SHADOS: A COMPUTER MODEL TO SIMULATE LIGHT ENERGY DISTRIBUTION IN SMALL FOREST OPENINGS

Burnell C. Fischer

and

Clair Merritt

Department of Forestry and Natural Resources
Purdue University
West Lafayette, Indiana 47907

ABSTRACT

Small forest openings contain microclimates which are distinctly different from those found either in open conditions or under continuous forest canopies. These unique microclimates are desirable for several management objectives and are subject to manipulation through appropriate cutting procedures. A computer model, titled SHADOS, has been developed to predict the sun-shadow pattern on the floor of openings of any size, shape and orientation, and for any time of day. The model can also calculate direct, diffuse and total light energy impinging on any given point on an opening floor for instantaneous or integrated time periods. The model has been successfully tested against measured solar radiation in a small forest opening. Two examples of program use are described.

INTRODUCTION

Small forest openings whether man-made or natural contain certain unique microclimates which are distinctly different from that found under a continuous forest canopy. In a sense small forest openings have a self-contained "edge effect" which can be beneficial to certain plants and animals, and which can be utilized as a vegetation manipulation technique by man. This, of course, is not a newly recognized concept. Foresters and wildlife managers have long made use of small openings for regenerating certain tree species and for creating favorable wildlife habitats. The trend towards reducing the size of clear-cuts and the increased use of the selection reproduction method in Central Hardwoods has emphasized the need to understand these microclimates in more detail so that closer control can be obtained in management situations.

Two basic approaches have been employed in the past to evaluate forest openings. The most widely used is descriptive in nature. This approach involves cutting forest openings of various sizes, shapes, and orientations in specific forest situations and then observing reactions within the opening, such as species distribution, plant growth, or snowmelt, to the complex set of environmental conditions which have been created. Despite the popularity of this approach, results continue to be less than conclusive.

The second approach, which has been taken in this paper, is more analytical in nature. Utilizing background information provided by descriptive studies, carefully designed experiments are constructed to gather data concerning one or more specific environmental factors. These data then provide a more quantitative basis for establishment of management strategy.

Since solar energy is the primary driving force for all ecosystems, the amount and distribution of solar energy entering any environment greatly affects the characteristics of that environment. One of the more obvious differences between the floor of a forest opening and the floor under a dense forest canopy is the level of solar energy received. Although a considerable body of knowledge concerning solar energy in the natural forest environment has accumulated in the past 50 to 60 years, little forest research has been devoted to determining

the levels and distribution of solar energy within forest openings. Instead, most studies of solar energy have been concerned with characterizing light regimes above, within and below forest canopies (Anderson, 1964; Reifsnyder and Lull, 1965; Reifsnyder, 1967; Muller, 1971; and Hutchison and Matt, 1977).

Forest researchers have conducted a variety of studies relating to forest openings. Geiger (1965) discussed the difference in environmental conditions between the floor of a forest stand and the nearby forest edge and then expanded this discussion by describing the unique environmental conditions in small forest openings. Regeneration research by Leak and Wilson (1958), Barrett, et al. (1962) and Marquis (1965a, 1966) indicates that patch cuttings may be useful in establishing yellow birch, a heretofore difficult species to regenerate. Van Arsdel (1961) found that small openings which were smaller in diameter than the height of the surrounding timber favored blister rust infection in Lake States white pine. Johnson (1971), Schneider (1970) and Minckler et al. (1973) all studied hardwood establishment and growth in small openings finding that both midtolerants and tolerants did well. According to Johnson (1971), this indicates that improvement of species distribution in forest openings is possible.

McCaffery and Creed (1969) concluded that forest openings were significant to deer populations in northern Wisconsin. James and Cordell (1970) even found that visitors to campsites prefer partial shading over sunny or shaded locations, thus encouraging campground managers to manipulate vegetation. This could possibly be accomplished with judicious placement of small patch cuttings.

Halverson (1972), Halverson and Smith (1974), Leaf and Brink (1972), and Satterlund and Haupt (1972) have shown how "designed" forest openings of particular size and dimensions may be useful in predicting snowmelt.

Though all of the above studies either directly or indirectly indicate that silvicultural manipulation to create small forest openings for partial shading may be beneficial to certain plant species and man, few measurements of solar energy patterns within small forest openings have actually been made. Berry (1964),

Clements (1966) and Roussel (1968) each recorded light measurements in small forest openings using photometric devices. Minckler (1961) and Minckler et al. (1973) sampled light energy distribution in 18 circular openings varying in size from ¼ to twice the height of the surrounding timber and encompassing three topographic positions. A Brockway light meter was used and sampling was conducted at 1½- and 2-hour intervals from 9 AM to 3 PM on a series of summer days. Five positions within each opening were sampled: the center, north, east, west and south edges.

Fairbairn (1963) recognized the importance of direct solar radiation and opening size on regeneration by developing a regeneration cutting classification system based on opening size. Marquis (1965b) stimulated interest in studying light in small forest openings by implying that foresters could design small clearcuttings to control the light regime for desired forest species. A series of studies at Purdue University under the direction of Clair Merritt was accordingly undertaken to produce a practical computer model of light distribution within small forest openings (Brown and Merritt, 1970; Burroughs, 1974; and Fischer, 1974). The model predicts the sun-shadow pattern on the floor of forest openings of any size, shape, aspect and slope, and for any selected time and day. In addition the computer model can calculate the direct, diffuse and total light energy received at any point on an opening floor for instantaneous or integrated time periods.

Development of the Model

Model development occurred in two stages. First, a computer model, called SHADOS, was developed to simulate sun-shadow patterns, and direct, diffuse and total light energy received by small forest openings. Secondly, methodologies were developed and utilized to intensively measure the light energy distribution in a small forest opening.

The original model was developed by Brown and Merritt (1970). Improvements were subsequently made by Burroughs (1974) and Fischer (1974). A graphical display subroutine was developed so that a two dimensional opening map showing opening perimeter coordinates, shadow projections and, if desired, points on the

opening floor could be computer drawn for any given time period. A solar calculator to estimate the direct and diffuse solar radiation in the atmosphere was also developed so that the total downcoming shortwave radiation is simulated for a clear day. Instantaneous direct solar radiation received by a point in the sun for a particular point is calculated using a formula by Fons et al. (1960). Instantaneous diffuse solar radiation at a point assuming clear sky conditions and no obstructions to the sky from zenith to the horizon in all directions is determined using a formula by List (1966). The SHADOS computer program can then calculate the amount of direct radiation a given point in the forest opening receives for the time period under consideration. Direct radiation is calculated by determining whether a given point on the opening floor is in the shade or sun for each sample time. When a point is found to be in the sun, the instantaneous direct beam solar radiation for that particular time is calculated and assumed for the entire time interval. A summation of direct energy is then derived for the total time period of interest.

The total amount of solar radiation received by a point in a forest opening can be determined by calculating the amount of diffuse sky radiation received and adding this to the direct radiation total. Diffuse sky radiation is determined by using the view factor concept. Reifsnyder and Lull (1965) utilize the term "view factor" to designate that fraction of the total sky any point on the opening floor "sees." The mathematical calculation of view factors is extremely difficult in any but the simplist situations and always time consuming. However, it is this fraction of the total sky that represents the approximate fraction of diffuse solar radiation that any point on the floor of an opening actually receives as diffuse sky radiation, assuming the sky is a uniform source of diffuse solar radiation.

Two methods of view factor determination were tested. These methods are the photographic determination using a fisheye lens (Anderson, 1971) and the mathematical determination using a computer program entitled Confac I written by Toups (1965).

Although fisheye photos record the true view factors of points on the opening floor, the technique was found unsatisfactory.

The second technique for determining view factors involved the computer program of Toups. This Fortran IV program permits simultaneous calculation of a large systematic grid of view factors for any forest opening. Data entry is simple requiring only the dimension of the opening floor on a coordinate system as one surface and the coordinates and height of the surrounding perimeter trees as a second surface.

Careful determination of the height and perimeter location of the "effective canopy", that is, the location of the actual shadow projection point of each perimeter tree, resulted in close agreement between the photographic and mathematical view factors.

The amount of diffuse sky radiation received by each point is determined by multiplying its view factor, previously calculated and read into the program, times the total amount of diffuse solar radiation available for the time period under consideration. This quantity of energy is then added to the direct beam energy received for each point to arrive at a total energy value for that point.

In addition, the program also divides the direct and total energy received at each point by the total amount of direct and total energy available to determine the percentages of energy received.

Two other possible sources of light energy impinging on the floor of forest openings, i.e., direct and diffuse canopy radiation, were determined to be not significant for model development. Direct canopy radiation, i.e., sunflecks, was extremely variable and confined to a relatively small area in the opening for any point in time. Diffuse canopy radiation was found to comprise a very small portion of the total light energy at the opening floor.

Testing the Model

The model was successfully tested against light energy data collected in a small rectangular opening cut in a red pine stand at the Cunningham Forest near West Lafayette, Indiana. Using anthracene-in-benzene chemical light meters and an Eppley

pyranometer, measurements were taken during eleven clear sky periods for one-half and whole-day integrations. The chemical light meters were found to correlate well with the Eppley and could sample a large number of locations simultaneously and inexpensively (Fischer and Merritt, 1973). For ease of display and analysis the energy values were converted to relative energy values by dividing by the total solar radiation received above the canopy for the particular time period involved. Relative energy values were then multiplied by 100 to convert to percentages. These percentages for each energy period were then contour mapped on a 5% contour interval. An example of one of the energy periods is shown in Figure 1.

As might be expected, patterns of observed shortwave energy distribution in the forest opening were similar in all measurement periods. The shaded southern portion of the opening received the lowest levels of energy and the center of the opening received the highest levels of energy. Sun-shadow lines cast by the tops of the east, west and south perimeter trees were recognized as areas of fluctuating energy levels because of direct canopy radiation, i.e., sunflecks. The sun-shade line cast by the south side of the opening remained relatively stationary throughout a given solar day. This resulted in a narrow east-west band on the floor of the opening with a rapid transition from low to high energy across the width of the band. The sun-shade lines cast by the east and west stand boundaries, on the other hand, moved rapidly across the opening and resulted in a uniform distribution of sunflecks across the opening floor.

Comparison of the patterns with Minckler's work (1961, 1973) show marked agreement. In his openings of size 1H and larger, the center received the most light followed by the north, west, east and south edges. In 1½H openings, which was the size of the Cunningham Forest opening, Minckler observed the center to receive 70 percent full light, the north about 65 percent, the west and east about 35 to 45 percent and the south about 15 to 20 percent. Though these ranges show close agreement with the Cunningham data, the results appear to be about 10 percent higher at each location. This difference is related to the sampling procedures used by Minckler. While the Cunningham data are based on day-long integrations, Minckler's data were taken only during the relative high energy periods near the middle of the day when most of the opening is immersed in direct-beam radiation thus giving higher percentages of total light.

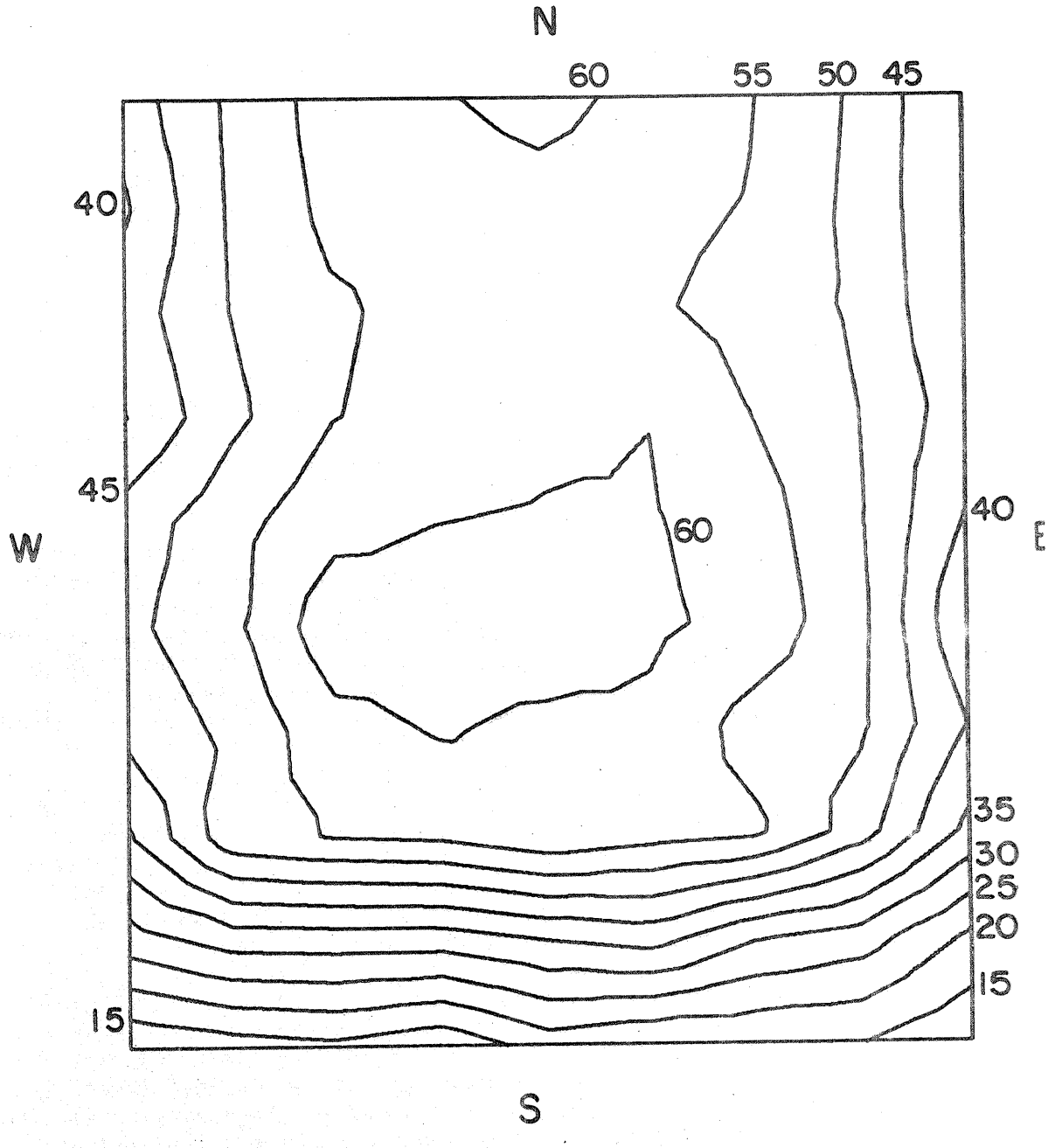

Figure 1. Contour map of measured solar radiation expressed in percent of total solar radiation for the Cunningham Forest opening for June 10, 1973. Scale: 1 in. = 10 ft.

Other tests of SHADOS by Burroughs (1974) using data provided by E. H. Tryon of West Virginia University further confirmed the accuracy of the model.

Comparison of measured solar radiation values with those estimated by SHADOS shows that the light energy distribution in a small forest opening can be successfully simulated (Figure 2). However, two small areas of the opening floor proved particularly difficult to simulate. The shadow cast by the top few feet of the southern perimeter trees, a narrow "gray" band characterized by many sunflecks, was found difficult to approximate and could not be accurately modeled. The second area of the opening floor found difficult to model was that zone along the edges of the opening where direct radiation is reduced by the lateral extension of lower branches. This constitutes a very small proportion of most forest openings although it is obviously an important factor in very small forest gaps where the edge dominates the gap. This is ignored in the model.

Applications of the Model

The model is based upon three coordinate axes and two assumptions concerning the physical characteristics of the opening. The axes are oriented with the positive y-axis toward the north and the positive x-axis toward the east and the positive z-axis toward the zenith. It is assumed that the projection of the opening in the xy-plane can be approximated by a polygon. It is also assumed that the opening floor consists of a set of points F such that every point (x, y, z) in F has the property that $z = f(x, y)$, where f is an appropriate function.

The program assumptions and constraints, and the input data necessary to successfully run the SHADOS program are clearly defined by introductory comment cards in the program listing. The required input data are the coordinates and heights of the trees defining the opening boundary, slope, aspect, latitude, the day of the year, time interval of interest and the coordinates of the points on the opening floor where energy sums are of interest.

Two examples showing the applicability of SHADOS to forest management problems are given below.

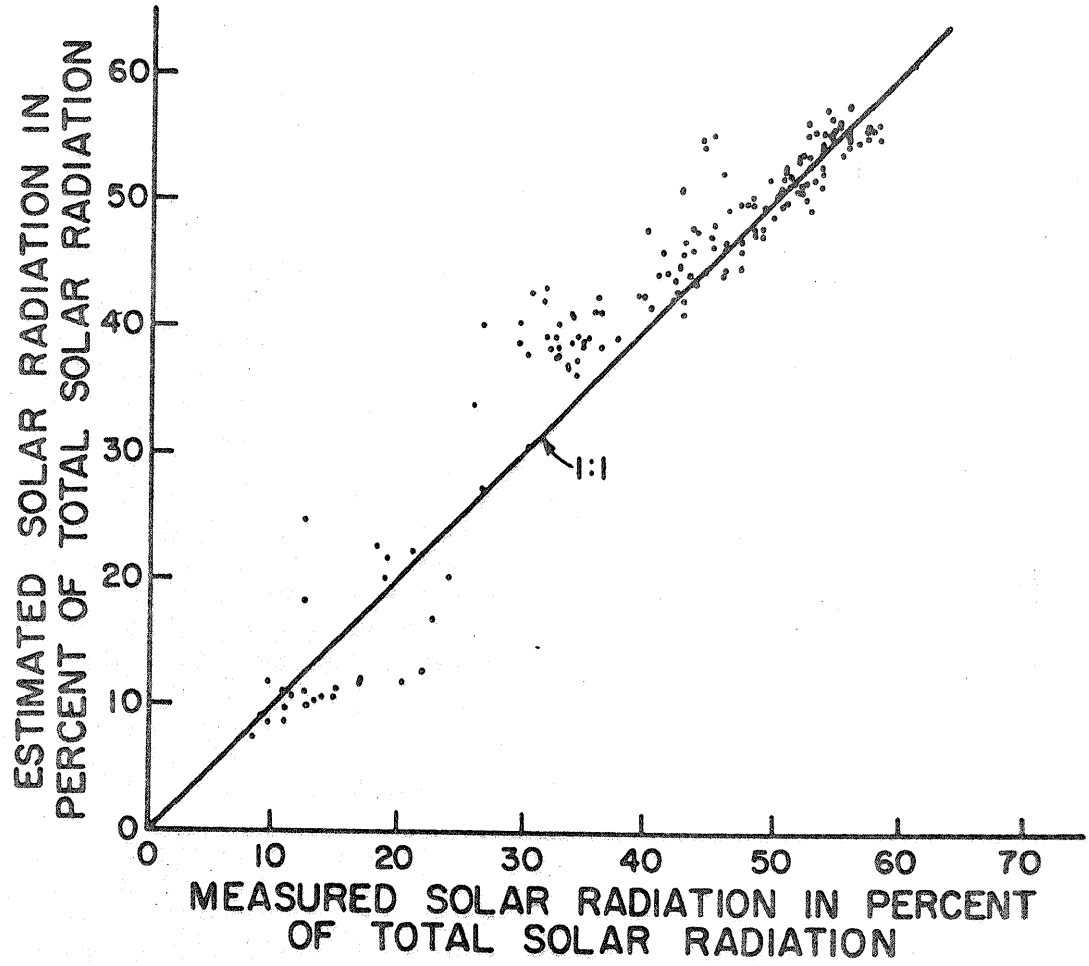

Figure 2. Scatter diagram of estimated versus mean measured solar radiation for the effective canopy height model. Measured values are means of August 3-5, 1973, for the Cunningham Forest opening. Estimates are based on .55 atmospheric transmission coefficient and 15 minute time interval.

Example 1

A natural resource manager wishes to compare light energy distributions in circular clearcut forest openings 50 feet in diameter varying in perimeter tree heights, slope and aspect. A 50 foot diameter opening is approximately 0.045 acres in area and represents the average crown area of two 20-inch DBH upland oaks in a fully stocked stand.[1] Table 1 gives the various opening parameters and the associated direct energy distributions on the forest floor.

As is shown in Table 1, change in perimeter canopy height is the main factor influencing distribution of direct solar radiation in this example. Slope and aspect appear to have less influence although 15 degrees is a modest slope. An opening with an effective size of only ½H would be quite limiting to species needing full sunlight. If the perimeter trees surrounding a circular forest opening are 100 feet tall and large amounts of direct sunlight are needed to provide the best growing conditions for an intolerant or midtolerant species, a minimum opening size of 2H or approximately 200 feet in diameter would be necessary. This size opening represents an area of approximately 0.72 acres or the combined crown area of thirty-two 20-inch DBH upland oaks in a fully stocked stand.

Example 2

Foresters in the Central Hardwoods rarely deal with forest cuttings of regular dimensions. These more complex openings are the result of variable topography, erratic tree size distributions and the non-timber objectives of small, private nonindustrial woodland owners.

An example of such an actual irregular opening is shown in Figure 3. This opening is 0.54 acres in size with a southwest aspect (220°) and a slope of 10 degrees. The perimeter timber

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[1]Ashley, B. 1978. Personal Communication.

Table 1. Direct energy distributions for circular forest openings, 50 feet in diameter, of varying perimeter tree heights, slopes and aspects. Distributions are expressed in percentages of opening floor receiving direct sunlight and are calculated for May 24, 1978 at latitude 40°14' between 8:00 AM and 4:00 PM solar time.

Perimeter tree height in feet	Opening size in tree heights (H)	Slope degrees	Aspect in degrees of north zenith	Percentage of opening floor receiving No direct sunlight	1-25	26-50	51-75	>75
25	2H	0	0	14	0	10	66	10
25	2H	15	0	14	0	10	66	10
25	2H	15	180	14	0	10	52	24
50	1H	0	0	38	0	62		
50	1H	15	0	38	24	38		
50	1H	15	180	33	5	62		
100	½H	0	0	86	14			
100	½H	15	0	86	14			
100	½H	15	180	62	48			

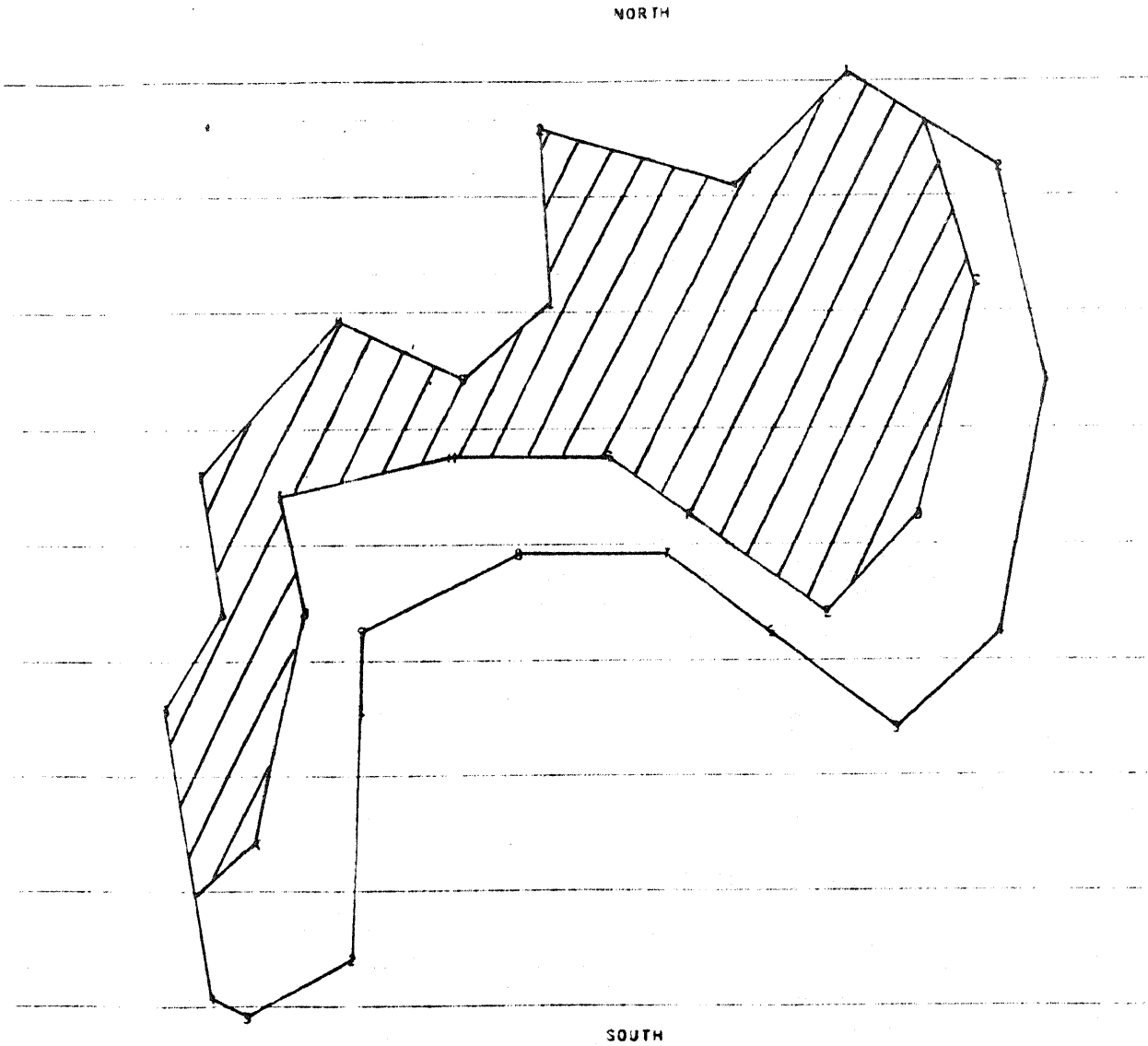

Figure 3. Shadow simulation by SHADOS of cut forest opening on a Tree Farm in Indiana. Striped portion of opening is in direct sunlight at 11:00 AM solar time on May 24.

stand is a mixture of yellow-poplar, hickory, sassfras, basswood and red, white and black oak of sawtimber size (20" + DBH) averaging about 70 feet in height. Opening dimensions are approximately 1H in the north-south axis and 2H in an east-west axis. The opening was divided into equal area quadrats and the direct solar radiation received was calculated for each quadrat for seven day-length periods at two week intervals from March 29 through June 21. The results of this sampling are given in Table 2.

These results show the low levels of direct solar radiation available for plant growth at the forest opening floor. Even though seedlings of many tree species benefit from partial shading, growth of the valuable upland central hardwoods such as black walnut, white ash, black cherry, yellow-poplar and the oaks is generally regarded to be maximized in full or nearly full sunlight. However, forest openings of the dimensions illustrated in this example, although appearing to be of sufficient total area, are not likely to achieve optimum light levels for maximum seedling growth.

Table 2. Distribution of direct solar radiation on the floor of an opening cut in a Tree Farm in Indiana.

Percent of Direct Solar Radiation Available	Percent of Opening Floor
0	28%
1 - 10%	28%
11 - 20%	19%
21 - 30%	11%
31 - 40%	15%

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