Insolation Transmission Through a Deciduous Tree Canopy:

A Winter Study

by

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(ABSTRACT)

This study measures the shading properties of tree branches as they affect the amount of available sunlight (insolation) reaching structures placed within the visible tree shadow. Measurement was accomplished by placing a grid in throughout the entire shadow pattern formed by each study tree between the hours of 9:00 am and 3:00 pm. Data was collected at each point of the grid to determine the percent insolation blockage or penetration, through a tree canopy. This data was then transferred to a graphed tree shadow pattern and interpolated to create tree shading density contours in the tree shadow pattern. Data was analyzed to determine the effects of sample tree shadow patterns upon the passive solar heat gain of windows located within the tree shadow.

This study offers as a guide to future research, the beginning of a tree typology. The typology categories trees commonly grown and available in Virginia, into form and size categories. The typology also begins to assimilate data collected by other researchers on summer and winter canopy densities, leaf drop and leaf onset periods. The typology creates a

framework for future research and serve as a means to record which trees have been investigated, and which have not. Another attribute of the typology is its potential benefit to designers. It can be utilized as a tree selection tool for energy conserving landscape designs.

Several additional questions and suggested improvements for data collection have been provided for those who care to continue research into this area.

ACKNOWLEDGEMENTS

Winston Churchill once said. "Writing a book is an adventure. To begin with, it is a toy and amusement. Then it becomes a mistress, then it becomes a master, then it becomes a tyrant. The last phase is that just as you are about to be reconciled to your servitude, you kill the master and fling him to the public." In the process of conducting and writing this thesis, I have experienced the same adventures, from amusement to the tyrant. Many have supported and encouraged me from becoming reconciled to my servitude, and I am pleased to have the time to recognize and thank them.

I would first like to thank Professor Dean Bork, my committee chairman, Ben Johnson, and Professor John Randolph for their valuable time, advise, guidance and support during the difficulties when we first attempted to conduct this investigation, and also, for their help in completing this thesis. My thanks also goes to the faculty and staff of the Landscape Architecture department as well as all of my friends.

Foremost, I would like to thank my family, and especially [redacted], who's love, support and patience strengthened and encouraged me not just during my thesis but throughout my three years at Virginia Tech.

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CHAPTER I

INTRODUCTION

Man has utilized structures and landscapes to conserve energy and enhance comfort throughout recorded history. Dependence on fossil fuels is a recent phenomenon in human history, and has contributed to the abandonment of time tested principles of efficient design. Boyd Hutchison and Fred Taylor observed that:

> "In recent times, culturally and perhaps economically mediated responses to environmental conditions have resulted in maladaptive environmental modifications that, . . .were made intolerable by virtue of the cheap and abundant supplies of fossil fuels that powered machines designed to neutralize the effects of adverse environmental modifications." (Hutchison, 1983 pp.20)

A few forward-looking researchers continue the search for alternative energy sources and energy conservation measures, in spite of the present abundance of inexpensive fossil fuels. In doing so, environmental impacts associated with the use of fossil fuels, and future economic impacts when nonrenewable energy sources are depleted, may be reduced.

One area of continuing research related to energy conservation, focuses on the use of vegetation and site modifications to reduce heating and cooling loads in buildings. The utility of plants to reduce energy demands in structures hinges upon: insulation properties of the vegetation and thus their usefulness in reducing heat loss or heat gain; ability of vegetation to control wind speeds and directions; and the shading properties of trees and shrubs, specifically trees. Insolation, not to be confused with insulation, is the rate at which solar radiation encounters a surface area. In the case of deciduous trees, the concern is with the amount of available insolation which passes through the tree canopy.

PURPOSE AND OBJECTIVES

This investigation will concentrate on the shading properties of trees and how these relate to the amounts of available sunlight reaching structures placed within the tree's shadow pattern. One purpose of this investigation is to determine the insolation blocked by the bare branch canopy in the entire tree shadow pattern between the hours of 9:00 AM to 3:00 pm. During the process of this investigation, several additional relevant questions will be addressed. Does a predictable pattern of solar blockage occur within the shadow pattern? Does the density of shade and shadow pattern vary between the northeast and northwest branching? Does a relationship between the insolation pattern exist between trees of the same species? A second objective of this investigation is to develop criteria which aid passive solar landscape design and result in reduced energy consumption in buildings. The third objective of this study will be to develop a framework, called the Tree Typology, to aid researchers in selection of trees for future research, and designers in tree selection for passive solar landscapes.

LITERATURE REVIEW

It will be helpful to have a general understanding of work which has been conducted to date. The available literature can generally be divided into two categories: basic research and applied research. Basic research is defined here as research conducted primarily to produce data and information, while applied research tends to focus on development of design aids and criteria. These categories, however, are not mutually exclusive. There are some investigations which overlap the two areas. This review has categorized these into their most appropriate grouping.

BASIC RESEARCH

One of the earliest studies relating to insolation through tree canopies was conducted by Johnson, et al., in 1979. The study focused on creating an index that would represent the percent solar blockage by the leaves and bare branches of fifteen deciduous tree species. The investigation utilized two silicon-cell based pyranometers which integrated the solar radiation over an eight hour period. An instrument was placed in the open as a control and the additional pyranometer was located beneath the dripline at the northern face of each tree. Figure 1 on page 4

Results from the winter observations demonstrated that bare branches alone can block a substantial amount of light, in turn reducing potential heat gain to a structure. Blockage from the bare branch canopy ranged from 26% Eastern Redbud (Cercis canadensis) to 63% American Beech (Fagus

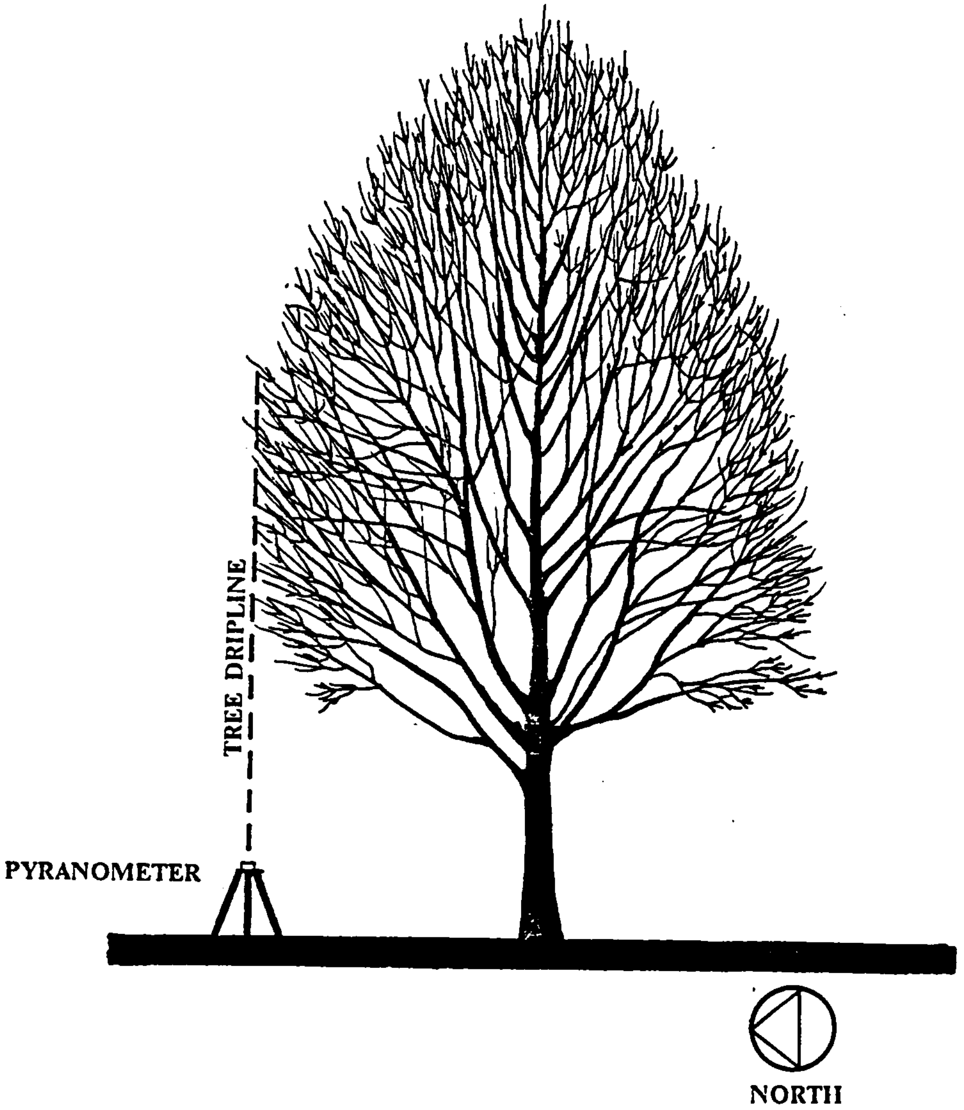


Figure 1. Instrument positioning for Johnson, et al. investigation.

grandifolia). Findings from the summer study ranged from 36% American Plane (Platanus occidentalis) to 74% Sugar Maple (Acer saccharum). From the summer and winter data for each tree, comparisons were made resulting in a yearly shading index number. Trees which had an index number favoring dense summer shade and low winter shade (< 40%) were selected as trees best suited for energy conserving landscapes. Of these trees, Norway Maple (Acer platanoides) and Red Maple (Acer rubrum) showed the strongest potential for shading during the warmer months, and allowed light to penetrate during the leafless period (Johnson, 1979).

The study by Johnson, et al. theorized the most dense shade in a tree shadow would be located at the north point at the tree's dripline. An investigation piloted by Holzberlein during that same year demonstrated the densest shading occurred along the outer edges of a tree's shadow, while the inner shadow core resulted in the least blocking of light.

The study directed by Holzberlein focused on two key issues: the visual error in estimating solar insolation through bare branch canopies due to penumbral shading, and leaf abscission and development periods of various tree species for optimum solar gain during cold periods. Penumbral shading cannot be easily determined by the human eye. Small objects such as twigs located far from the surface, cast diffuse undefinable shadows which cannot be detected visually, but reduce the direct beam radiation.

Holzberlein's research project investigated the penumbral shading of deciduous tree twigs using a photovoltaic cell connected to a milliameter.

The instruments were positioned to read solar radiation reflected from a flat white illumination screen positioned perpendicular to the incoming solar radiation. Five instruments were located in each shadow of four native trees (Ash, Pecan, Sassafras and two Black Oaks), while three additional instruments were positioned just outside of the shadow to serve as controls. Figure 2 on page 7

Results of this study demonstrated that tree branch canopies intercept a substantial portion of available insolation. The study also noted that the amount of insolation varied in a tree's shadow. Insolation increased towards the shadow edges where the penumbral shading caused by twigs alone greatly reduced the amount of solar radiation. Data ranged from 42 to 88% blockage, with the least shading located within the tree shadow centers.

Holzberlein's investigation also recorded the critical time periods for leaf out and leaf drop of various tree species. A three year investigation was conducted to determine the exact dates of leaf onset and leaf drop within each species. Although the exact dates for leaf fall and onset did not remain the same every year, the sequence by which each species lost and developed leaves remained the same. After investigating the leaf abscission and onset periods of numerous tree species, it was concluded that the native Ash, Sugar Maple, and Persimmon were the most suited for solar design as a result of their early leaf drop and late leaf onset (Holzerblein, 1979).

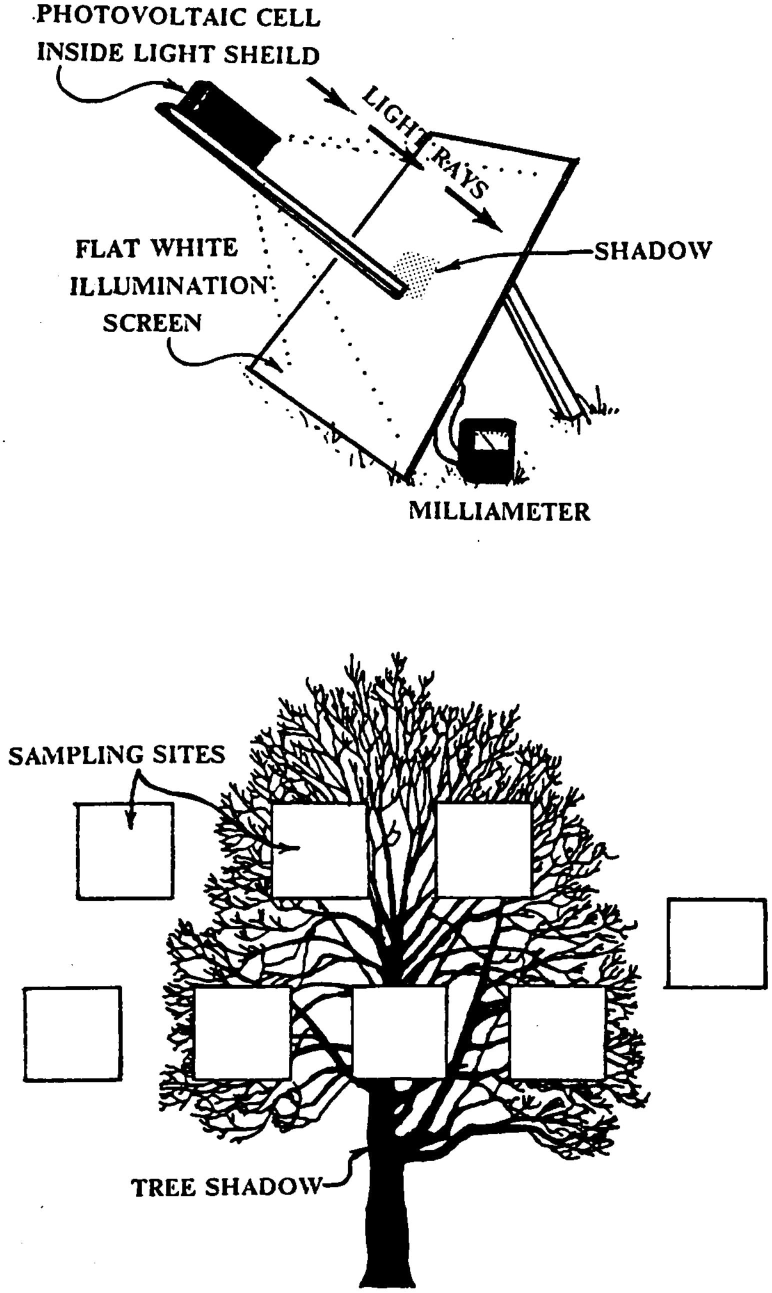


Figure 2. Instrument position in Holzerblein investigation.

Overall, this study demonstrated that variations occur throughout a tree's shadow, and researchers or designers must consider these variables in their work. The issue in question is whether the information from Holtzberlein's investigation could be actively used by researchers or designers. At present, there are two reasons why this information cannot be used. The first results from data being collected in short intervals for each hourly shadow, and the other stems from a lack of quantitative data to strengthen the research. In 1983, Youngberg expanded Holzberlein's research by collecting data at numerous points within each hourly shadow. Youngberg measured solar insolation passing through the bare branch and leaf canopies of six trees for a two year period. Data was collected with a thermopile pyranometer mounted on a mobile track which recoded nine readings per run. After each run was completed, the track was repositioned. This was repeated seven times, producing 63 readings per hour, with the duration of each reading being 30 seconds. Readings were transferred by a data logger to a computer for analysis. Data taken within the tree shadow was then compared to information gathered by a pyranometer in full sun in order to control atmospheric variations such as cloud cover. Figure 3 on page 9

Analysis of the data from a Sycamore confirmed other researchers' conclusions of substantial insolation reduction by the bare branch canopy. Forty to fifty percent of the available solar radiation was blocked by the winter canopy of the Sycamore. During full leaf, 90% of the available insolation was blocked. Other species demonstrated the same full leaf

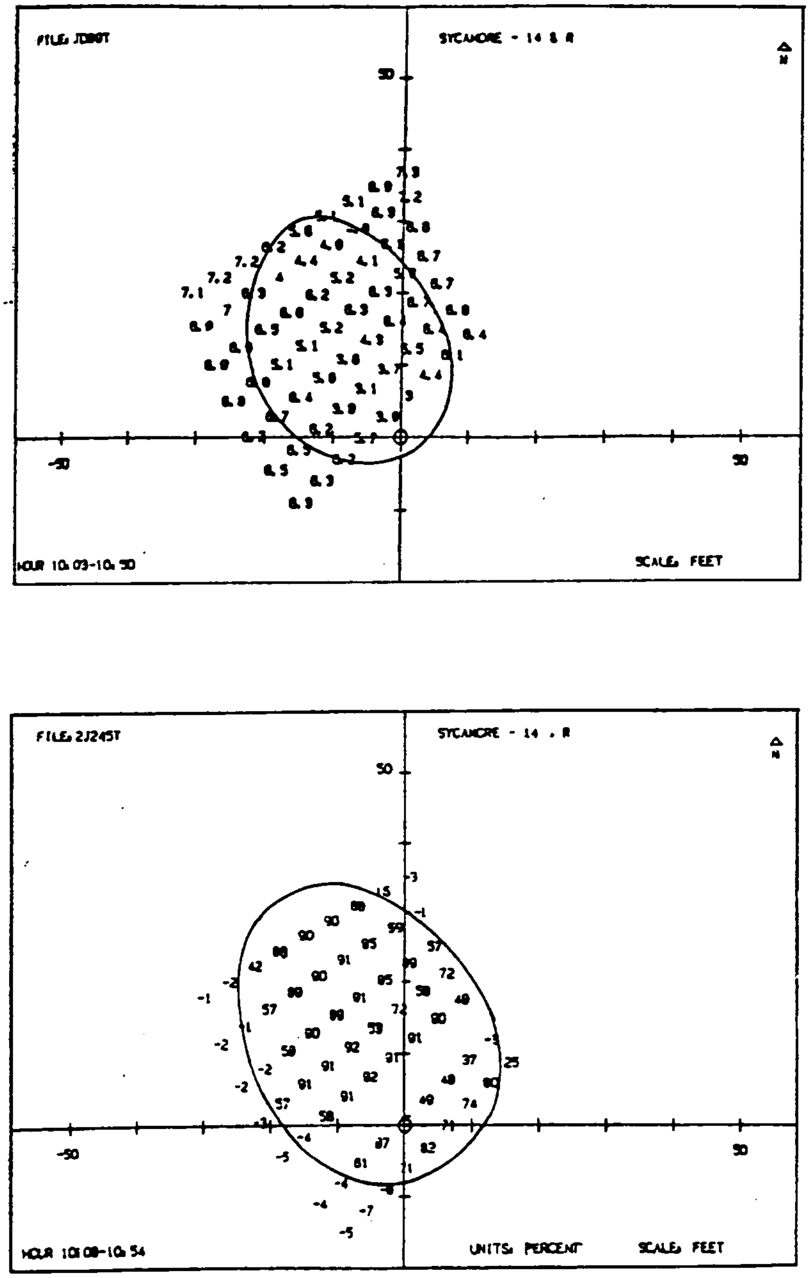


Figure 3. Example of data readings from Youngberg study.

blockage with bare branches blocking 25-60% of the solar radiation (Youngberg, 1983).

Youngberg's investigation utilized a different technique to collect data within the tree's shadow. Although the study illustrated variations within a tree's shadow, one fundamental problem still existed. Data was collected for 30 second intervals at each point for each hourly shadow. Even though this time period reduced errors caused by solar altitude changes, it did not accurately represent the shading for each point since instantaneous insolation varies with branches and time.

Studies up to that period examined the horizontal aspects of a tree's shadow. Little work had been conducted on the effect of insolation through tree canopies upon a vertical surface and few had studied the effects of solar altitude, tree size, diffuse radiation, or time on insolation through tree canopies.

Gordon Heisler in 1983, directed a study which explained some of the previous variables that might affect insolation through the canopies of London Plane (Platanus x acerfolia), Pin Oak (Quercus palustris), and Norway Maple (Acer platanoides) trees. Heisler investigated the influences of solar altitude, diffuse radiation, and the relationship of vertical to horizontal surfaces.

Heisler's investigation sampled these three deciduous trees by various methods. The bare branch study used five pyranometers arranged in a two meter circle around a shadowband pyranometer. This array was located in the center of the tree's shadow and was relocated every five minutes to follow the shadow's center throughout the day. The summer study utilized six Linke-Feussner pyrheliometers instead of the thermopile pyranometers to measure the direct beam radiation. Unlike the bare branch study, these instruments were randomly distributed in the tree shadow.

Findings emphasized that the tree's size, density, the diffuse radiation, the object's distance from the tree, and the sun altitude and azimuth must be considered when modeling the effects of the tree's shade on solar reductions. Total radiation was reduced by the leaf canopy up to 70% for the Pin Oak (Quercus palustris) and 86% by the London Plane (Platanus x acerfolia) tree. No data was provided for the Norway Maple. Reductions on a vertical surface were much less than the horizontal surface readings. The branch canopy for these sample trees reduced radiation by 37-54% respectively at an altitude angle of 60 degrees. Radiation reduction was observed to decrease as the elevation angle decreased (Heisler, 1982).

In 1984 Gardner and Sydnor collected insolation readings on a vertical surface through the bare branch canopies of a large sampling of trees. They also looked into the effects of canopy volume, silhouette area, and form upon insolation. Their investigation observed five deciduous tree genus in leaf and leafless. The genus included Acer, Gleditzia, Gymnoclodus, Pyrus and Zelkova. Utilizing four Epply pyranometers located at different elevations on the northern dripline, the pyranometer stand recorded data for six hour periods during the summer studies and five hour periods during the winter study. Results of the leaf canopy studies demonstrated that there were no significant relationships between the percent shading and the volume of the canopy, the canopy width, cross-sectional area, or the tree shape. There was, however, a correlation between the percent of shade and the tree's height. Figure 4 on page 13

The leafless investigation was not conducted as thoroughly as the leaf study, but in comparison with data collected during the summer study, no relationship was observed between density of the summer canopy and the winter branch density. In other terms, a tree with an extremely dense summer canopy may not have a dense bare branch canopy in the winter. Of all the trees observed, the Kentucky Coffee (Gymnoclodus dioicus) was found to block 68% of insolation in leaf and 10% by bare branch (Gardner and Syndor, 1984).

This study collected large quantities of data over a daily period to provide statistically sound results and conclusions. Readings demonstrated that density does vary between the trees upper and lower branches. The study also answered a number of questions about the relationship of tree densities to volumes, sizes, widths and forms. One difficulty in utilizing this particular design for other research, arises from the instability of the stand on which the pyanometers are mounted. A tall stand is very unstable in windy conditions, and may contribute to errors in the data.

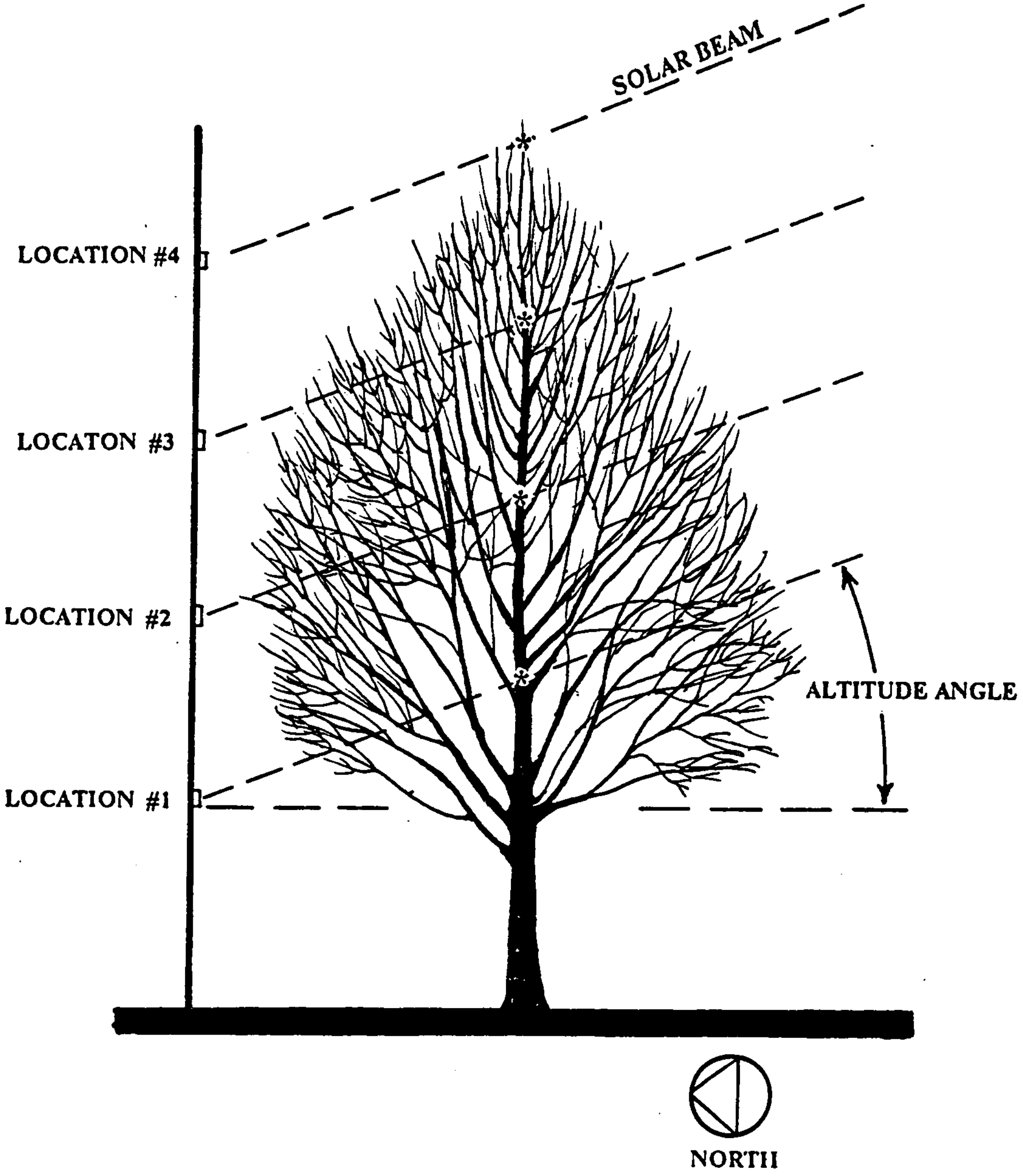


Figure 4. Gardner and Syndor instrument location.

Heisler in 1985, expanded his previous investigation by exploring insolation reductions through summer and winter canopies on vertical surfaces. The purpose was to determine the net annual effect which tree shading imposed upon the south and west wall exposures. The experiment utilized six pyranometers on three stands, with half of the instruments located 0.76 meters off the ground, and the remaining positioned 1.98 meters high. These stands were arrayed in a line running east-west at the northern face of each tree, and also on the north-south line at the east face. Measurements from these were then compared with data collected from an exposed control group facing south. Figure 5 on page 15

Results of the investigations supported earlier research conclusions that substantial reductions can be caused by the branch canopy. The bare branch canopy blocked 30 to 34% of the available insolation to the west facing wall. This same canopy in leaf blocked 65 to 85% of the insolation during June and July. In comparison, the west wall during summer intercepted 250 to 310% more insolation than that which was intercepted by the south facing walls. This was probably due to the lower solar altitude which projected a longer shadow than the noon shadow. In the winter, the south facing walls received 2.0 to 3.2 MJ (Mega Joules) per square meter for the trees sampled. These readings were 60 to 110% lower than data collected in June and July. Snow on the ground increased this difference from 130 to 160% of the June/July reductions. Overall, snow did not significantly reduce the percent of the total insolation collected when no snow was on the ground. Another interesting observation was a variation between the tree core density and the shadow edges. Edges of the trees

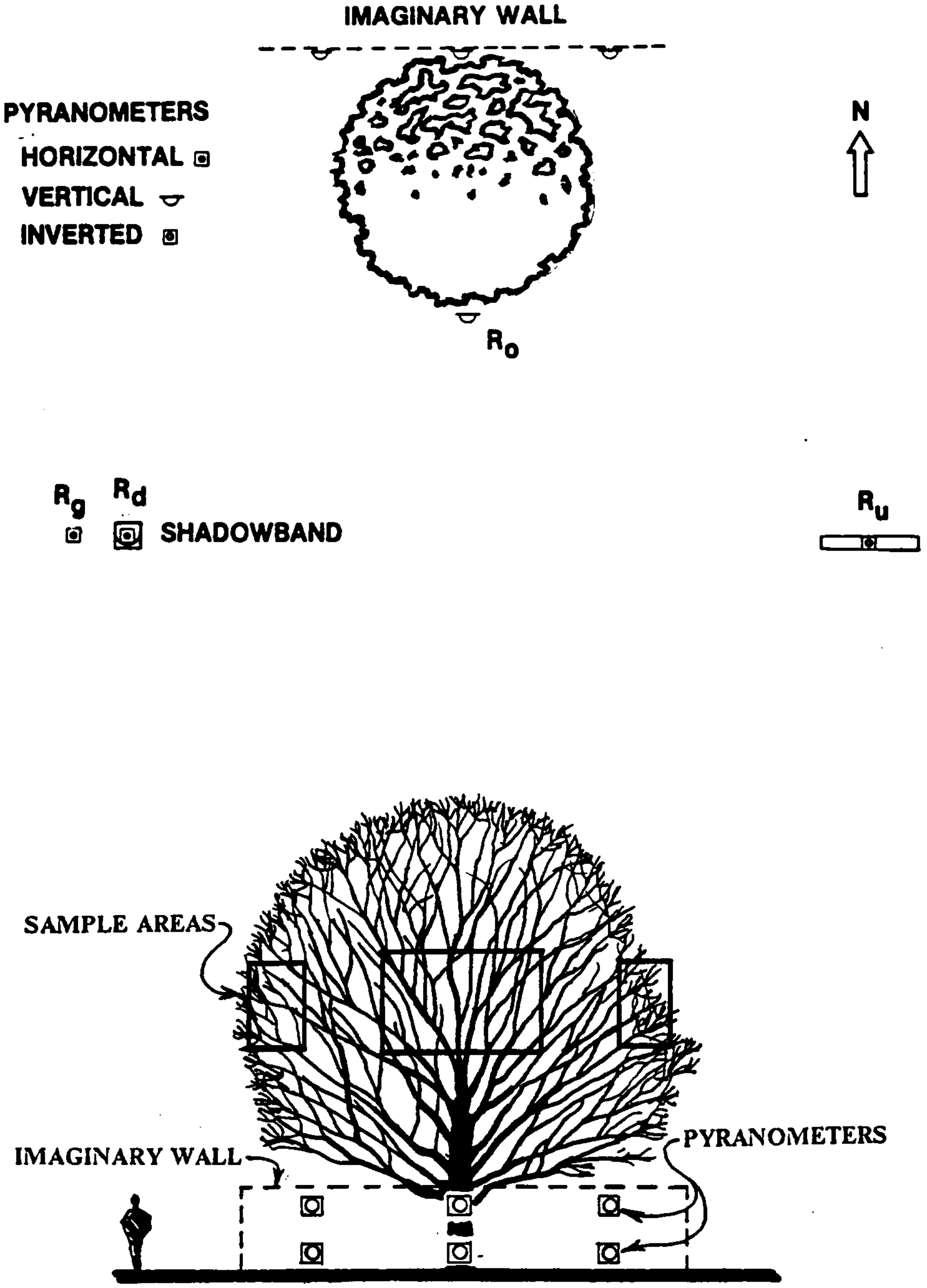


Figure 5. Instrument placement for 1985 and 1986 Heisler studies.

ranged 6 to 20% less insolation than the tree shadow centers, this could have resulted from penumbral shading (Holzberlein, 1979).

Heisler expanded upon his previous study by observing the tree shadow pattern on a structure through the use of a scale model representing a tree and a one story building. The data collection process for the sample trees was conducted exactly as the previous investigation. Six pyranometers were positioned on three stands. On each stand, one pyranometer was located 0.76 meters off the ground, while the second instrument was positioned 1.98 meters off the ground. The stands were then positioned in a line running east and west at the northern face of each tree, and on the north-south line at the east face. To obtain density and irradiance reductions on vertical surfaces, data collected was compared with a control grouping exposed to the south. Using the scaled building model and two previously sampled trees scaled down to the model scale, shadow patterns were evaluated on the west and south walls in various solar altitudes. Average reduction factors for the selected trees were then derived through data collected by pyranometers, and then applied to the shading patterns. The final procedure determined the annual effect of the tree's shade on the structure's energy requirements. Figure 5 on page 15

Interpretation of the resulting data demonstrated that the insolation was slightly higher on vertical surfaces than on horizontal surfaces. Shading on the west wall was observed to be much less in the winter and greater during the summer. This is beneficial in passive solar application since during the winter, light would be accessible to the structure for heat gain. During the summer, shading of the west and east facing walls is most critical during the evening and morning in order to reduce unwanted heat gain. South facing walls produced different results, the smaller the tree the greater amount of shading on the wall. Shade from larger tree's fell mostly on the roof area, allowing access for light to wall surface. Although this would vary depending on the structures distance for the tree.

Another conclusion from the study stated the climate and type of structure were determining factors when considering whether a tree should be positioned on a south face.

> The caution against trees on the South pertains primarily to air conditioned buildings. For buildings that are not air conditioned, maximization of summer shade without regard for winter insolation reductions may be the best design. Cooler interior temperatures in summer may be well worth the extra heating costs in winter, and the maximization of summer shade may obviate the need to install air conditioning (Heisler, 1986 pp. 357).

Further findings supported earlier claims by Gardner, Sydnor and Wagar, et al.(1986), that the average density of the canopy increased with a tree's size until maturity (Heisler, 1986).

APPLIED RESEARCH

Numerous books and articles have been published to provide designers with a working knowledge of the effects of vegetation on energy consumption, and the means to utilize plantings for higher efficiency (Foster 1978, Hutchison, et al. 1982, Moffat and Schiler 1982, Olgay and Olgay 1963). Some of those older publications, though, provided the designer with misguided assumptions. One common fallacy involved planting deciduous trees in temperate climates, south of a structure. It was thought that this location would shade and cool a building in the summer while in the winter it was expected light would penetrate the branches to allow heat gain into the structure. As reviewed in previous research, using trees in this manner would reduce potential heat gain 30 to 50% in the winter months. In temperate climates, research now suggests leaving the south face free of obstruction and planting trees on the east and west sides of a building. Heisler's findings are an exception: "For buildings that are not air conditioned, maximization of summer shade without regard for winter insolation reductions may be the best design." With proper concern for placement, trees can be successfully planted to block the sun during the morning and evening summer hours, thus reducing unwanted heat gain while allowing winter sun light to heat the structure.

A photographic dot count procedure was developed by Wagar and Heisler as an inexpensive, simple, and quick tool for researchers, designers and nursery managers to use in studying and choosing trees for energy efficient building designs. The investigation studied 69 samples of three tree species: (20) Kentucky Coffee tree (Gymnoclodus dioicus), (25) London plane (Platanus x acerfolia) and (24) Modesto Ash (Fraxinus velutina Modesto), by photographing the trees at three azimuth angles and at 33° and 45° elevation angles. The slides of the tree crowns were then superimposed onto a 16 dot per square inch grid and the number of dots coinciding with branches were counted. To provide a density factor for each tree, this number was then divided by the total number of dots in the total tree crown. The Kentucky coffee tree had the lowest density at 16-34% while the London plane and the Modesto ash had the highest, 28-61% and 31-70% respectively.

Although this study was concerned with developing a tool for research and practical application, it also noted several interesting findings. The first of these found the density of a canopy increased with a tree's size, but the distribution varied between the species. The ash reached its highest density at a 33 foot crown diameter after which the density decreased again. The Kentucky coffee tree and London plane densities, however, increased linearly with tree age.

Another form of applied research relates to the development of computer aided design or CAD. SOLMAT (Solar Control Matrix System) was one of the first CAD system to be developed. The program significantly reduced the tedious and time consuming calculations required to locate trees for maximum cooling benefits. SOLMAT can be broken into three stages. The first stage allows the designer to define the structure's size and orientation, and then the program locates the specific positions for various tree species that meet the designer's criteria. Then, the designers archive a plant matrix which allows them to select the most ecologically suited species. Also included in the matrix are the canopy density, mature size, form, growth rate, phenology, life expectancy, maintenance ,and cultural requirements of each species. The final stage provides designers with the optimum height to bole range, which can be controlled through the use of pruning.

SOLPLOT, another computer aid, locates trees around a structure to obtain maximum shading in the summer and also to allow maximum solar access for heat gain in colder months. The program considers the latitude of the site, orientation and window dimensions, and time of the year for which the user is designing. SOLPLOT then plots the distance from the windows with the maximum limb and tree heights. A disadvantage of SOLPLOT is that it does not supply the designer with an accessible tree file which would aid in selecting trees to meet the criteria. Instead, the author provides written criteria for tree selection.

Other software such as Obstruct Grasp (Schramm and Grist 1978), Urban 1, 2 and 3 Canopy (Terjung and Orouke 1980), (Frank et al. 1981) and SUNDIAL (Fregonese 1983) have been developed to aid designers to perform the same tasks.

In summary, various types of research have been conducted on insolation transmission through the bare branch and leaf canopies of deciduous trees. Research has concluded the bare branch canopy alone can block 30 to 80% of the incident solar radiation, reducing heat gain substantially during the winter months. Planting recommendations suggested locating trees on the east, west, or north faces of structures. South facing walls may then use mechanical means, such as overhangs, to shade structures during the warmer seasons, and allow heat gain during the winter. Recently, some work conducted by Heisler begins to suggest that even this design criteria may need further study.

Additional information has also developed from research in the area of insolation. First, the leaf onset and abscission periods, winter and summer densities, species, size, latitude and location of trees around a structure are critical characteristics which designers must consider when positioning trees for energy conservation. Density, a key characteristic, was found to vary according to a tree's age, size and species. While previously sited works are relevant contributions to the field, additional quantitative information needs to be collected to create stronger foundations for design decisions.

CHAPTER II

PROCESS

THEORY

Previous research has investigated various aspects of insolation transmission through tree canopies. Studies have collected data from one to 63 points in each hourly shadow or daily period. Insolation measurements in the shadow of tree canopies were also collected from horizontal and various angled surfaces to determine the effects of shading for various altitudes. Few investigations have observed the variations of insolation within the entire tree's shadow. Investigations by Youngberg (1979) and Holzberlein (1983) studied some variations within tree's shadows for short durations of 30 seconds to several minutes at each data point. These measurements were recorded for each hourly shadow and did not consider the daily periods of measurement. Unlike previous research, this study has been conducted within a tree's entire visible shadow formed between the peak solar collection times of 9:00 am and 3:00 pm.

This investigation will determine if a shading density pattern exists within a tree's winter shadow pattern, and between trees of the same species. Also, this study will investigate the northeast and northwest facing branches of individual trees to determine if a bilateral symmetry exists between their shading densities.

APPROACH

The following section provides a detailed description of the process which this investigation used to gather data. This process was divided into several phases. The first of these calculated shadow length factors, solar time periods and solar azimuth angles for specific dates during the investigation. The next phase utilized these factors, time periods and azimuth angles to plot each study tree's shadow pattern. Once the shadow pattern was produced for each tree, a grid was plotted within the tree's shadow pattern. The grid's ultimate size was dependent on each tree's shadow pattern size and shape. The final phase used the previous information to locate the grid around each study tree. Once the grid was plotted, insolation measurements commenced.

METHODS

The specific tree species studied is the Sugar Maple (Acer Saccharum). This readily available and highly used tree was chosen due to its desirable landscape characteristics of good form, health and fall color. Its early leaf fall and late leaf onset, are also desirable characteristics for passive solar landscapes in temperate climates.

All of the sample trees for this investigation were located at the 37.3°N latitude at the Virginia Polytechnic Institute and State University golf course, Blacksburg Virginia. Security of the instruments -Pyranometers- against theft or vandalism was an important consideration since the instruments would be left unattended most of the day. The VPI golf course offered this protection and had an ample supply of mature Sugar Maples which met the selection criteria. Figure 6 on page 25

Selection criteria for the sample trees was based on the following:

- The area must be free of obstruction between the critical times of 9:00 to 3:00 in order to reduce any potential errors caused by the shade of adjacent objects.
- Tree forms must represent the species since the study is concerned with similarities between the same forms and species.
- They must be a mature specimen of 15 to 30 years of age. These are the average ages of trees found in the nursery or around a structure. Also, they are at their peak form and health.
- They must be healthy. Trees which are in ill health may have a lower branching density which would not represent the species.

Before the actual study commenced, several calculations and plans needed to be performed to aid grid placement and data collection. The first phase of the project involved the calculation of hourly shadow lengths for 9:00/3:00, 10:00/2:00, 11:00/1:00 and 12:00 on the dates during which the study was conducted. These lengths were calculated based on the following equations:

$$\sigma = 23.45 \sin(360 \times (284 + N)/365)$$

σ = Solar Declination
N = Number of days into the year
(N = 1 = Jan. 1, N = 365 = Dec. 31)

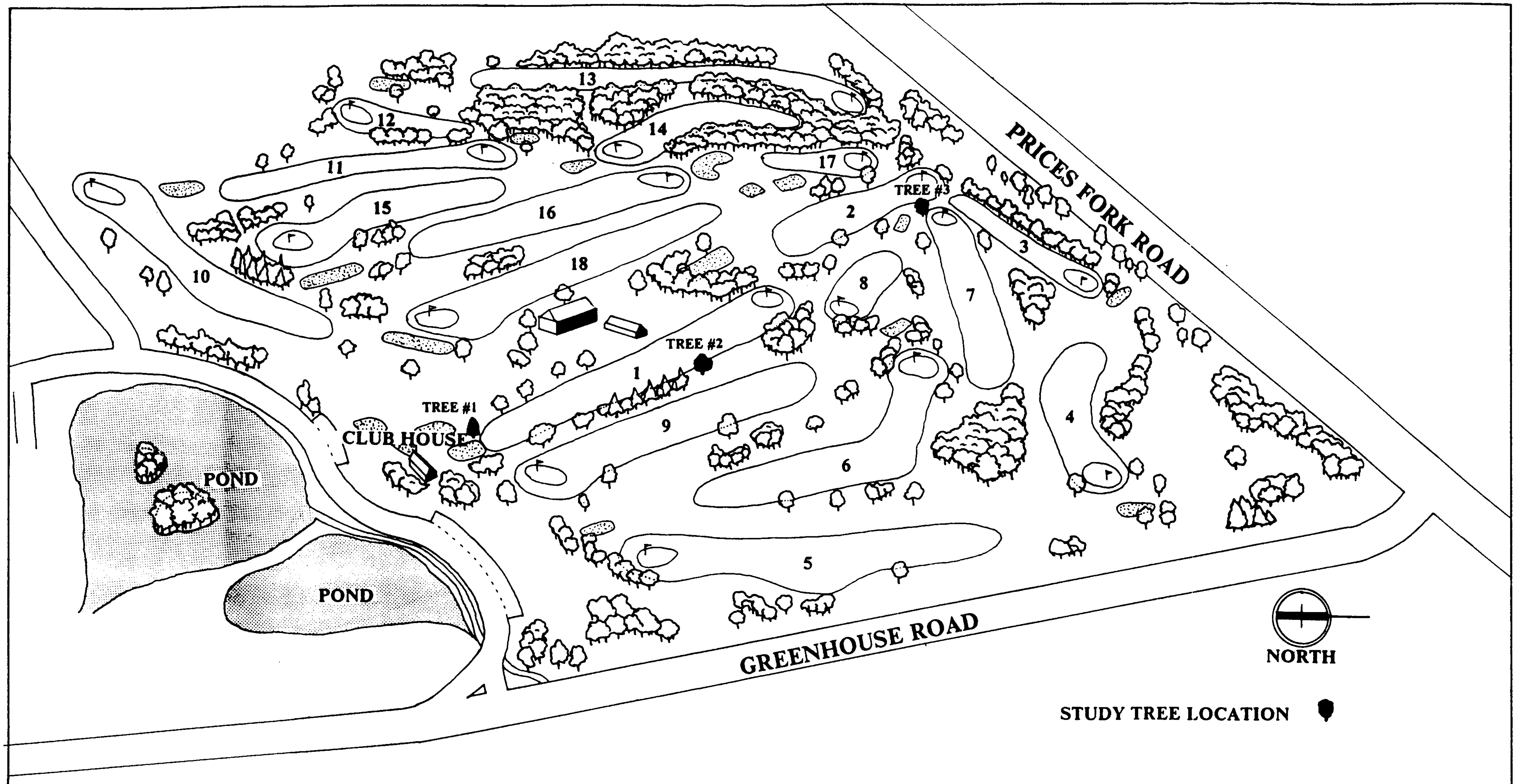


Figure 6. Tree location on Virginia Polytechnic golf course.

$$\sin\alpha = (\cos L \times cos\sigma \times cosh) + (\sin L \times sin\sigma)$$

α = Altitude Angle
h = Hour Angle (15^0 each hour away from noon)
L = Latitude 37.3^0

$$1/\mathrm{Tan}\,\alpha = \text{Shadow length factor}$$

Shadow length factor = (Shadow length per foot of height)

Results from the previous equation gave the shadow length per foot of height at specific dates for the period from January to March at ten day intervals for each hour from 9:00 am to 3:00 pm.

The second phase of this process calculated the azimuth angles for each hour at the time intervals of 9:00 am to 3:00 pm in the same ten day periods used in calculating the shadow length factor.

$$\sin\alpha^1 = (\cos\sigma \times \sin h)/\cos\alpha$$

α^1 = Azimuth angle

All time in this research is in solar time not local time. Local time is a fixed time while solar time always places 12:00 noon during the period when the sun is exactly due south. In using solar time, measurements taken at 9:00 am and 3:00 pm were taken three hours before or after the sun reached its highest altitude and due south. Converting local time to solar time is based on the following equation, and was calculated for the same ten day intervals as the previous factors.

ST = LT + 4(LTmeridian - longitude) + E

LT = Latitude

LTmeridian = Local time meridian. (see table 1)

E = Equation of time factor. Figure 7 on page 29

Shadow length factors, solar time differences, and azimuth angles for the time period when this investigation was conducted can be found in Table One.

Once the azimuth and shadow length factors were calculated each sample tree's diameter, lower limb height and overall height, was obtained. The canopy diameter and lower limb height was easily found by using a tape measure. Overall tree height would have proved more difficult without the aid of a transit.

As each tree was about to be studied, the shadow length factors were multiplied by the sample tree height to obtain the shadow lengths for each hour at the study date. Shadow length calculations used factors 15 to 20 days in advance of the date the study was to commence. The decision for

Table 1. LT meridian table (Leckie, 1981)

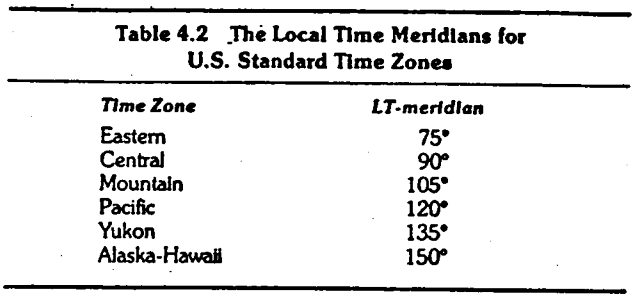
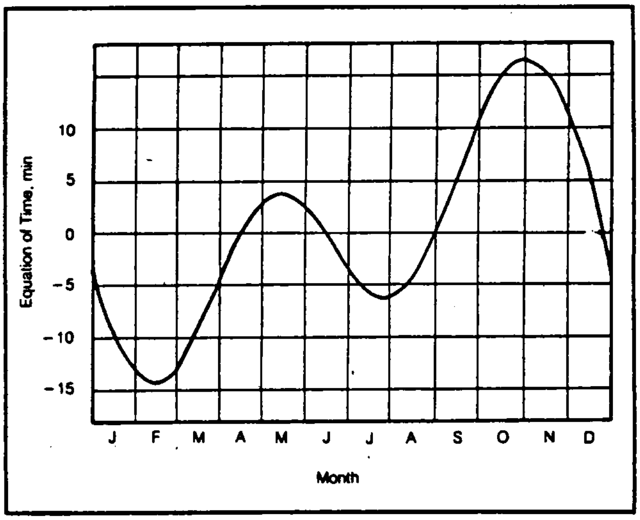


Table 4.2 The Local Time Meridians for U.S. Standard Time Zones

Time Zone	*LT-meridian*
Eastern	75°
Central	90°
Mountain	105°
Pacific	120°
Yukon	135°
Alaska-Hawaii	150°



Equation of time *(E)*.

Figure 7. Equation of time (E) (Leckie, 1981)

Table 2. Shadow length factors, time differences and azimuth angles for 37.3°N lat.

		AZIMUTH/SHADOW ANGLE (DEG AWAY FROM NOON)			SHADOW LENGTH (FT/TREE HT.)		SOLAR TIME DIFFERENCE
MONTH	DAY	9:00/3:00	10:00/2:00	11:00/1:00	9:00/3:00	12:00	(MIN.)
JAN.	10	43.29	29.00	14.54	3.25	1.70	-29.18
	20	44.35	29.62	14.82	2.99	1.58	-33.18
	30	45.80	30.46	15.21	2.70	1.45	-35.68
FEB.	9	47.64	31.50	15.69	2.41	1.30	-35.38
	19	49.84	32.71	16.25	2.13	1.16	-35.38
	29	52.40	34.07	16.86	1.88	1.02	-35.68
MAR.	10	55.29	35.54	17.51	1.67	0.89	-33.18
	20	58.46	37.06	18.18	1.49	0.77	-29.18
	30	61.86	38.57	18.83	1.33	0.67	-25.68

using the advanced factors was based on the concern of loosing data points as the shadow shortened during the study. In choosing these specific time periods for the shadow and grid plotting, the shadow produced would be the shortest possible after data collection and delays in the investigation due to weather. Figure 8 on page 32 .

After the hourly shadow lengths were determined, the tree diameter was plotted on grid paper at a scale of 1"=10'. The hourly azimuth and shadow lengths were then plotted to produce the tree shadow pattern between 9:00 am and 3:00. pm. When the tree shadow pattern was graphed, a 24 to 26 point grid was overlayed to locate the points at which data was to be collected. The process by which this was accomplished is as follows: Figure 9 on page 33

- The true north line was located on the plot
- Six feet from the trunk on the true north line, the lower grid line point was plotted.
- Two feet in from the trees noon shadow top, the upper grid line point was plotted on the true north line. This distance also accounted for the shadow shortening during the data collection.
- The distance between these two points was determined and divide by three to locate intermediate points along the true north line.
- The grid was constructed by extending perpendicular lines through each point along the true north line, then spacing data points along each of these perpendicular lines. The intervals between these grid points was adjusted ±2' in order create a tighter fit between the grid in the shadow pattern.

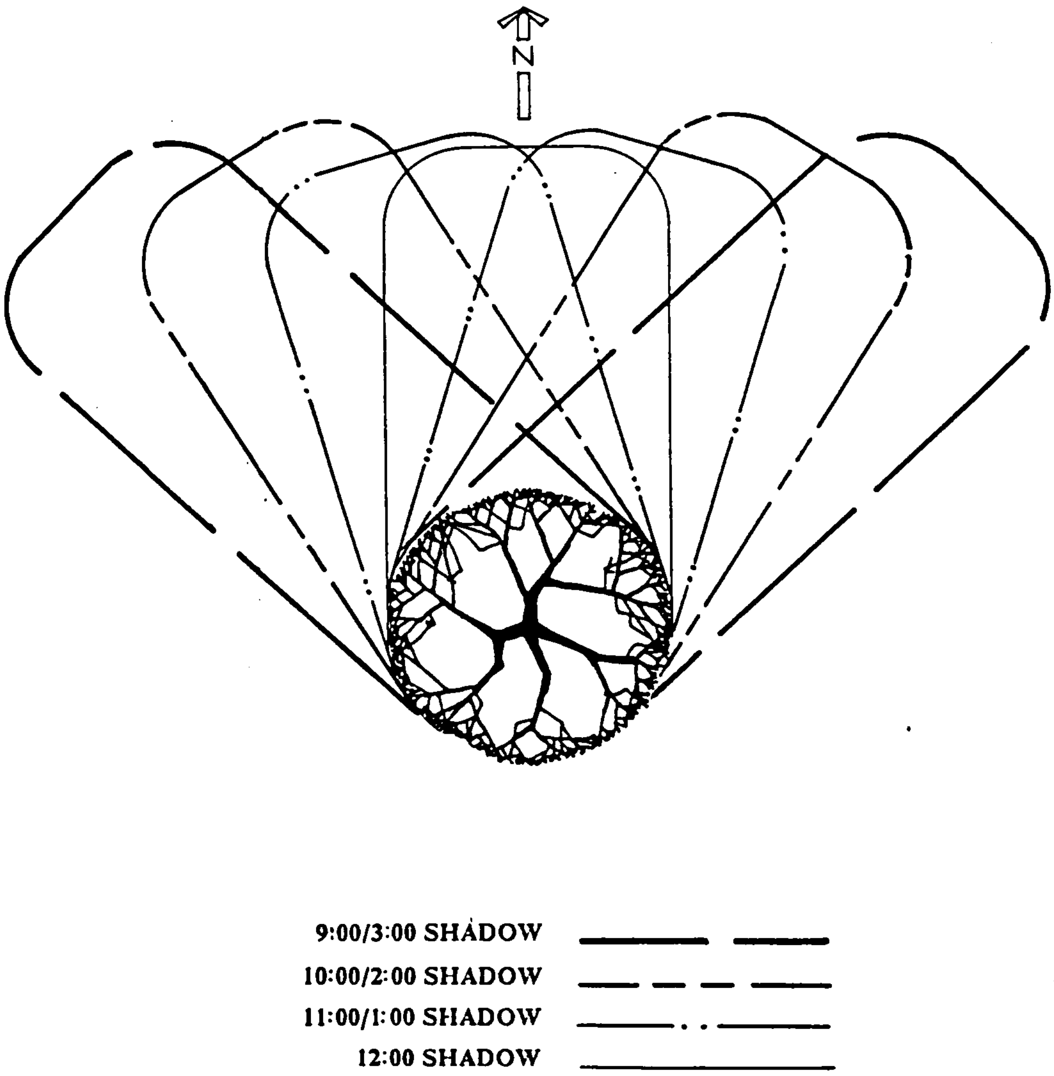


Figure 8. Visible hourly shadow positioning.

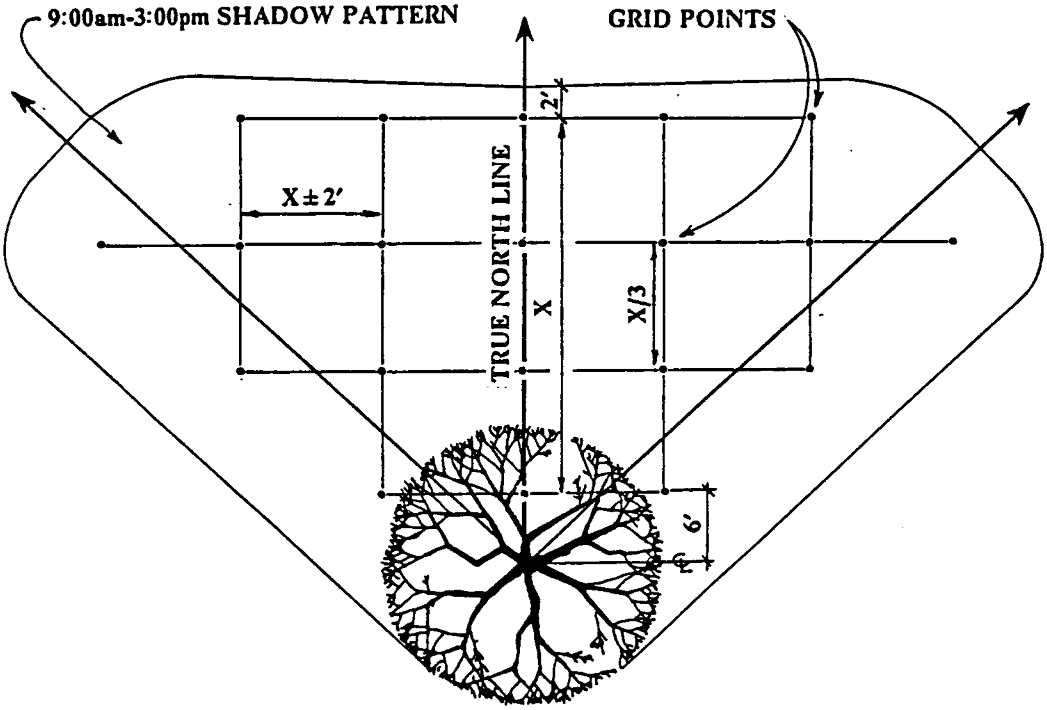


Figure 9. Grid plotting diagram.

MAIN STUDY

Once a study was to commence on a sample tree, and the shadow grid pattern was constructed, the grid was plotted in the field adjacent to the sample tree.

- A compass was used to establish the true north line in the field. A string line was anchored at the north point of the tree trunk. Several feet from the trunk the north/south points of the compass were laid in line with the string, the line was then pulled taught and directed till the needle pointed to the magnetic north deviation. In this region the magnetic deviation is 4°W of true north. Once the line was set on true north, the other end of the line was anchored, this provided the true north line. Figure 10 on page 35
- Using information from the graphed grid, the grid points were measured out on the true north line.
- By triangulation from each north line point and the trunk, the remainder of the grid points were marked Figure 11 on page 36

When the field grid was in place, actual data collection commenced. Two calibrated silicon celled pyranometers were positioned to collect data. The Hollis LM-3000 Solar Integrator connected to the Hollis MR-5A pyranometer was selected for its ability to measure and record insolation over a period of time, its portability, and its ability to operate in a wider range of weather conditions. Data was recorded on pressure sensitive chart paper in a graphic form based on Langleys per minute (Cal/Cm^2/Min). The graph output was also integrated on the chart into an event marking scale. One pyranometer was located in the open, free of any obstruction to serve as a control instrument, and to provide an accurate reading of the available insolation. The additional instrument was positioned at a data point, level with the trunk and ground line. If instruments were

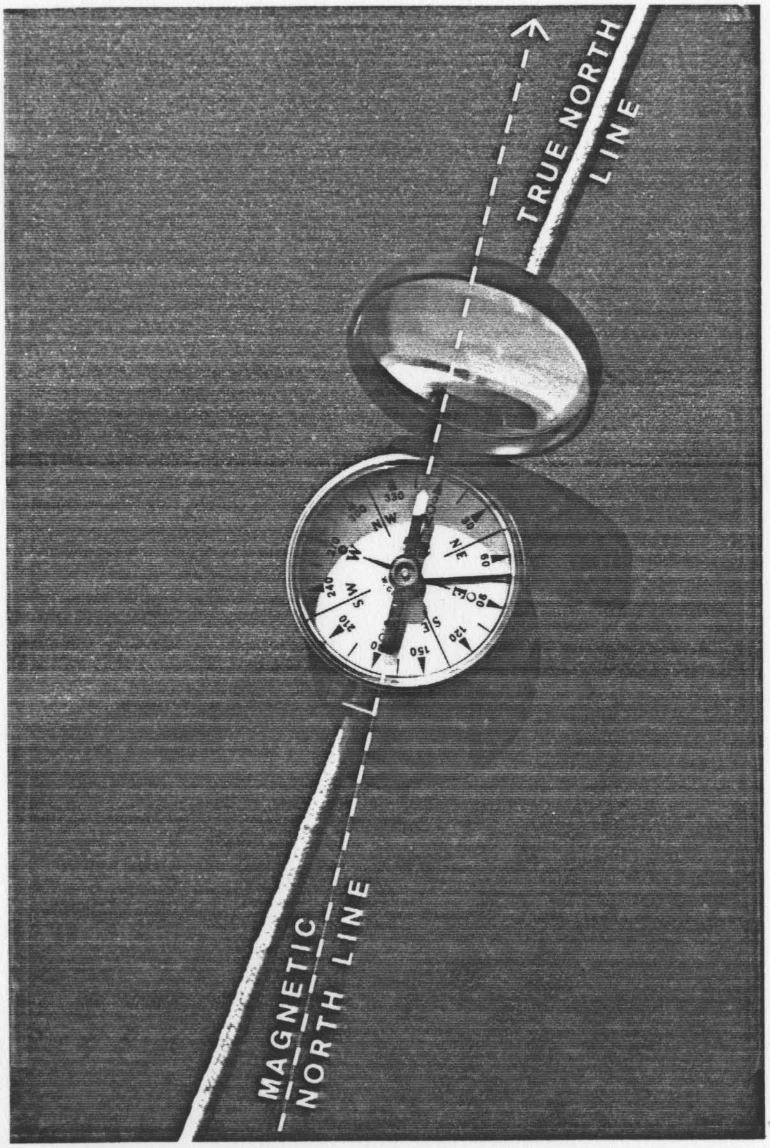


Figure 10. Location of true north line with compass

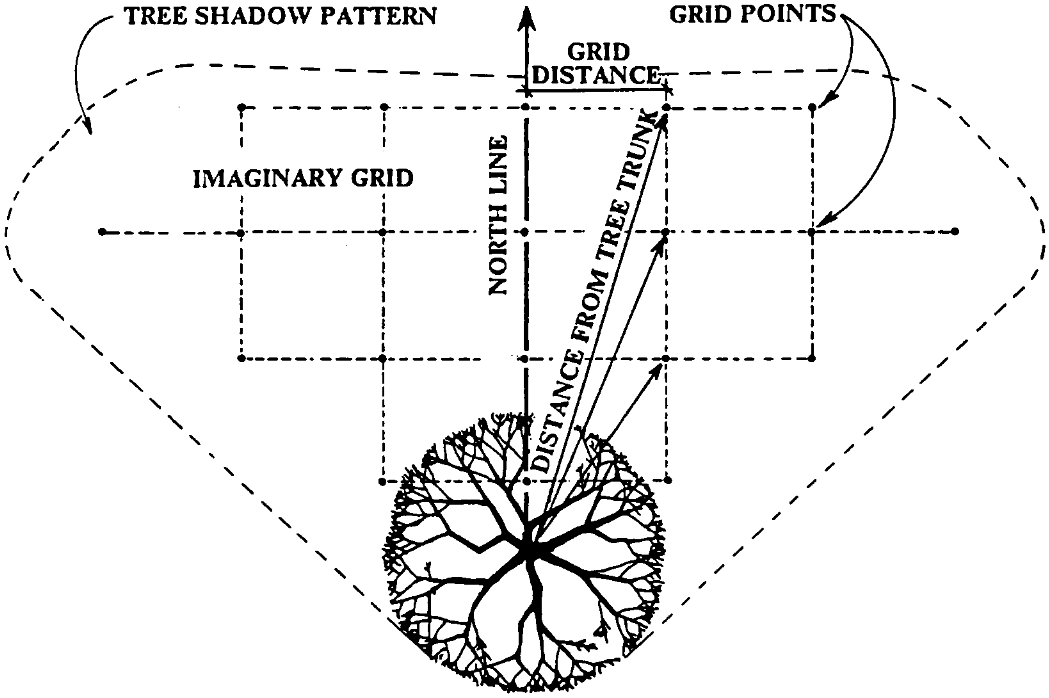


Figure 11. Triangulation of grid points.

placed above the trunk and ground line, data would not be representative of that ground point as a result of the solar elevation angle. The variable instrument data was compared to data collected with the control instrument to account for any insolation fluctuations due to changing cloud cover. Clouds can have a dramatic effect on insolation readings, depending on their density and speed. Pyranometers collect the direct beam radiation in order to determine the amount of insolation blockage by the branches. Clear skies allow light rays called direct beam radiation, to pass to the ground surface. As direct light beam radiation encounters objects it is absorbed or reflected, creating a visible shadow of the object. Clouds disperse the direct beam radiation into indirect or diffuse light beam radiation. Pyranometers require direct beam radiation in order to determine the amount of insolation reduced by branches and twigs. Slow dense clouds block the direct light beam radiation. As this type of radiation is reduced, readings of insolation blockage by branches and twigs increases since there is no direct beam radiation to be blocked. High cirrus clouds, however, have little effect on readings (Heisler, 1985). With this in mind, readings were collected when the skies were clear, with thin cirrus, or with a few fast moving dense clouds.

Please note at this point that shadow length factors were miscalculated, and the 9:00/3:00 shadows were shorter in the shadow plots than for the actual trees. Also, since the grid is dependent on the shadow size some data points were missed. Shadow length factors presented in this document are accurate. Miscalculation of the shadow lengths did not drastically effect results of the shading contour diagram. Possible errors which might occur in the contour diagrams or in the analysis will be discussed later.

Due to limited time, the instrument measuring insolation transmitted through the tree canopy (variable instrument), collected data only during the period at which each point was shaded. It did not measure the insolation from the entire period of 9:00 am to 3:00 pm (solar time). Since light and shading period vary with each grid point, different results may arise if data was collected for each point during the entire time period rather than just the shading period. Future research should be conducted to determine if substantial differences exist between these two approaches to collecting data.

An instrument was located at a study point 15 to 30 minutes before the tree's visible shadow had passed over, and the instrument remained on that point 15 to 30 minutes after the time it was exposed again to the sun. Grid points lying close to the 9:00 am and 3:00 pm outer edges collected data until the visible shadow had passed, but only data collected from 9:00 am to exposure and exposure to 3:00 pm were utilized for this investigation.

The shadow plot developed earlier showing the grid points and hourly shadow locations was of great aid in determining times to position and remove the instruments for data collection. With aid of this shadow diagram, one to three data points could be collected per day. Please note that all measurements should consider solar time. For example, at 3:00 pm local time on March first, the actual solar time was 2:25 pm.

The starting and stopping local time for data collection at each study point were recorded. When data collection at each point was complete, the chart paper with the recorded data was removed for further analysis, and the instrument was repositioned at a new point to commence data collection again. Each pair of charts were attached to a standardized form that recorded weather conditions, point number location of the tree, data, tree name and local starting and stopping times (See figures 12 and 13). The next steps were then followed:

- The local start and stopping times were converted to solar time.
- The collection period time length was determined.
- Using 1"=10 scale, the length of the graph was measured.
- The graph length (in inches) was divided by the time length to obtain the charting speed multiplier.
- Since data pertaining to this study must be between the hours of 9:00 am and 3:00 pm, data collection which started before 9:00 or ended after 3:00 needed to have the 9:00 and 3:00 times marked on the data tape. If data collection started before 9:00 or ended after 3:00, the difference between the actual solar starting time and 9:00, or the stopping time and 3:00 was determined. This difference was multiplied by the tape speed multiplier to obtain the distance on the chart from the starting time to 9:00 or from the stopping time to 3:00.

Example:

Tape Speed Multiplier =.0183 in/min
Solar Time Collection Period = 12:07 pm - 3:49 pm

3:49 - 3:00 = 49 min.
49 min. x .0183 in/min = .8967 in

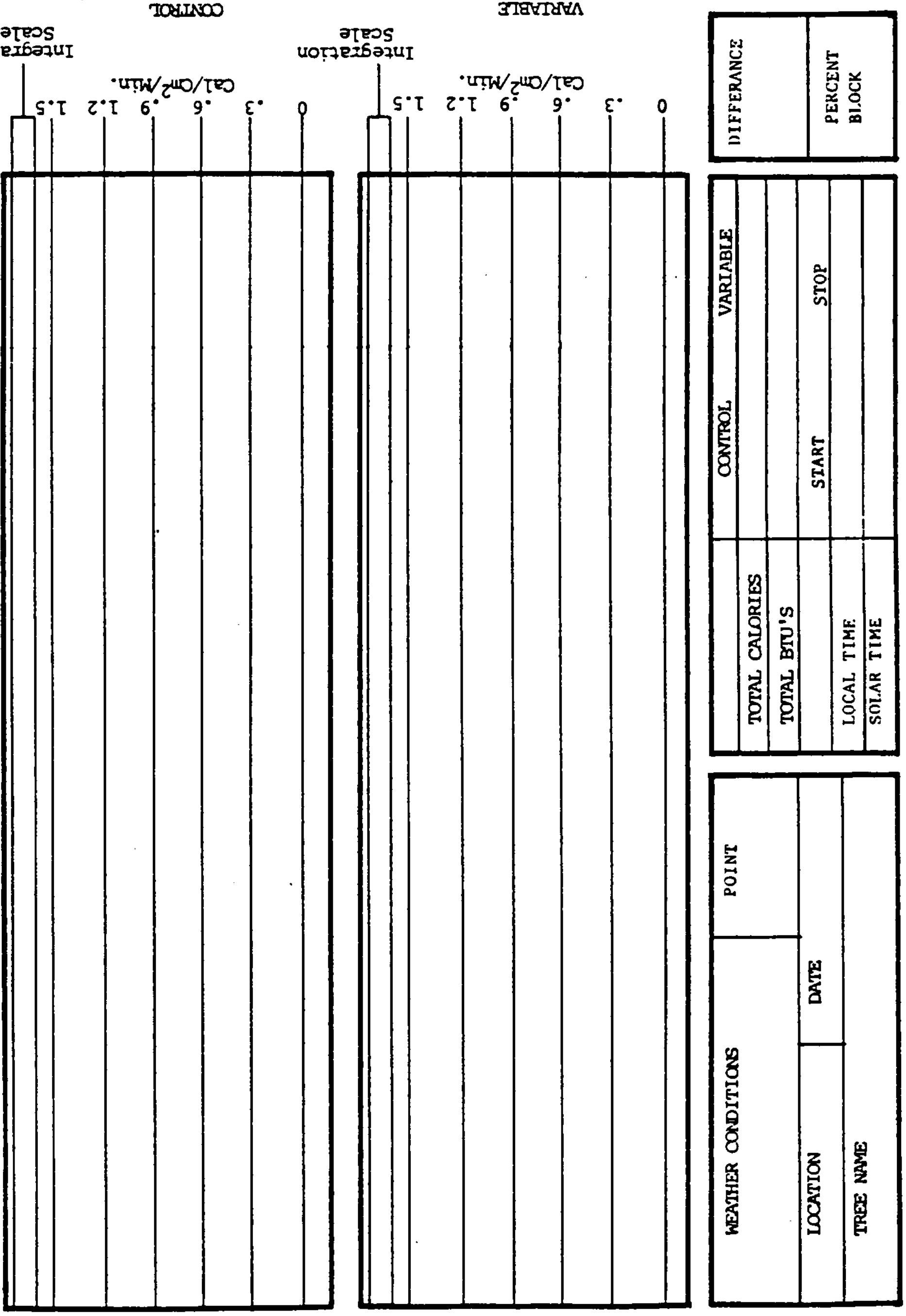
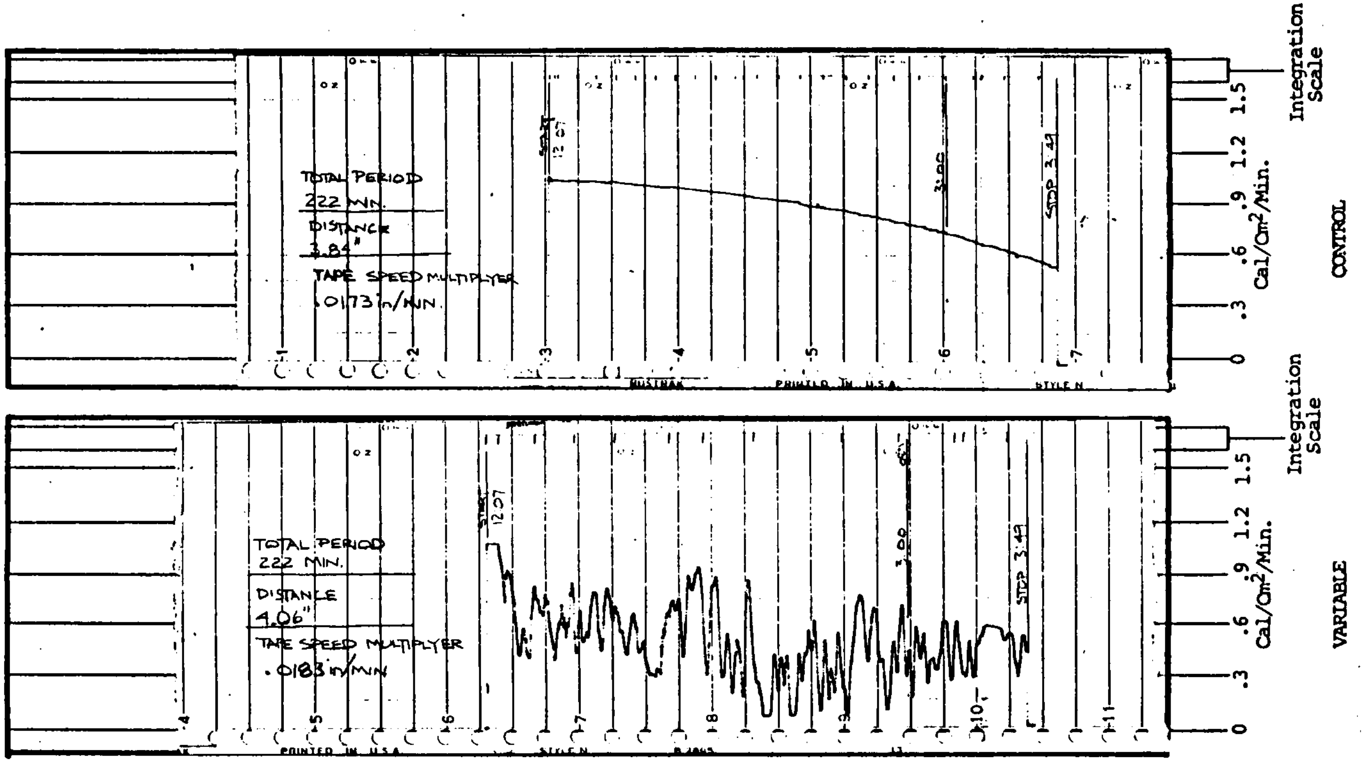

WEATHER CONDITIONS
POINT
LOCATION
DATE
TREE NAME
TOTAL CALORIES
TOTAL BTU'S
LOCAL TIME
SOLAR TIME
CONTROL
VARIABLE
START
STOP
DIFFERANCE
PERCENT BLOCK
VARIABLE
0 .3 .6 .9 1.2 1.5
Cal/Cm^2/Min.
Integration Scale
CONTROL
0 .3 .6 .9 1.2 1.5
Cal/Cm^2/Min.
Integration Scale

Figure 12. Example of data collection form.



TOTAL PERIOD 222 MIN.

DISTANCE 3.84"

TAPE SPEED MULTIPLYER .0173 in/MIN.

TOTAL PERIOD 222 MIN.

DISTANCE 4.06"

TAPE SPEED MULTIPLYER .0183 in/MIN

WEATHER CONDITIONS SUNNY	POINT 8
LOCATION HOLE # GOLF COURSE 7	DATE 3/11/88
TREE NAME SUGAR MAPLE #3 (LEWEY)	

	CONTROL	VARIABLE
TOTAL CALORIES	ERROR 190-13.26=176.74	91.30
TOTAL BTU'S		
	START	STOP
TIME	12:41 PM	4:23 PM
SOLAR TIME	12:07 PM	3:49 PM

DIFFERENCE 85.44
PERCENT BLOCK 48.34%

Figure 13. Tabulated data form example.

On the data tape, .8967 inches left of the actual stopping time is 3:00 pm.

- The starting and stopping points were marked on the integration scale.
- Once the starting and stopping times were marked on the integration scale, the integration scale was read to determine the amount of total langleys (insolation) gathered during the data collection period.
- The difference between the control and variable instrument totals were determined and divided by the total clear sky langleys obtained from the control instrument. This provided the percent block for that point in that time period.

In order to reduce the data collection period for each tree, a preliminary study was conducted to determine if data collected at corresponding points on the NE and NW shadow halves, were significantly different. It was assumed that if the study demonstrated a relationship between each shadow half, then data would need to be collected over only one half of the data points. When the information was transferred to the graph for analysis, data collected from one point of the corresponding pair could be duplicated onto the other point in the corresponding pair.

Preliminary data was collected for three corresponding pair of points in the shadow of sample tree number one. Tree one demonstrated a relationship between each pair of corresponding grid points. The first corresponding pair of data points demonstrated that the tree canopy blocked 15.73% and 15.89% of the available insolation. The second pair of data points demonstrated a reduction by the canopy of 19.24% and 16.81%. The third pair collected 39.67% and 48.01% of the available insolation. There was a very narrow range between each corresponding point. Statistical analysis demonstrated that there was a significant correlation between each pair. As a result, data was collected for one point from each corresponding pair. The shadow diagram for Tree One was created by duplicated data for each corresponding point which was not measured.

Results from the statistical analysis of the preliminary study for Tree Two took longer than anticipated. While waiting , the decision was made to collect all of the data points in case results from the analysis proved negative. When all of the data was collected and the shading contours were plotted, visual analysis proved there was no symmetry between the NW and NE halves. Interestingly enough, when the statistical results were received, they demonstrated a significant correlation between the NE and NW halves. Reasons for this discrepancy may be the original number of point pairs were not representative of the entire shadow pattern, or the statistical analysis used for this test was incorrect. It was later decided to collect all of the data from the third tree without performing the preliminary study.

Data for tree number one, was collected for one point in the corresponding pair of points, and was later transferred onto the corresponding points which did not have data. Trees two and three had data collected for all of the grid points. Once all of the data was collected and transferred onto the tree graph grid points, the insolation gradation lines were interpolated between each point in units of five langleys. These contours were interpolated similar to the interpolation of topographic contours. The shadow edge line in this case, represented the edge 0% insolation reduction.

CHAPTER III

RELEVANCE OF RESULTS TO BASIC RESEARCH

This chapter presents and analyzes the tree shading contour diagrams derived from the data collection phase of this investigation. The chapter also relates these findings to the area of pure research. It is divided into two parts. The first section determines the accuracy of the readings. The last section centers on the findings from the tree shading contour diagrams and how they respond to the investigation's original questions.

During the conclusion of the data collection process, an attempt was made to recollect data from grid points in order to determine the reliability of the instruments. This proved to be difficult since extremely cloudy weather and early bud break on the sample trees thwarted any indepth collection, or representative readings. Only two points were retaken in the process. Both times, heavy cloud cover effected the results, but some relevant information on the effects of clouds on insolation can be formulated from the data collected.

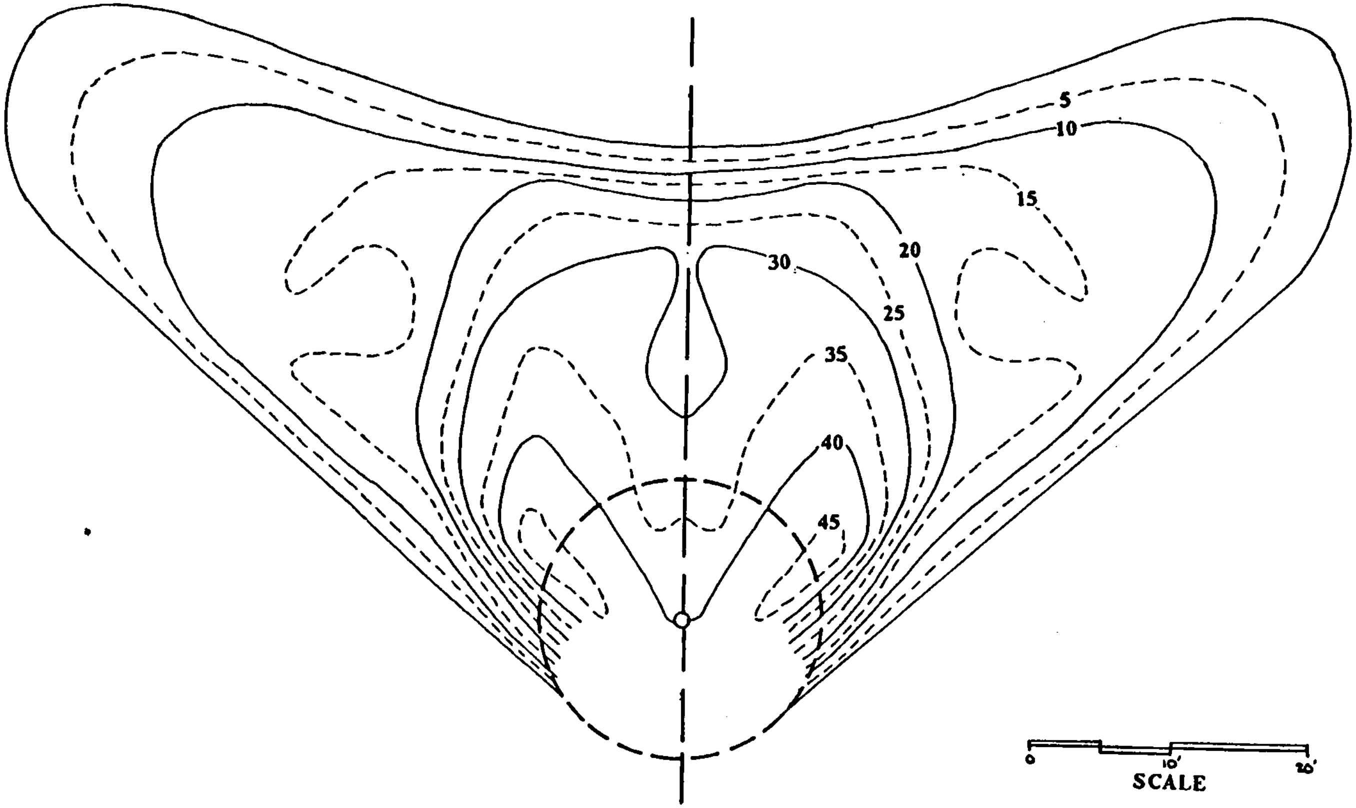
One reading on a day of high thin cirrus clouds, measured 7.61% less insolation than on a day when there was at least a 50% cloud cover. When a clear sky reading was compared to a reading collected during cloud cover of less than 50%, the clear sky insolation was 3.55% less than the cloudy day. In general, from these readings, as cloud cover increases insolation reduction by branches increases. This data, although sparse, contradicts expected findings and findings by Heisler's study in 1985, where insolation reduction was observed to be less on cloudy days than on clear sky days.

Figures 14 , 15 and 16 represent the tree shading contour diagrams of the sample trees in this investigation. Each contour represents a 5% blockage of insolation. It is important to note that the 9:00 and 3:00 upper 5% and 10% contours may not be as accurate in their positioning since data was not collected in those upper areas. If these locations are incorrect, then the next possible positioning for the contours would be closer to the shadow edge.

As mentioned previously, data for each point was not collected during the entire time between 9:00 and 3:00 but only during the time when the point was shaded. Measurements, therefore, do not represent daily insolation blockages, but insolation blockage during the shading period.

As a result of the process of this experiment, and the time constraint for data collection, statistical analysis of the contour diagrams could not be performed. Instead, visual comparison between the tree contour diagrams proved to be the most convenient and accurate method for analysis. Visual comparison of and between these diagrams provided several answers to the original questions of this investigation. The main question of this study wanted to determine if a shading pattern existed in the tree shadow pattern. As figures 14 , 15 and 16 demonstrate, a definable pattern does exist and can be easily plotted from the data collected.

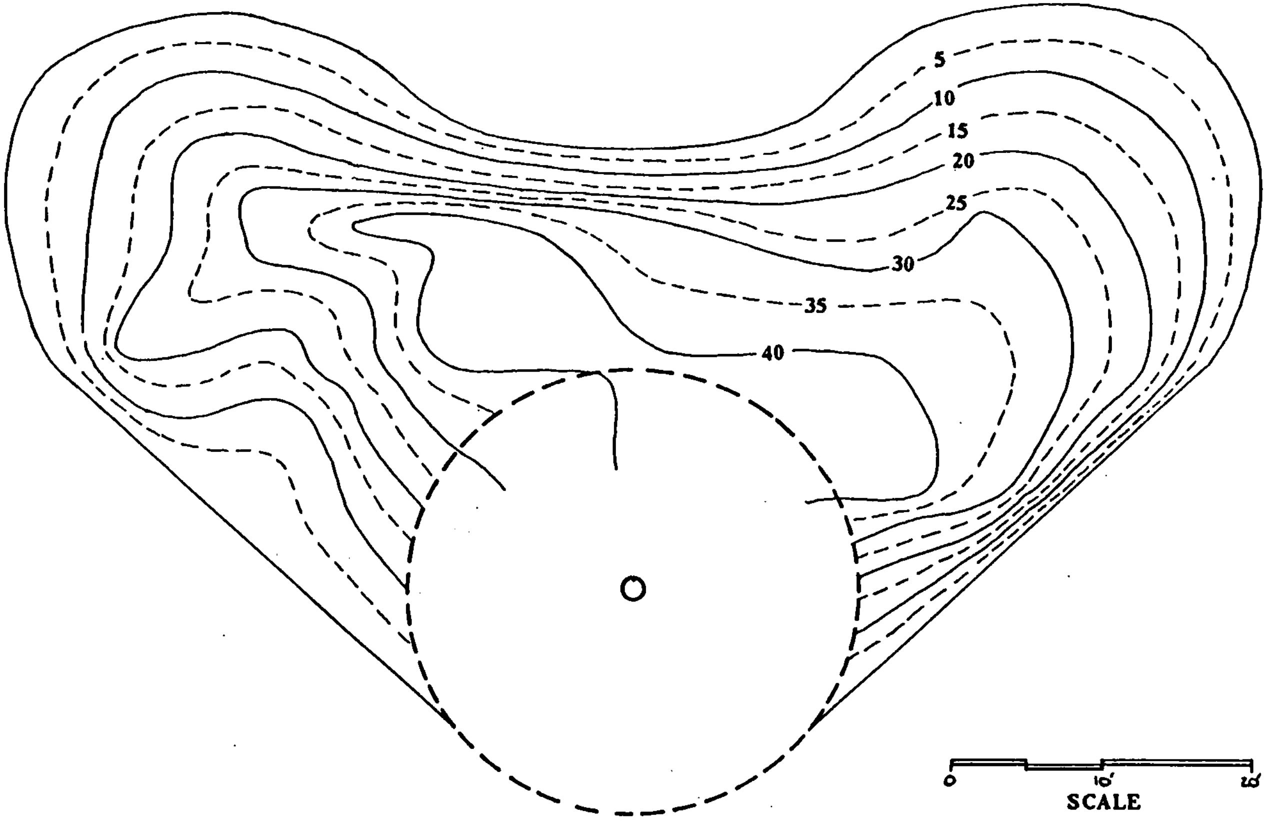
RELEVANCE OF RESULTS TO BASIC RESEARCH



Note: Each contour represents percent insolation blockage by the tree canopy on Feb. 9.

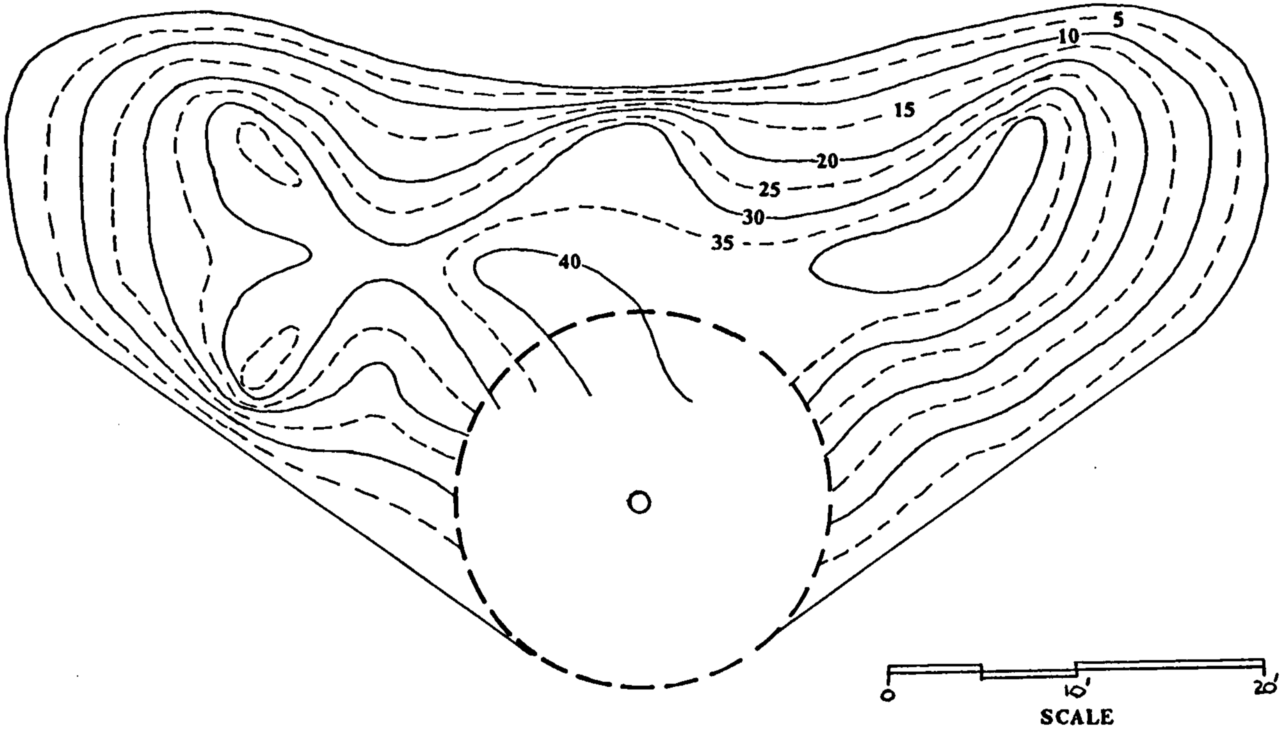
Figure 14. Tree One shadow contour diagram (duplicated data).

Figure 15. Tree Two shadow contour diagram (actual data).



Note: Each contour represents percent insolation blockage by the tree canopy on Feb. 29.

Figure 16. Tree Three shadow contour diagram (actual data).



Note: Each contour represents percent insolation blockage by the tree canopy on Mar. 10.

Another question pertained to whether the NE and NW shadow halves had a bilateral symmetry between their shadow contour patterns. Preliminary studies for Tree One showed a relationship between each of the three pairs of corresponding grid points. Data was only collected then, for one point from each pair of corresponding points. The data was then duplicated for the other grid point of the pair. As a result, when interpolating the contours, Tree One visually demonstrates this symmetry between each of the NE and NW halves. From detailed studies of all data points in Trees Two and Three, it is assumed that the three points used for the preliminary study may not be a representative sample for each half of the tree shadow pattern. In this case, the shadow pattern for Tree One may not actually represent the true overall shadow pattern. For this reason, only Trees Two and Three were used to determine if a symmetry existed between each of the shadow halves. Although the average density between each of the two halves is approximately the same, visual comparisons between each half of the contour shadow patterns demonstrate that there is no bilateral symmetry. In fact, the NW halves tend to be more irregular in their patterning then the NE halves. This difference may result from two probable causes.

The first cause may arise from the effects of wind, especially winter winds, on the growth habit. Extreme winds have been known to force trees into irregular leaning shapes, such as wind blown pines of the California coast. Although winds on the site may not be very strong, they may produce some imperceivable effects to branch growth. Winds on the site originate from the west in the summer, and NW in the winter. Of these winds, winter winds may produce the greatest effect upon the branching. Winter winds may damage or freeze tree buds, especially when they are opening in the spring. If this does occur, the winds would be controlling the growth on the NW tree face more than the NE face.

A second explanation for this variation between the shadow halves may result from unselective pruning by spherical projectiles (golf balls). Tree Two is located on the fringe of a fairway, at a distance and location where golf balls frequently hit the western half of the tree canopy. Many times when locating instruments around the tree, balls were observed to break twigs and probably bud, off the tree. This unselective pruning may be controlling the western half of Tree Two.

The third question in this investigation is whether the shadow pattern remained constant among trees of the same species and form. Comparison again, shows there is no significant relationship between trees of the same species and form. Variables which might influence these results are the age of the trees, their size, or period in which each sample tree was studied. These variables may be controlled if two trees of the same species, age and size are used, and if data was collected simultaneously at the same data points within the shadows of these two trees.

In addition to providing some insight into the investigation's original questions, there were several interesting observation's within the same areas of the shadow contour diagrams. The first observable feature lay along the NE and NW outer shadow edges and around the intersection of the shadow edge and north line. Along these areas, the shading contours seem to be more compact than within the other areas. Compacting at the north line intersection may result from the higher solar altitude. At solar noon, the sun's high altitude causes the incoming solar flux to pass through a larger cross-sectional area of the tree's canopy. The greater cross-sectional area results in a larger amount of branch interception, thus increasing the shade density toward the edge of the shadow. Compacting of the contours along the NE and NW outer edges is difficult to account for without further investigation. One possibility for the contours being at such close intervals may be the result of penumbral shading. An indepth understanding of how data was used from grid points in these areas may explain why the contour intervals are so close. Data collected from grid points averaged insolation readings as the entire shadow passed over the instrument. Data used from these outer grid points, though, only accounted for readings between 9:00 am and when the instrument was exposed again to the sun, or from the instrument exposure to 3:00 pm. These readings basically averaged the insolation transmission through the outer tree twigs. Holzberlein concluded that twigs -the tree shadow edge- reduced the most insolation in the tree shadow. If this is true, the twig density along these outer areas may be holding the average shading density up, closer to the shadow edge. Higher density closer to the shadows edge creates a shorter distance for the insolation to increase, in turn the contours compact as the insolation increases in the shorter distance to the shadow edge.

RELEVANCE OF RESULTS TO BASIC RESEARCH

Another relationship between the shadows is the location of the highest shadow density contours. The contours of greatest density are located along the tree's dripline at the northern face of the tree. This supports Johnson, et al.'s assumption, that the most dense area in a tree's daily shadow is on the northern point of a tree's dripline. Collecting daily measurements at this position provides the researcher with the most dense shade possible for this tree species. This does not, however, refute penumbral shading which Holtzberlein observed. His studies observed the shadow of trees in an instant of time, and how that varied within different areas of a tree's shadow. Johnson, et al., and this study average the shadow readings as the shadows move over the instruments.

There seems to be no variation of percent insolation density between these different ages of tree specimens. Tree One was 15 to 20 years of age, and it blocked 45% of the insolation. Tree Two was 25 to 35 years old, and blocked 40% of the insolation. Tree Three was 20 to 25 years old, and it reduced insolation by 40% as well. This is a very small difference between three different ages. Some earlier studies demonstrated the average insolation does change with age, but as it applies to the overall shadow patterns, this is may not be the case.

CHAPTER IV

RELEVANCE OF RESULTS TO APPLIED RESEARCH

Insulated walls protect a structure against any substantial heat loss or gain. The effects, then, which trees have upon the heat gain of walls would be minimal. Trees positioned in front of windows, however, substantially reduce passive solar gain to a structure. This part of the study shall determine the effects of the sample tree's shading upon the heat gain of a window.

The window size used for this phase of the investigation measured 20' wide by 15' tall. Two window positions were tested in the shadow patterns of Tree One and Tree Two. The first position (A), was centered and perpendicular (running E-W) to the true north line, and located 3' out from the tree's dripline. Position B is located in the morning half of the shadow pattern, on the same E-W line that window position A was on, and 7' west from the true north line. Figure 17 on page 55

The following procedure was used to analyze these window positions.

- Each hourly shadow length factor in which date the tree shadows were studied, were multiplied by the window height. This produced the length not of the shadow, but of the direct light pattern which passed through the window.
- The light patterns formed by the window at each hour was plotted.
- Each hourly window light pattern was overlayed onto the tree's corresponding hourly shadow pattern. Figures 18, 19 and 20 on pages 55 to 57

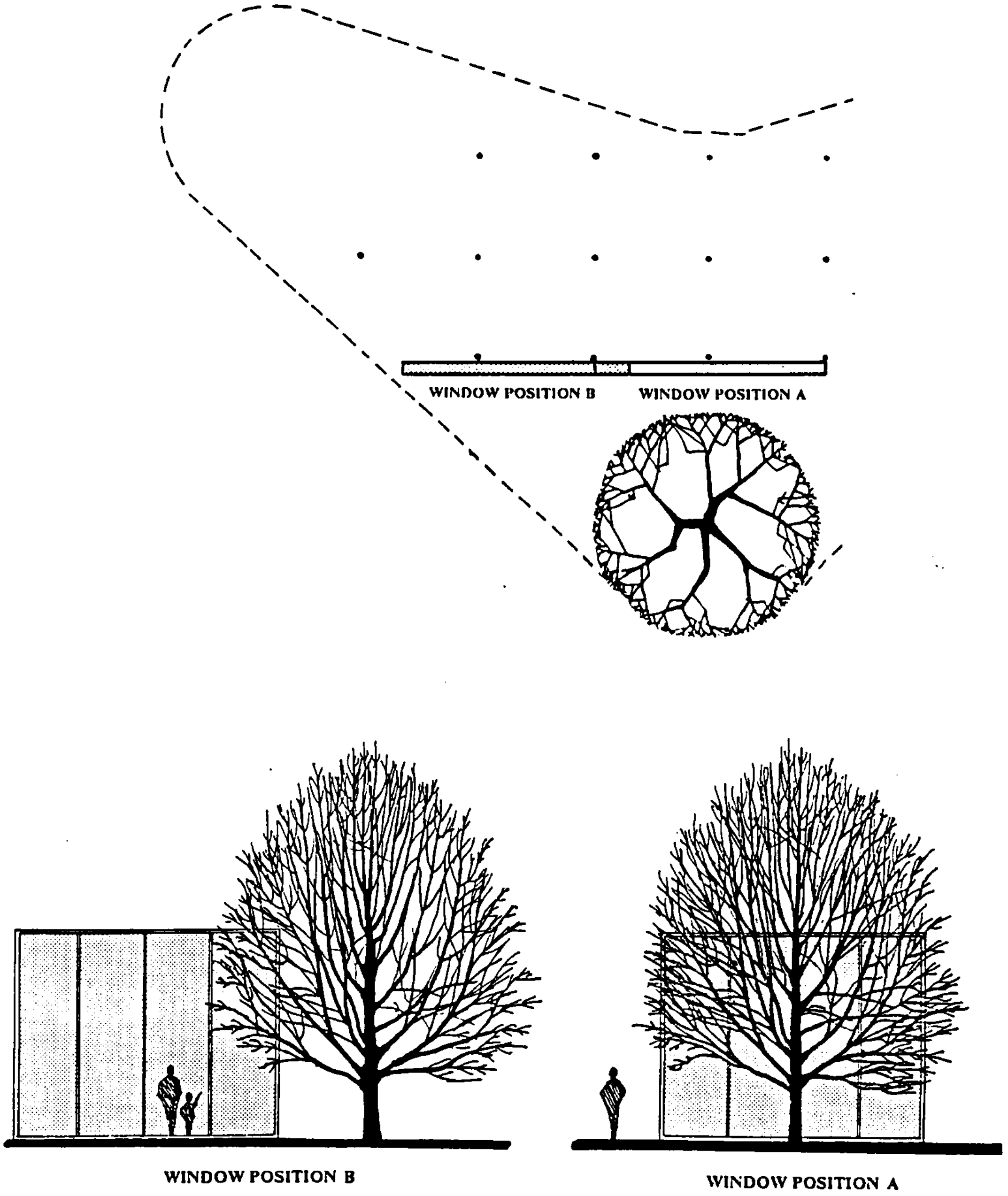


Figure 17. Study window positions

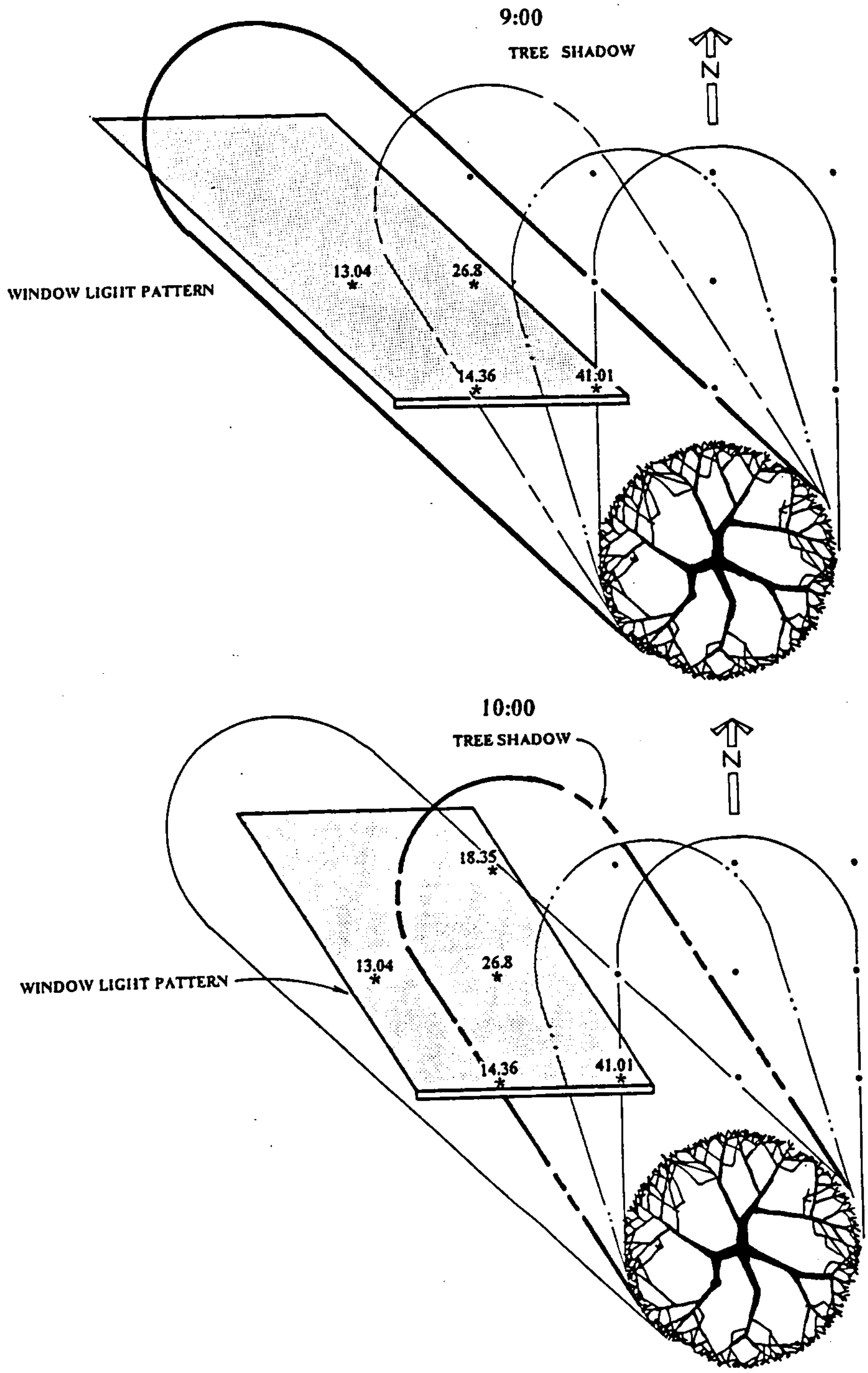


Figure 18. Example of 9:00 and 10:00 window light and tree shadow patterns.

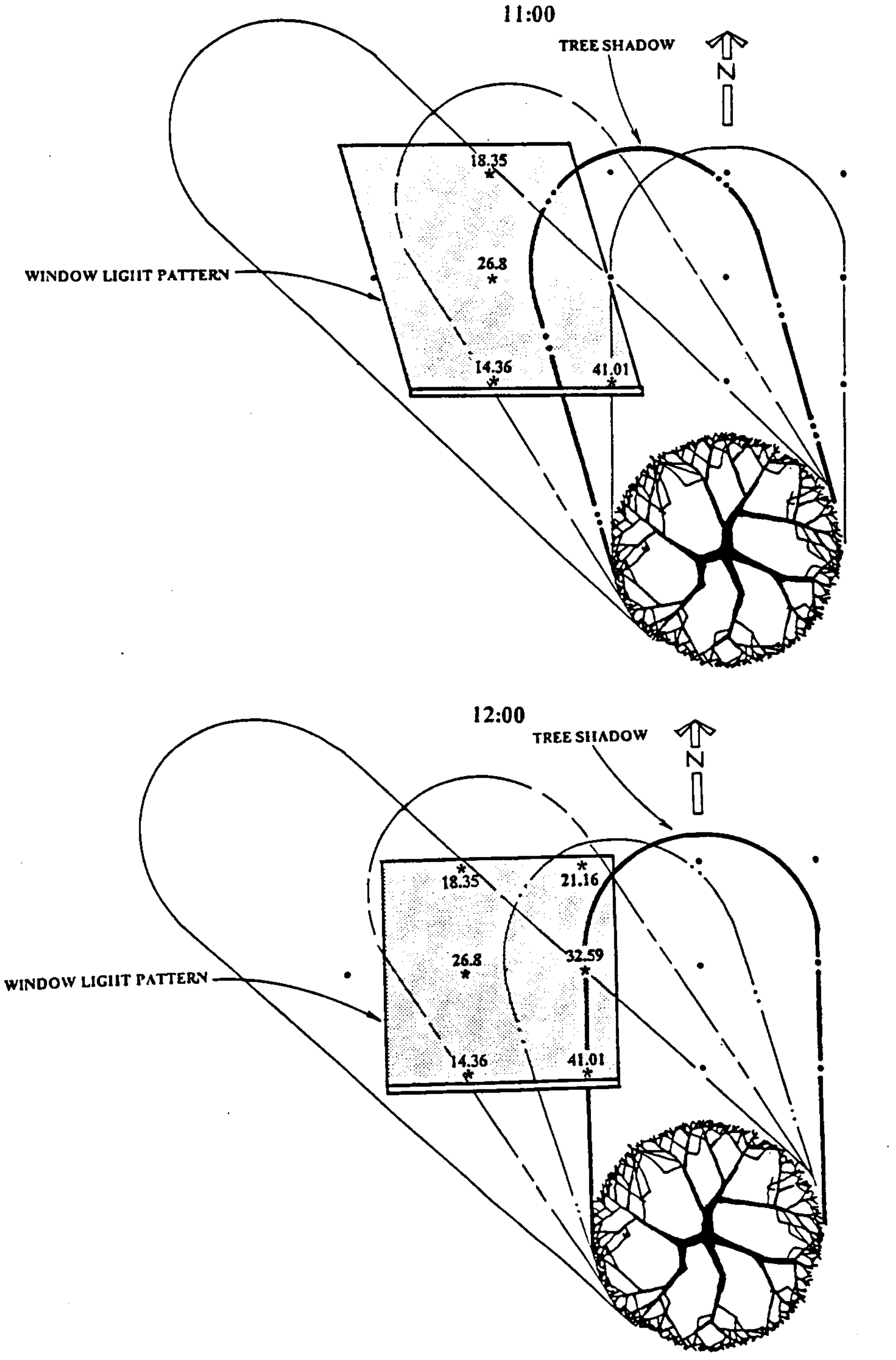


Figure 19. Example of 11:00 and 12:00 window light and tree shadow patterns.

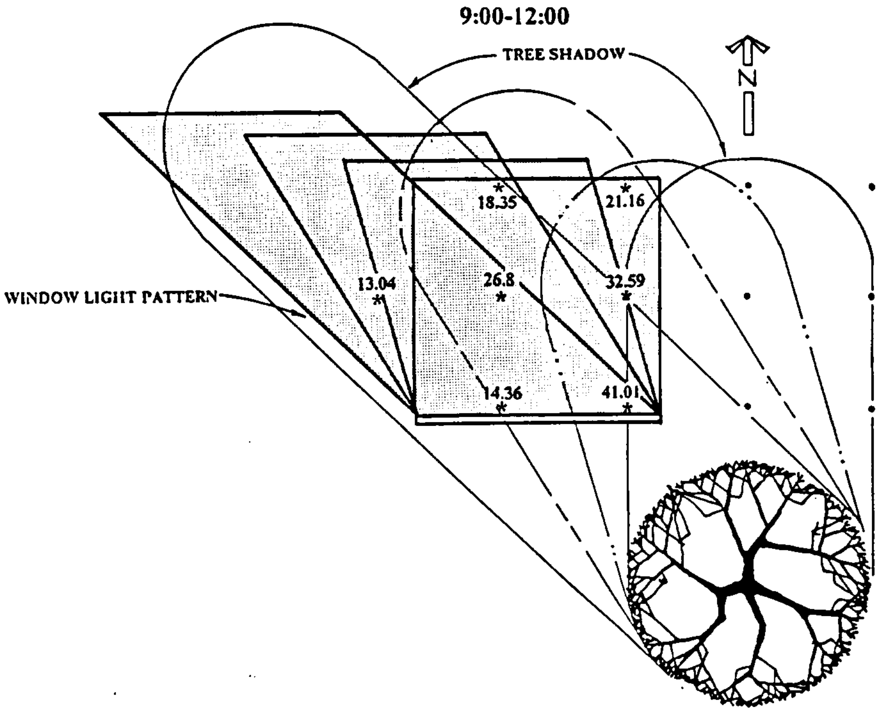


Figure 20. 9:00 am to 12:00 pm hourly window light and tree shadow patterns.

- The tree's shadow and the sun light areas within the window's light pattern were determined.
- The areas were converted into a percentages by dividing each area from the total window light pattern area.
- The data points within the shadow area of the window light pattern were averaged to obtain the percent blockage.
- The percent shade derived from horizontal data, and sun areas were multiplied by the percent light penetration for the shadow and sun area to achieve a weighted average.
- The weighted averages were summed to provide the overall percent light penetration into the window at each hour.

The overall light penetration percentages derived from the previous calculations allows one to determine the changes of shading throughout the day. The above procedure requires using light penetration figures derived from horizontal data and applying them to a vertical window. The Accuracy of transposing horizontal percents to vertical surface insolation was tested and can be found in Appendix A.

In order to determine the effects of insolation upon a structure, data collected by this investigation must be transposed from horizontal readings to daily and seasonal insolation readings for vertical surfaces. Insolation tables already exist for clear sky insolation of various angled surfaces at hourly and daily intervals. Insolation information used by this study was obtained from ASHRAE tables in <u>More Other Homes and Garbage</u>. These tables, though, did not have information for the 37.3°N latitude. This information had to be interpolated from the 32°N and 40°N latitude tables. All readings in these tables were based on BTUh/sq foot.

Table 3. Hourly percent insolation tables

TREE #1
Feb. 9

window position A

9:00			
	SHADOW	SUN	TOTAL
AREA	252	216	468
% OF TOTAL AREA	53.85	46.15	100
% LIGHT PENETRATION	63.05	100	----
WEIGHTED AVERAGE	33.95	46.15	80.1
OVERALL % PENETRATION			80.1
OVERALL % BLOCK			19.9

10:00			
	SHADOW	SUN	TOTAL
AREA	297	135	432
% OF TOTAL AREA	68.75	31.25	100
% LIGHT PENETRATION	71.55	100	----
WEIGHTED AVERAGE	49.19	31.25	80.44
OVERALL % PENETRATION			80.44
OVERALL % BLOCK			19.56

11:00			
	SHADOW	SUN	TOTAL
AREA	304	92	396
% OF TOTAL AREA	76.77	23.23	100
% LIGHT PENETRATION	72.05	100	----
WEIGHTED AVERAGE	55.31	23.23	78.54
OVERALL % PENETRATION			78.54
OVERALL % BLOCK			21.46

12:00			
	SHADOW	SUN	TOTAL
AREA	380	0	380
% OF TOTAL AREA	100	0	100
% LIGHT PENETRATION	70.84	100	----
WEIGHTED AVERAGE	70.84	0	70.84
OVERALL % PENETRATION			70.84
OVERALL % BLOCK			29.16

Table 4. Hourly percent insolation tables

TREE #1

Feb. 9

window position B

9:00			
	SHADOW	SUN	TOTAL
AREA	452	16	468
% OF TOTAL AREA	97.00	3.00	100
% LIGHT PENETRATION	76.20	100	----
WEIGHTED AVERAGE	73.91	3.00	76.91
OVERALL % PENETRATION			76.91
OVERALL % BLOCK			23.09
10:00			
	SHADOW	SUN	TOTAL
AREA	234	198	432
% OF TOTAL AREA	54.17	45.83	100
% LIGHT PENETRATION	77.29	100	----
WEIGHTED AVERAGE	41.87	45.83	87.70
OVERALL % PENETRATION			87.70
OVERALL % BLOCK			12.30
11:00			
	SHADOW	SUN	TOTAL
AREA	128	268	396
% OF TOTAL AREA	32.32	67.68	100
% LIGHT PENETRATION	73.38	100	----
WEIGHTED AVERAGE	23.72	67.68	91.40
OVERALL % PENETRATION			91.40
OVERALL % BLOCK			8.60
12:00			
	SHADOW	SUN	TOTAL
AREA	57	323	380
% OF TOTAL AREA	15.00	85.00	100
% LIGHT PENETRATION	63.20	100	----
WEIGHTED AVERAGE	9.07	85.00	94.07
OVERALL % PENETRATION			94.07
OVERALL % BLOCK			5.93

Table 5. Hourly percent insolation tables

TREE #2
Feb. 29

window position A

9:00			
	SHADOW	SUN	TOTAL
AREA	180	212	392
% OF TOTAL AREA	45.92	54.08	100
% LIGHT PENETRATION	55.05	100	----
WEIGHTED AVERAGE	25.28	54.08	79.36
OVERALL % PENETRATION			79.36
OVERALL % BLOCK			20.64

10:00			
	SHADOW	SUN	TOTAL
AREA	220	132	352
% OF TOTAL AREA	62.50	37.50	100
% LIGHT PENETRATION	62.33	100	----
WEIGHTED AVERAGE	38.96	37.50	76.46
OVERALL % PENETRATION			76.46
OVERALL % BLOCK			23.54

11:00			
	SHADOW	SUN	TOTAL
AREA	323	120	323
% OF TOTAL AREA	62.85	37.15	100
% LIGHT PENETRATION	62.33	100	----
WEIGHTED AVERAGE	39.17	37.15	76.32
OVERALL % PENETRATION			76.32
OVERALL % BLOCK			23.68

12:00			
	SHADOW	SUN	TOTAL
AREA	200	100	300
% OF TOTAL AREA	66.67	100	100
% LIGHT PENETRATION	69.61	100	----
WEIGHTED AVERAGE	46.41	33.33	79.74
OVERALL % PENETRATION			79.74
OVERALL % BLOCK			20.26

Table 6 Hourly percent insolation tables

TREE #2
Feb. 29

window position B

9:00			
	SHADOW	SUN	TOTAL
AREA	302	92	392
% OF TOTAL AREA	77.04	22.96	100
% LIGHT PENETRATION	65.01	100	----
WEIGHTED AVERAGE	50.08	22.96	73.04
	OVERALL % PENETRATION		73.04
	OVERALL % BLOCK		26.96

10:00			
	SHADOW	SUN	TOTAL
AREA	130	222	352
% OF TOTAL AREA	36.93	63.07	100
% LIGHT PENETRATION	65.01	100	----
WEIGHTED AVERAGE	24.01	63.07	87.08
	OVERALL % PENETRATION		87.08
	OVERALL % BLOCK		12.92

11:00			
	SHADOW	SUN	TOTAL
AREA	75	248	323
% OF TOTAL AREA	23.22	76.78	100
% LIGHT PENETRATION	60.01	100	----
WEIGHTED AVERAGE	13.93	76.78	90.71
	OVERALL % PENETRATION		90.71
	OVERALL % BLOCK		9.29

12:00			
	SHADOW	SUN	TOTAL
AREA	6	294	300
% OF TOTAL AREA	2.00	98.00	100
% LIGHT PENETRATION	55.05	100	----
WEIGHTED AVERAGE	1.10	98.00	99.10
	OVERALL % PENETRATION		99.10
	OVERALL % BLOCK		0.09

Table 7. Clear sky insolation tables

FEB. 9

Clear Sky Readings

BTUH/SQ. FT. TOTAL
INSOLATION ON SURFACE

HOUR	NORMAL	HORIZONTAL	VERTICAL
9,3	266.53	122.78	167.92
10,2	291.24	169.84	211.72
11,1	302.70	198.55	237.32
12	306.35	208.67	246.46
SURFACE DAILY TOTALS	2027.29	1191.01	1480.38

FEB. 29

Clear Sky Readings

BTUH/SQ. FT. TOTAL
INSOLATION ON SURFACE

HOUR	NORMAL	HORIZONTAL	VERTICAL
9,3	307.52	151.76	155.17
10,2	298.00	199.21	194.79
11,1	308.00	228.48	218.52
12	310.45	238.48	226.96
SURFACE DAILY TOTALS	2137.49	1397.38	1363.92

Using the clear sky insolation tables, effects of tree shade on various surfaces and daily readings were determined as follows:

- The overall percent light penetration from tables 3,4,5 and 6 were multiplied by each hourly period of insolation for normal, horizontal, and vertical surfaces in table 7. This provided the amount of insolation to each surface in each individual hour. For windows located north of the tree, the shading pattern should be the same for each of the corresponding hours of 9:00/3:00, 10:00/2:00 and 11:00/1:00. The light penetration number used for each morning hour was duplicated to its corresponding afternoon hour. The window in morning shadow is shaded in the morning and free of obstruction in the afternoon. In this situation, there should be two different numbers for each corresponding hour.
- Once all surface insolation for each hour was determined, each of the hourly surface readings were summed to obtain a daily insolation reading on the windows.
- Surface daily totals (table 8) were divided by the clear sky surface daily totals (table 7) to produce the percent daily insolation of the total available clear sky conditions.

All of the information for daily insolation obtained from the previous calculations can be found in tables 8 and 9. Once all of the calculations and tabulations are completed, several conclusions, which can aid in developing design criteria, can be formulated.

Based on data gathered from a horizontal surface, window position A for both trees had from 10% and 0% additional reduction of insolation from 9:00 to noon. Tree One transmitted 80% of the available insolation at 9:00; By noon this had decreased by 10% to 70% of the available insolation. Tree Two showed very little change in insolation. At 9:00,

Table 8. Insolation tables.

TREE #1
FEB. 9

window position A

BTUH/SQ. FT. TOTAL
INSOLATION ON SURFACE

HOUR	NORMAL	HORIZONTAL	VERTICAL
9,3	213.49	98.35	134.50
10,2	234.27	136.62	170.31
11,1	237.74	155.94	186.39
12	217.02	147.82	174.59
DAILY TOTALS	1588.02	929.64	1156.99
CLEAR SKY TOTALS	2027.29	1191.01	1480.38
% PENETRATION	78.33	78.05	78.15
% BLOCK	21.67	21.95	21.85

TREE #1
FEB. 9

window position B

BTUH/SQ. FT. TOTAL
INSOLATION ON SURFACE

HOUR	NORMAL	HORIZONTAL	VERTICAL
9	204.99	94.43	129.15
10	255.42	148.95	185.68
11	277.27	181.87	217.39
12	288.18	196.30	231.84
1	302.70	198.55	237.32
2	291.24	169.34	211.72
3	266.53	122.78	167.78
DAILY TOTALS	1886.33	1112.22	1381.02
CLEAR SKY	2027.29	1191.01	1480.38
% PENETRATION	93.05	93.38	93.29
% BLOCK	6.95	6.62	6.71

Table 9. Insolation tables.

TREE #2
FEB.29

window position A

BTUH/SQ. FT. TOTAL
INSOLATION ON SURFACE

HOUR	NORMAL	HORIZONTAL	VERTICAL
9,3	244.05	120.44	123.14
10,2	227.85	152.32	148.94
11,1	235.06	174.38	166.77
12	247.55	190.16	180.98
DAILY TOTALS	1661.47	1084.44	1058.68
CLEAR SKY	2137.49	1397.38	1363.92
% PENETRATION	77.73	77.61	77.62
% BLOCK	22.27	22.29	22.38

TREE #2
FEB. 29

window position B

BTUH/SQ. FT. TOTAL
INSOLATION ON SURFACE

HOUR	NORMAL	HORIZONTAL	VERTICAL
9	224.61	110.85	113.34
10	259.50	173.47	169.62
11	279.39	207.25	198.22
12	307.66	236.33	224.92
1	308.00	228.48	218.52
2	298.00	199.21	194.79
3	307.52	151.76	155.17
DAILY TOTALS	1981.68	1307.35	1274.58
CLEAR SKY	2137.49	1397.38	1363.92
% PENETRATION	92.27	93.56	93.45
% BLOCK	7.73	6.44	6.55

insolation in the tree's shadow was 79.36% of the available clear sky insolation, by 12:00 this had increased only slightly to 79.74%.

Window position B, however, gained 17 to 26% insolation from 9:00 to 12:00. Tree One allowed 76.91% of the available insolation to penetrate at 9:00, and by noon had allowed 94.07% through, a 17.16% increase in insolation. Tree Two permitted 73.04% of the insolation to be transmitted through the tree canopy. At 12:00, those had increased by 26.06% to 99.1%.

Looking at the daily insolation of the vertical surfaces from tables 8 and 9 gives an idea of the insolational differences between the two window positions. Daily totals for window A were 1156.96 BTUh/SQ FT, while position B received 1381.02 BTUh/SQ FT. Compared to the clear sky values, position A received 78.15% of the available daily insolation while position B received 93.29%.

Tree Two demonstrated very similar percentages. Window position A received 77.62% or 1058.68 BTUh/SQ FT of insolation, while position B received 93.45% or 1274.58 BTUh/SQ FT of insolation.

In this scenario, the window position A would have the greatest detrimental effects to a structure's heat gain. Window position B is be shaded till noon, after which time it is be exposed for afternoon heat gain. This outcome supports earlier landscape design criteria for planting trees outside of the solar access zone. With careful scrutiny of the tree's shadow azimuth angle, a tree can be positioned to shade a very small

Table 10. Insolation transmission on horizontal and vertical surfaces.

INSOLATION TRANSMISSION ON A HORIZONTAL SURFACE

	Window Position A		Window Position B	
	Tree		Tree	
	One	Two	One	Two
9:00	80%	79%	77%	73%
12:00	70%	79%	94%	99%

DAILY INSOLATION ON A VERTICAL SURFACE

	Window Position A		Window Position B	
	Tree		Tree	
	One	Two	One	Two
Daily BTUh/SQ FT	1156.96	1058.68	1381.02	1274.58
% OF CLEAR SKY VALUE	78%	78%	93%	93%

portion of a south wall or window of a structure while allowing light to enter during the late evenings and early mornings.

The study locations may not be the overall best positions for the windows. If the windows were kept in line and pulled farther back from the tree so position A is in the sun all day, insolation blockage would be reversed between the two windows. Window B would still be shaded in the morning hours, although not as much as in the previous analysis, while window A would have clear solar access (see table 10). Figure 21 on page 71

Current design recommendations advocate planting trees on the west or east sides of a structure. These locations, it is thought, would reduce unwanted heat gain in the summer and allow light in during the winter. Pruning the lower limbs could be used to shape the tree for solar access control. As the tree contour diagrams demonstrate, any tree directly against the west or east wall would shade the structure substantially in the winter. Manipulating the data from Tree Two- the largest sample tree- the lower limb height for solar access was determined. Tree Two measured 35' tall, 27' wide with a 7' lower limb height. If a 7' tall window were located 30' from the tree trunk on the east side, the lower limb height would need to be pruned to a minimum of 13' high to allow solar access on January 10. If one wanted solar access up to February 29, the lower limb height would need to be pruned to 29'. For trees to be pruned to such a drastic height without diminishing their aesthetic value in the landscape, they would have to be at an extremely mature age and size.

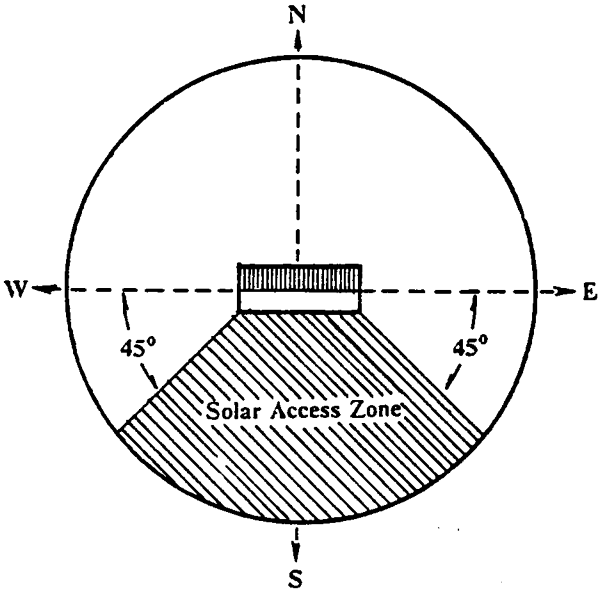


Figure 21. Solar access zone.

Younger specimens would be deformed if such measures were performed on them.

The tree typology, which will be discussed in the next chapter, was created to aid researchers in selecting trees which have not been studied, but it can also be utilized as a design aid. The typology provides designers with tree forms, sizes, densities, leafing out and leaf abscission periods for the 37.3°N latitude, in planting zone 6 of the USDA hardiness map.

CHAPTER V

TREE TYPOLOGY

At present, no common listing of tree densities and forms exists to aid designers in choosing trees for passive solar landscapes. What information does exist, is scattered throughout the literature. McPhearson's computer program SOLMAT, does begin to create a simple listing of trees which includes their density, time of leaf fall and opening, size, form and growth rate. SOLMAT is a beginning, but the listing is comprised of plants which grow in Utah and not common along the northeastern United States. Researchers also need a common framework to coordinate collection of data on various tree species, and to provide a rational for selection of tree species to include in future works.

To permit this document to direct and aid future research, as well as provide designers with a listing to aid in the selection of trees, a framework has been developed. This framework, aptly named the tree typology, provides designers with listings of tree densities and forms, while providing researchers with a foundation for further investigations.

The typology separates deciduous trees into six phenotypical, or form categories. These categories include circular, elliptic/oval, pyramidal, irregular, weeping and umbrella. Circular trees such as the Norway Maple and Red Bud, have mature heights equal to their widths. Elliptic/oval trees are those which are taller than wider, and with a rounded top.

Trees like the mature Pin Oak and Linden are examples of this form. Pyramidal trees like the Dawn Redwood, form a point at their apex, and usually tend to have a central leader. Irregular forms have no definable shape and usually have a horizontal branching habit. These are represented by the Flowering Dogwood and Honey Locust. As their name implies, weeping trees branches hang perpendicular to the ground. The best example for this form is the weeping willow. Finally, umbrella tree forms, such as the American Elm or Zelkova, form an funnel shaped canopy.

Tree form selection was based on standard classification of trees in various publications such as <u>Dirr's Manual of Woody Plants</u> and Wyman's <u>Trees for American Gardens</u>. All tree species have a tendency toward a specific form at maturity, although, forms may vary depending on cultural practices, genetic variability, age, and natural conditions such as wind or snow.

Reviewing the distribution and classification of tree sizes, this investigation subdivided each of the phenotype categories into three mature size categories. Small trees are any tree under thirty feet; medium sized trees are between thirty-one feet and fifty feet, and large trees are fifty-one feet or greater. Trees are represented in the typology by branching silhouettes typical to the species. These silhouettes were produced from publications or from photographs taken of mature, representative trees. Also included with each tree is their foliation and defoliation dates mature height, width, and, if available, average winter and summer light penetration. Except where noted, foliation and defoliation dates were based on studies conducted in Aurora, Oregon, 45°N latitude. Foliation refers to the appearance of the first true leaf, while defoliation dates occur when the tree was completely defoliated.

Although this typology is not exhaustive with the species it includes, it does incorporate deciduous trees which are currently available in the nursery trade. All representative trees can be grown in planting zone 6 of the USDA hardiness maps, in the 37.3°N latitude of the Eastern United States. This does not, however, limit the typology in any way. As additional studies are conducted, and newer species and cultivars become available, additional vegetation and research information can be incorporated into the typology.

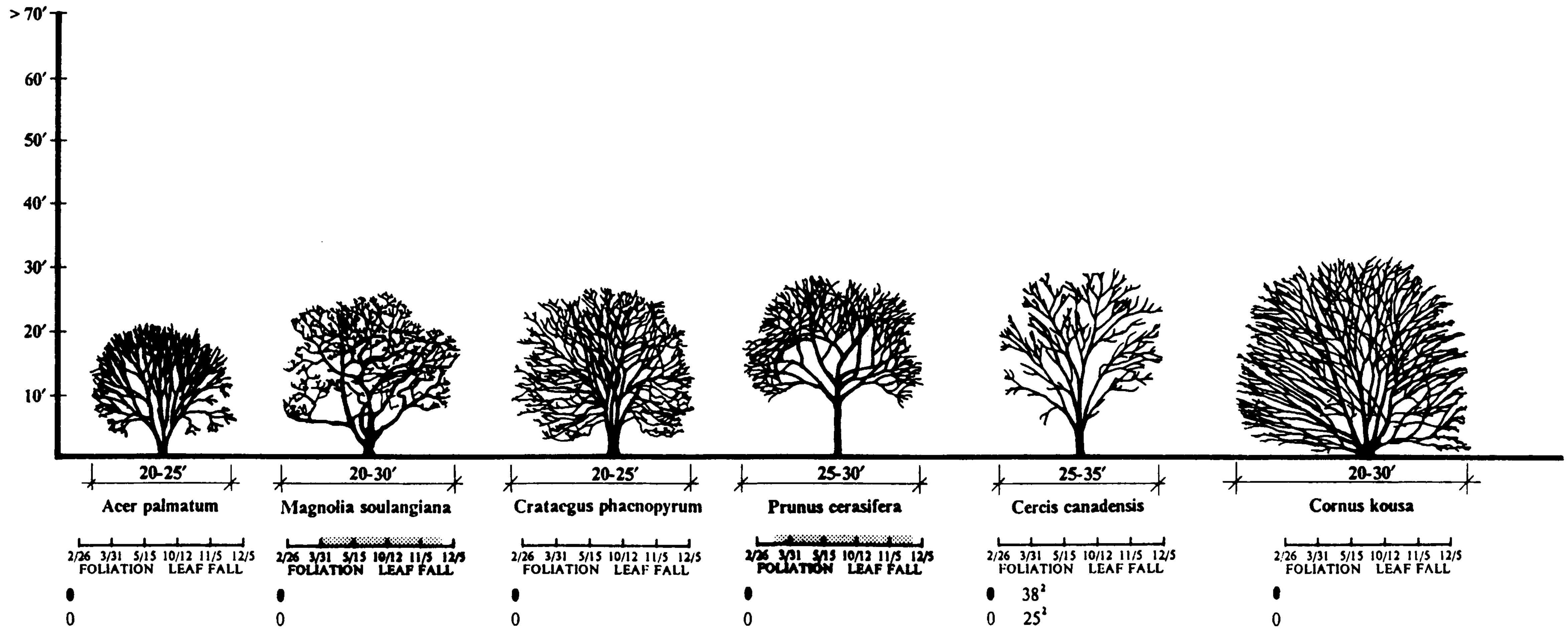


Figure 22. Tree typology

SMALL CIRCULAR TREE FORMS

[2] Johnson et al, 1979

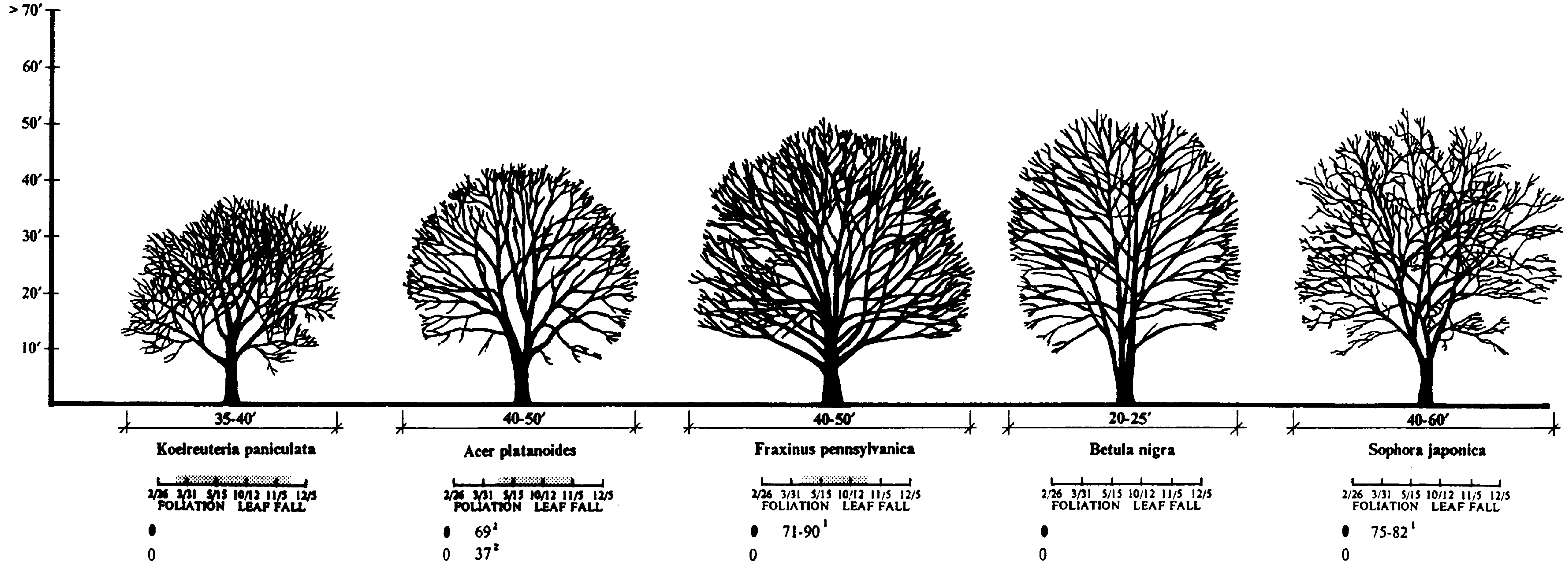


Figure 23. Tree typology

MEDIUM CIRCULAR TREE FORMS

[1] Moffat, Schiler, 1981 pp. 181-183

[2] Johnson et al, 1979

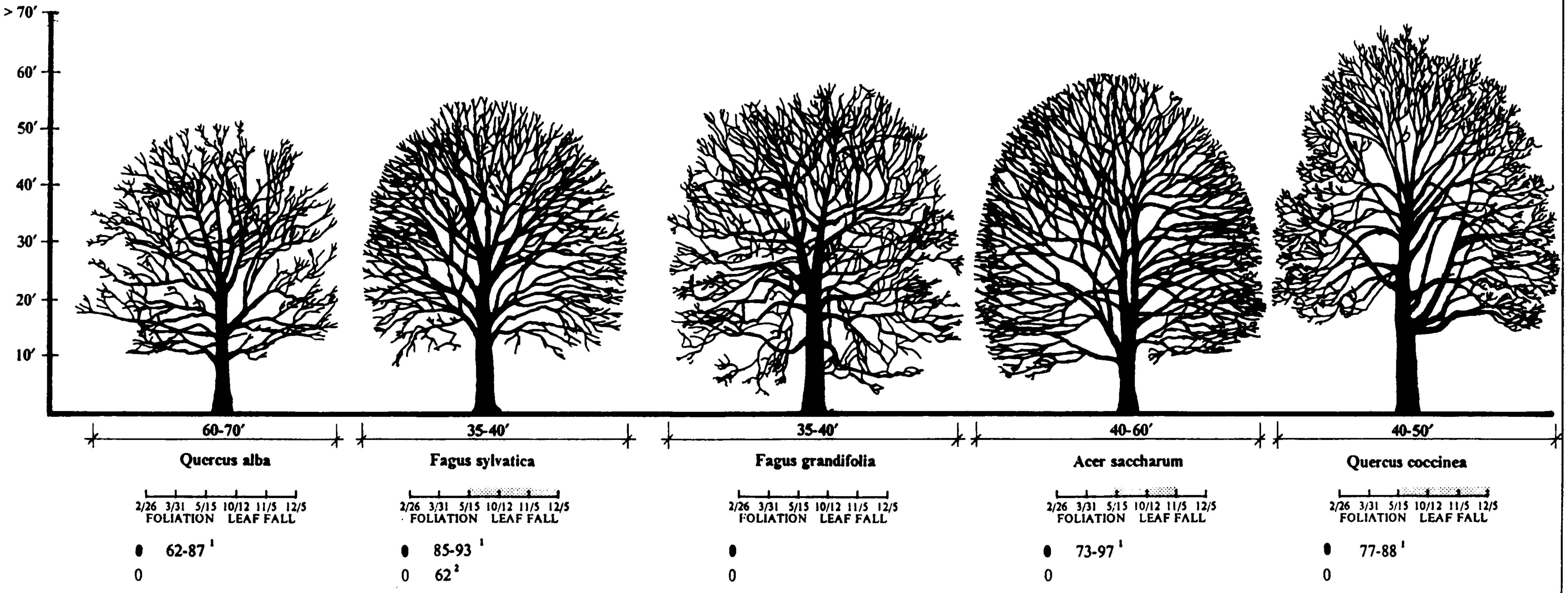


Figure 24. Tree typology

LARGE CIRCULAR TREE FORMS

[1] Moffat, Schiler, 1981 pp. 181-183

[2] Johnson et al, 1979

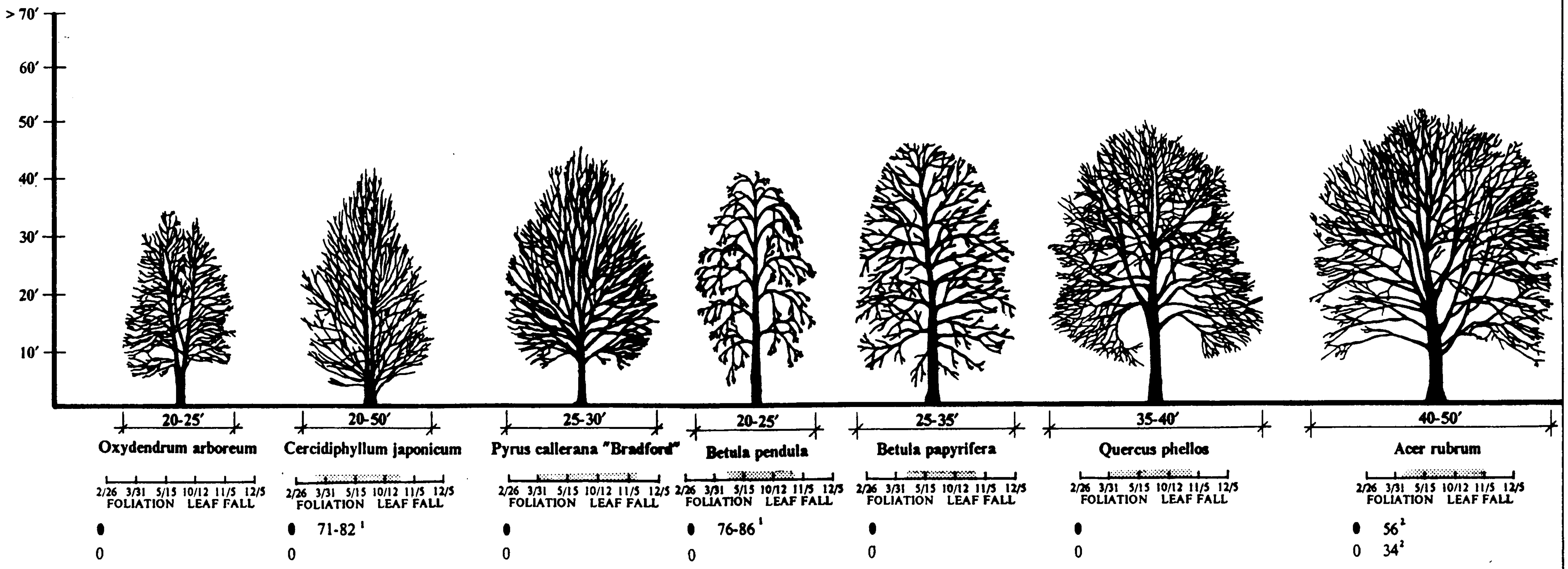


Figure 25. Tree typology

MEDIUM ELLIPTIC/OVAL TREE FORMS

[1] Moffat, Schiler, 1981 pp. 181-183

[2] Johnson et al, 1979

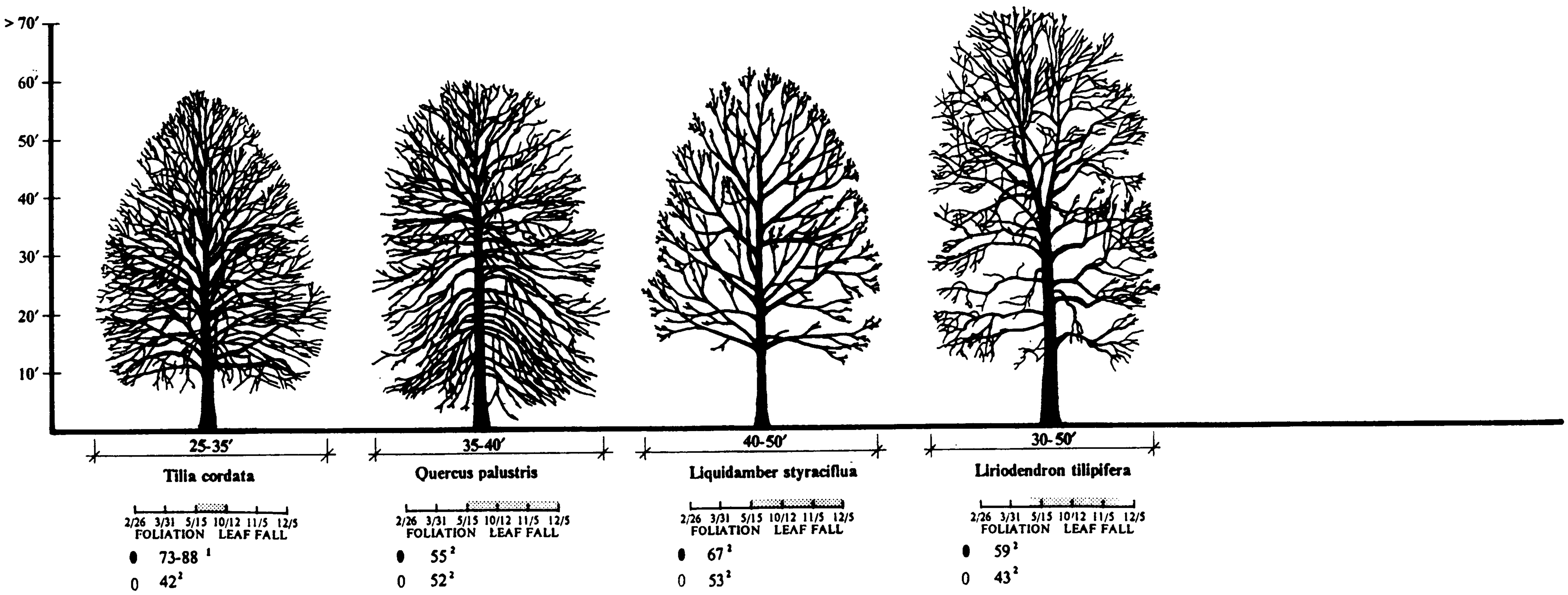


Figure 26. Tree typology

LARGE ELLIPTIC/OVAL TREE FORMS

[1] Moffat, Schiler, 1981 pp. 181-183

[2] Johnson et al, 1979

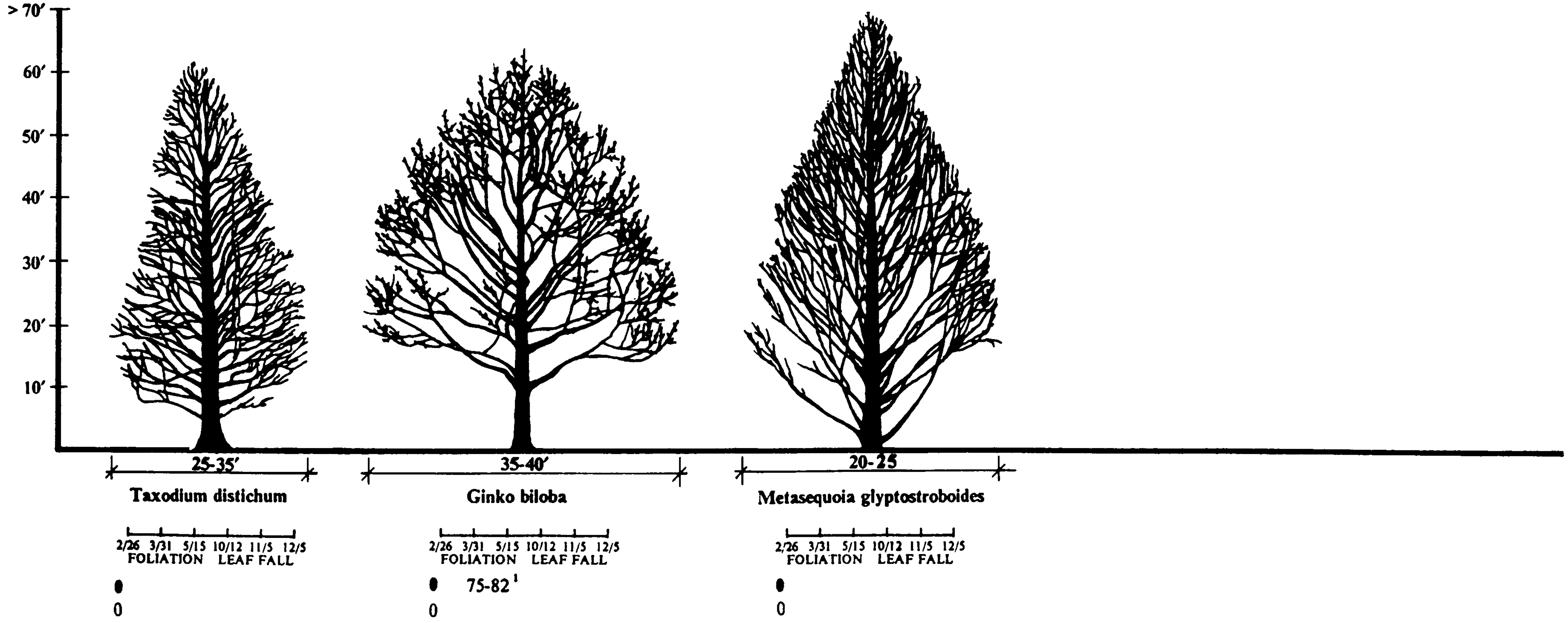


Figure 27. Tree typology

LARGE PYRAMIDAL TREE FORMS

[1] Moffat, Schiler, 1981 pp. 181-183

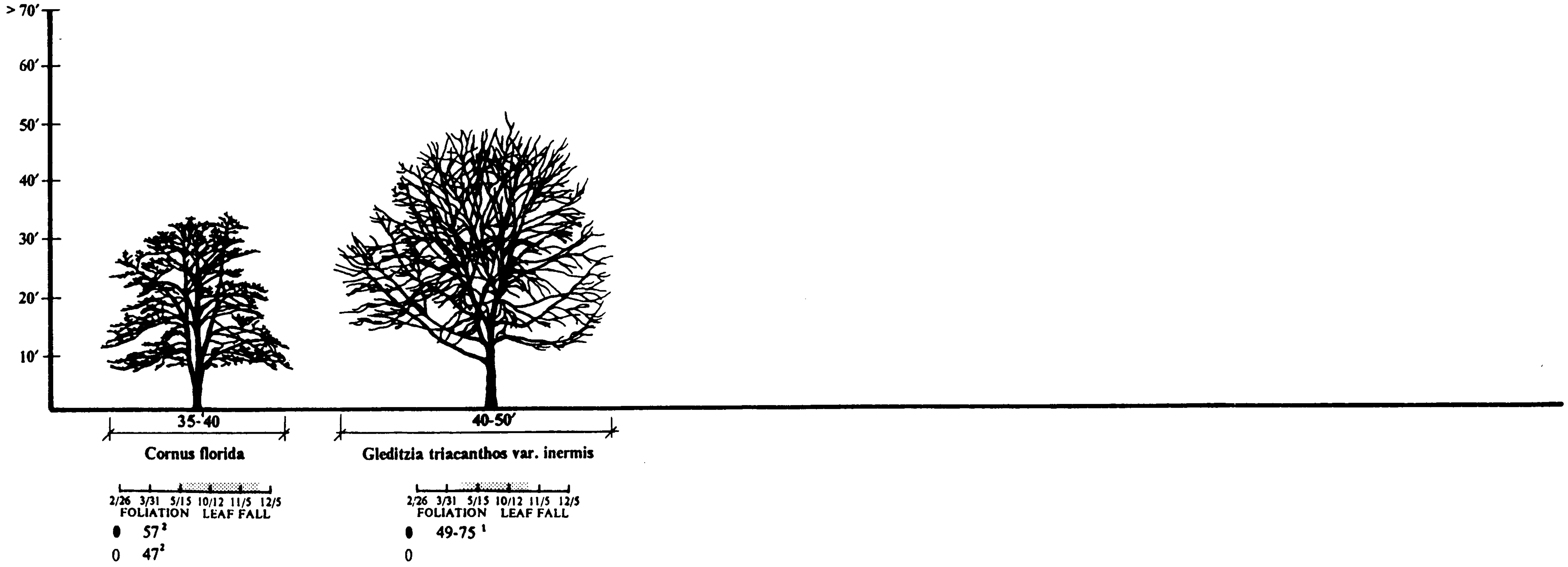
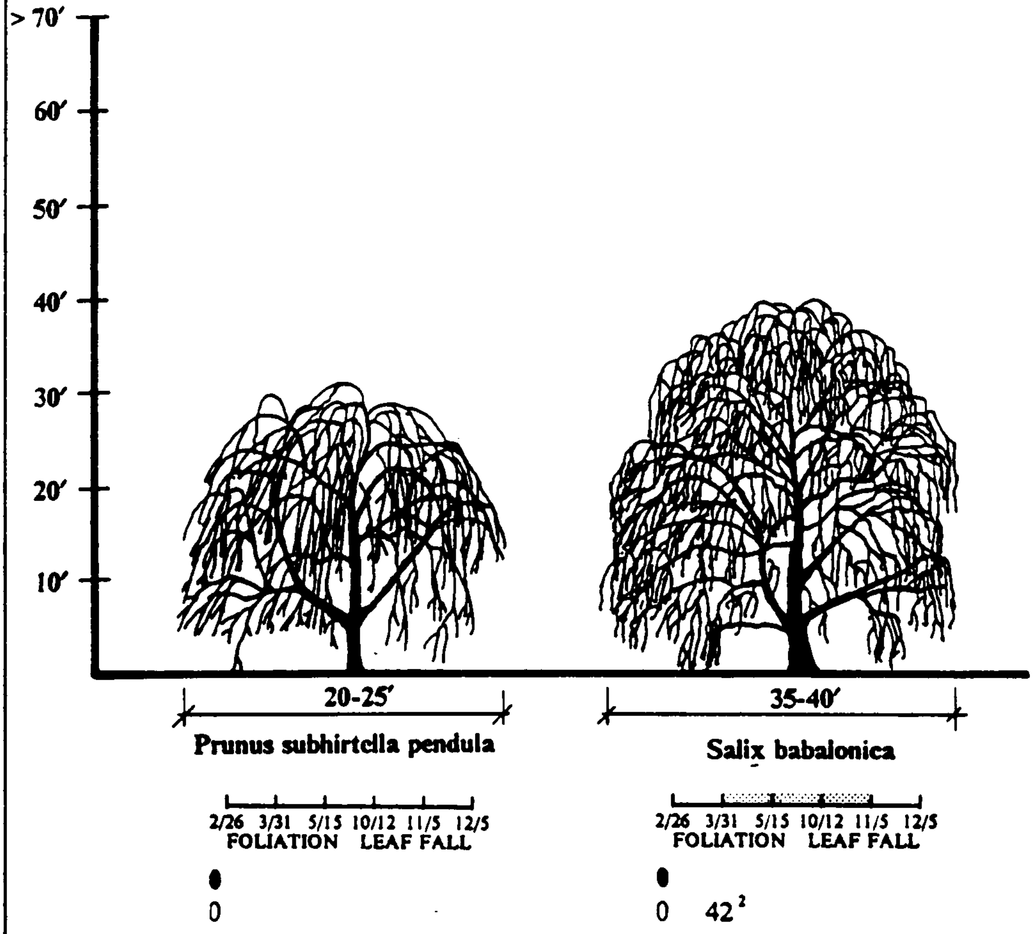


Figure 28. Tree typology

MEDIUM IRREGULAR TREE FORMS

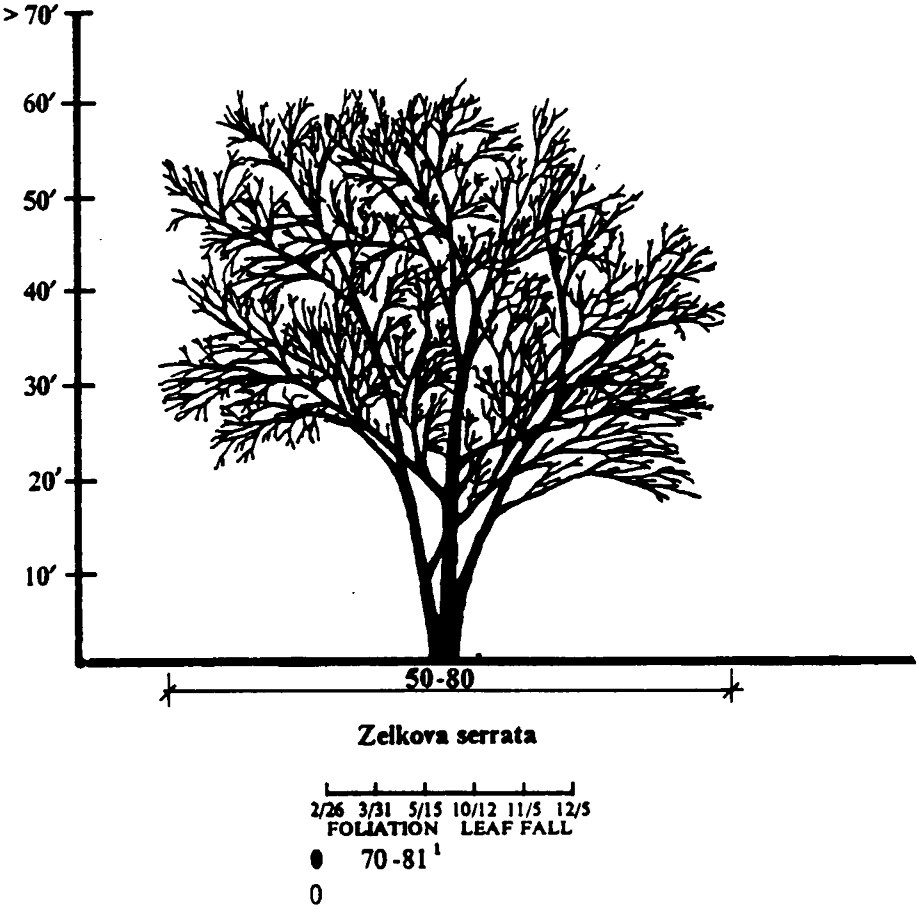
[1] Moffat, Schiler, 1981 pp. 181-183
[2] Johnson et al, 1979



MEDIUM WEEPING TREE FORMS

Figure 29. Tree typology

[2] Johnson et al, 1979



LARGE UMBRELLA TREE FORMS

Figure 30. Tree typology ¹Moffat, Schiler, 1981 pp. 181-183

CHAPTER VI

SUMMARY/FUTURE RESEARCH

In summary, it was observed that a shading density pattern does exist within the entire tree shadow pattern. The lack of symmetry between the NW and NE halves of the shadow patterns may have resulted from unselective pruning by either winds or golf balls. This investigation further demonstrated that the shadow contour patterning was not the same between trees of the same species and form. Please note, though, that this study did not control for the variables of solar altitude or tree age. There were, however, some similarities within areas of the tree contour shadow patterns, including a compacting of the contours in the northern area of the shadow patterns and along the outer edges of the shadow patterns. Also, the greatest density in the entire tree shadow patterns lyed along the tree driplines.

In the area of applied research, it was found that insolation and heat gain can vary dramatically depending on the tree and window positioning. Of the two window positions studied, the less desirable position in the Sugar Maple's shadow was due north and in the noon shadow. Although data is sparse, visual analysis of the contour diagrams demonstrate that trees planted on the east or western sides of a structure may not be as reliable as currently thought, for solar heat gain in the winter mornings or evenings. Foremost, this investigation developed the tree typology which aids designers to select trees for energy conserving landscapes.

After reviewing the presentation, findings and interpretations of this investigation, several questions remain unanswered. The following list provides some suggestions for continuing research in the area of energy conserving landscapes. These, again, have been divided into the two categories of basic and applied research.

BASIC RESEARCH

- Repeat this experiment to determine the reliability and validity of the investigation and its results. Trees need to be studied in pairs to control for the change of solar altitude, and to be able to compare between the tree shadow contour diagrams.
- Extend the investigation over the leafless period to determine the effects of solar altitude on the shadow contour diagram.
- Investigate trees from other form categories to determine if there is any substantial relationship or differences between forms.
- Studies on the effects of wind on tree insolation, and upon their shadow contour diagrams.
- Studies to determine if any differences arise between the shadow contour patterns if data was collected from 9:00 am to 3:00 pm for each point rather than during the shading period only.

APPLIED RESEARCH

- Studies on the effects of trees on heat loss as a result of winds.
- Transfer the typology into a computer form which can be utilized by designers.
- Although two window positions have been studied, other window positions need to be studied to determine energy variations as a result of location.
- Additional studies need to be conducted on the insolation effects upon the east and west wall exposures.

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APPENDIX A

In analysis of data from this investigation, percent horizontal insolation blockage was transposed onto vertical surface insolation data. Performing this analysis, the accuracy needed to be determined. This was accomplished by manipulating equations found in Solar Energy Thermal Processes.

Ht = Hb x Rb + Hd

Ht = Insolation on a surface at x° from a horizontal surface.
Hb = Direct beam radiation on a horizontal surface.
Rb = beam correction factor.
Hd = Diffuse beam radiation on a horizontal surface.

- Measurements from control and shaded instruments on Feb. 26 were broken down to Langleys for one hour between 12:00 and 1:00.

  Control instrument = 68.4 Langleys
  Shaded instrument = 39.92 Langleys

- These were broken down to their diffuse (Hd) and Direct (Hb) beam radiation. The radiation breakdown for Hd and Hb was estimated. Two estimates were used to test how much variation arose between the two different assumptions. The first estimate was divided into 90% direct and 10% diffuse beam radiation. The second estimate divided the beam radiation into 80% direct and 20% diffuse. The estimates were multiplied by the 12:00 Langley readings of the control and shaded instruments to produce the following direct and diffuse beam radiation divisions.

90/10	80/20
H = Hb + Hd	H = Hb + Hd
Control 68.4 = 61.56 + 6.84	Control 68.4 = 54.72 + 13.68
Shaded 39.92 = 35.93 + 3.992	Shaded 39.92 = 31.94 + 7.98

- The beam correlation factor (Rb) was calculated with the following equation.

$$Rb = \frac{\cos(\phi - s)\cos\delta\cos w + \sin(\phi - s)\sin\delta}{\phi\cos\delta\cos w + \sin\phi\sin\delta}$$

ϕ = Latitude
s = Degree of declination from horizontal surface
δ = Solar declination
w = Hour angle (15^0 each hour away from noon. Positive morning, negative afternoon).

δ = -9.415
s = 90^0
ϕ = 37.3^0
w = -15

Rb = .1974948

- The previous data was then calculated to determine insolation of a vertical surface.

90/10 beam distribution
0.1974948 x 35.93 + 3.942 = 11.088
0.1974948 x 61.56 + 6.84 = 18.998
11.088/18.998 = 58.36%

80/20 beam distribution
0.1974948 x 31.94 + 7.98 = 14.29
0.1974948 x 54.72 + 13.68 = 24.49
14.29/24.49 = 58.35%

- These vertical percentages were then compared to the actual measured horizontal percentages of blocked insolation for that hour. This provided an accuracy measure for the transposing of the horizontal readings to vertical. If the ratio of insolation transmission is within 10% between the horizontal and vertical measurements, we will accept the test that we can safely transpose horizontal data to vertical surfaces. As the ratios demonstrate, the transposing of horizontal data to vertical surfaces can be accepted.

Horizontal ratio	Vertical ratios	
Actual measurement	90/10	80/20
53%	58%	58%