, and comparisons of this cost to the savings achieved from the landscape, vary with climatic location and choice of plant materials. In Miami, a $5000 purchase cost of a low energy design, incorporating native plants yielded 15.2% return on the investment over a 20 year project life (Buffington and Black 1981). Native plants were utilized to reduce maintenance costs of irrigation, pesticides, and fertilizers. Energy escalation rates were 20% and plants were modeled at a mature size.

Table 15
Simulation Trees and Similar Species

| Tree Type | Similar Species |
|---|---|
| Mulberry | Ash<br>Pistache<br>Sycamore |
| Mesquite<br>Palo Verde | Acacia<br>Ironwood<br>Mexican Palo Verde<br>Blue Palo Verde |
| African Sumac | Citrus<br>Feijoa<br>Fig Trees<br>Loquat<br>Pepper Tree<br>Privet |
| Polydan | Bottle tree<br>Carolina Laurel Cherry<br>Magnolia<br>Pine tree<br>Red Gum Eucalyptus<br>Silk Oak |

In Tucson where irrigation is necessary and costly, using high water-demanding trees in a energy-efficient landscape design resulted in a greater cost than if the homeowner simply saved the money rather then paying for material and maintenance expenses (McPherson 1987). The use of drought tolerant and native species such as Mesquite and Palo verde rather than water-demanding plants would greatly reduce irrigation costs.

In both studies cited above, researchers assumed that the homeowner is only interested in monetary returns and if the savings were not equal or greater to other investments, the homeowner would not landscape. However, there are many benefits to landscaping that are not equated with a dollar value such as appreciation of aesthetics, value of wildlife attracted by trees, and the use of pleasant outdoor living areas. The value, found in trees for reducing energy use is a bonus to the many other pleasures they provide.

# CHAPTER 5

## SUMMARY AND CONCLUSIONS

Six tree species common in the Tucson landscape were measured for summer and winter shading coefficients (SC) using a photographic dot-matrix method. Statistical analysis showed interaction between pruning treatments and species. Further analysis showed pruning effects to be significant for Mulberry, Palo verde, Mesquite, Olive, and Polydan but not for African sumac. When separated into pruning classes, maximum mean SC differences ($p = .01$) among species were .37 winter and .26 summer. Of the 144 trees sampled, SCs ranged from .08 - .55 winter and .02 - .50 summer. The range of SCs for a species, within a season, and pruning class was 0 - .26. Relatively large variations within species, season, and pruning class suggest that factors other than pruning may influence SCs. Future research might examine influences of genetic and cultural factors such as, soil conditions, fertilization and pest control practices.

In order of highest to lowest SCs, species significantly different from each other for winter, pruning class neutral are Mulberry, Mesquite, and Olive. Mesquite and Palo verde were not significantly different nor were Olive, Polydan, and African sumac. For summer, pruning class neutral, Mulberry was significantly different from Mesquite, and from Olive. Mulberry and Palo Verde were not significantly different, nor were Olive, Polydan, and African sumac. Differences in canopy density varied with pruning classes. However, the greatest SC variations were among species rather than among pruning classes, suggesting that although pruning has a significant effect on SC, among species differences are more important.

SCs were also found to vary with season, within-species. Mulberry showed seasonal differences for the pruning neutral class, while Mesquite showed seasonal differences for pruning open and dense classes. Palo verde, Olive, Polydan, and African sumac did not have significant seasonal differences in any pruning class.

Several concerns arise regarding use of the photographic dot-matrix method. First, the change in spectral composition in the tree shadow is not detected. As solar radiation is reflected by leaves, a larger percentage of radiation under the tree canopy is of the long wave portion of the solar spectrum. This is not measured by the photographic method, therefore this data may slightly underestimate energy transmission. Second, the relationship of the leaf angle within the crown, photographed at various camera angles (reflecting sun angles) may affect SCs. A leaf structure that hangs perpendicular to the ground will block more radiation when a camera is positioned at a lower angle than when a camera is positioned at a higher angle. Because sun angles are constantly changing, measuring SCs to reflect numerous sun angles may prove to be more costly and time consuming than necessary, however no studies have examined the affect of various camera angles for different tree species in leaf. Further studies determining the amount of error associated with the change in spectral composition beneath tree crowns and the relationship of camera and leaf angles to SCs are needed.

SC data collected on the six tree species were incorporated in computer simulations to model the impact of tree shade from commonly used landscape trees on residential energy performance in Tucson. Tree shade was found to have a substantial impact on residential energy performance. Energy performance varied with the tree's SC, location, the number of trees, and residential construction type. Tree species found to have significantly different SCs did not have substantially different effects on annual energy savings ($5 - $12). evergreen and deciduous tree types did not have substantially different effects on energy performance (savings were within $3), therefore, both tree types can be successfully used to shade east and west walls in Tucson.

Annual energy savings ranged from $12 - $121 (2%-10%), when trees shaded east or west surfaces of the house. When trees are located to shade both east and west surfaces, savings will be greater. The least energy-efficient residential construction type, Masonry 50, showed the greatest savings from tree shade, although the percentage of savings was similar for all construction types.

One limitation of this study is the small range of SCs simulated. Although SC differences of .41 and .30 were found among-species, the greatest SCs differences simulated were .10. (simulated SCs were the average of the total sample of each species). SC differences of .10 resulted in a 1% difference in energy savings. Larger SC differences will result in greater savings. SC differences can be attributed to 1) among-species variation such as the species' different branching structures and leaf angles, 2) within-species variation reflecting genetic and varietal differences, and 3) cultural treatments of pruning, irrigation, pest control, and soil preparation.

When SCs of tree species are similar, other factors become more important in selecting trees for landscape use. The following concept (Table 16) is modified from a system developed for Portland (1987). Tree characteristics important for resource conservation in Tucson are rated for each species. Characteristics deemed important are: growth rate, mature size, maintenance, irrigation demands, and SCs.

Table 16
Rating System for Tree Species in Tucson

| rating value | growth rate | mature size | maintenance | irrigation demands | SC |
|---|---|---|---|---|---|
| 1 | slow | small | high | high | open |
| 2 | medium | medium | medium | medium | medium |
| 3 | fast | large | low | low | dense |

In this system, the higher the rating, the more suitable the tree species for reducing energy costs. For example, the Mesquite tree type rates 12: 3 (fast growing) + 2 (medium size) + 3 (low maintenance) + 2 (moderate water requirements to increase growth rate) + 2 (medium SC). African sumac rates 11: 2 (medium growth rate) + 3 (large size) + 2 (moderate water) + 1 (high maintenance costs) + 3 (dense SC). Any tree species can be evaluated to estimated resource conservation potential.

Design considerations may alter the priority given to the rating system. For example, the rating system is based on the assumption that a larger tree is more desirable because it provides more shade than a smaller tree. However, considerations for design scale may call for a smaller tree or a group of smaller trees. Also, the desired location or amount of space available for planting may dictate tree size and shape. Other design considerations that might alter the priority given to energy use are seasonal effects, use as a specimen, microclimate, and design theme (i.e. a desert effect). Substantial energy savings can be achieved through proper tree placement and selection, although the priority of these and other design considerations are likely to vary with the individuals or clients involved in the design.

This study quantified the amount of energy savings possible given particular shading scenarios, and has helped to further define the capabilities of various shade trees in Tucson to reduce residential energy loads. In designing landscapes, numerous plant characteristics are evaluated. Canopy density has not been considered important, but it can influence the energy use of a building. Further knowledge concerning these and other characteristics of trees will help us to design more integrated environments.

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