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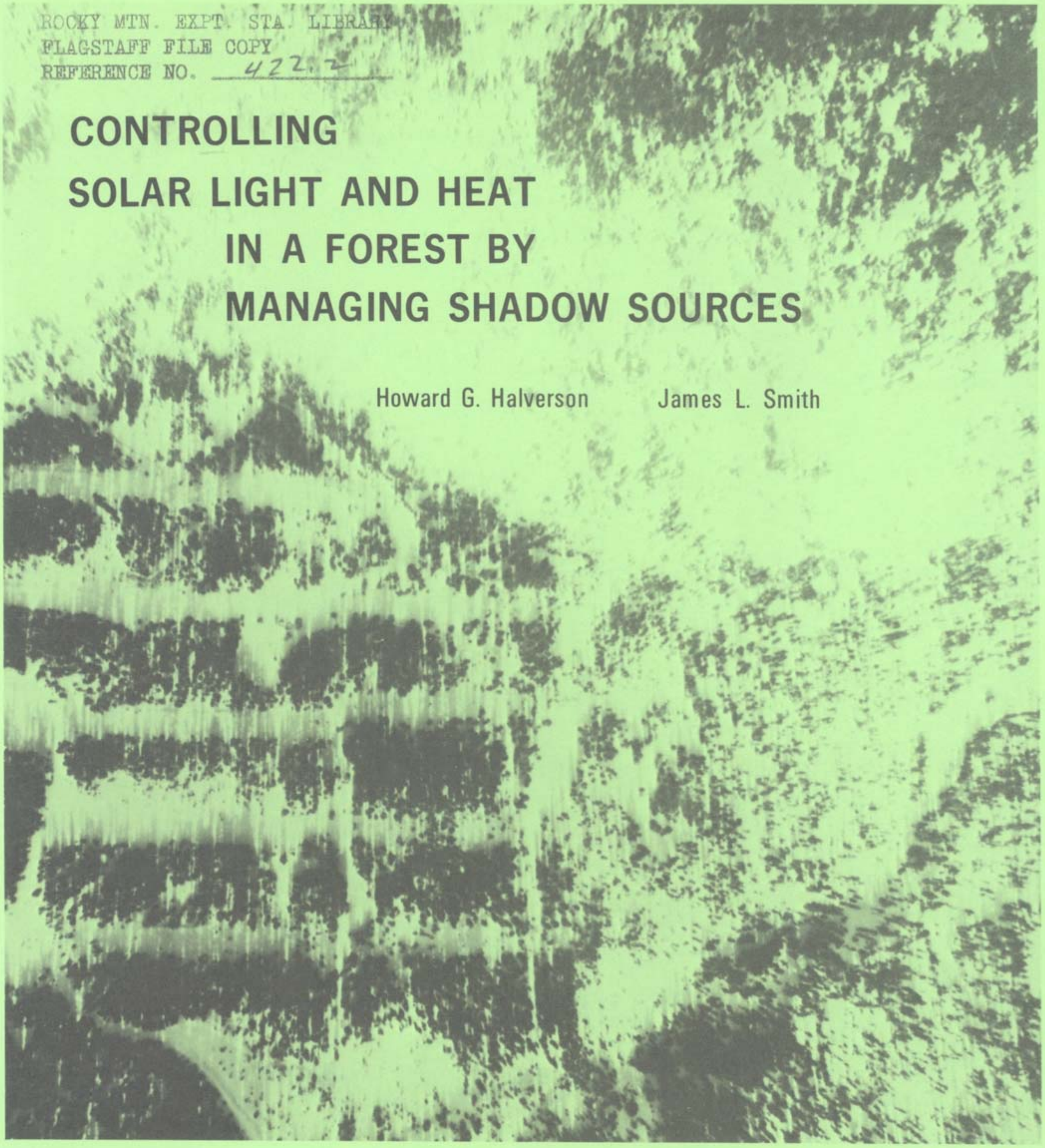

CONTROLLING SOLAR LIGHT AND HEAT IN A FOREST BY MANAGING SHADOW SOURCES

Howard G. Halverson James L. Smith

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Appendix

The Authors

are assigned to the Station's research unit on water yield improvement in the conifer zone, with headquarters in Berkeley, California. **HOWARD G. HALVERSON** earned a bachelor of science degree in forest management at Iowa State University (1960), and master's and doctor's degrees in watershed management at the University of Arizona (1962, 1971). He joined the Station staff in 1965. **JAMES L. SMITH,** in charge of the unit, earned undergraduate degrees in forest management and general agriculture (1949, 1951) and a master's degree in soils and silviculture (1950) at the University of Georgia. He received a doctorate from Michigan State University in 1954, and a year later joined the Forest Service. He became a member of the Station staff in 1963.

SUMMARY

Halverson, Howard G., and James L. Smith
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Solar radiation incident to the soil, snow surface, or boles of border trees in a timber harvest area is an important environmental factor. Incident solar radiation creates a secondary form of radiation which affects the forest. Objects, even air, which are warmed by absorbing solar radiation, emit longwave radiation at increasing intensity as their temperature rises. Since solar insolation is the primary energy source for processes such as forest development and snowmelt, controlling solar exposure is a realistic way to develop a desirable environment within the forest. Timber harvests can be designed to exert some control over insolation within a forest opening. By managing forests, we can control the presence or absence of shadows at a site during critical time periods. The shadow patterns developed provide a direct means of reducing or increasing solar insolation.

The forest manager must determine what level of solar insolation is necessary to reach the management objectives. The season or dates that are critical must also be determined. The shadow lengths can be integrated with site information to help develop a management scheme. By the computer method presented here, the shadow extent in an opening can be determined using readily available data. Inputs are the latitude, east and south slope components of the site, date expressed as day number, and the desired time interval between shadow calculations. Outputs include shadow lengths, given as totals and as east-west and north-south components for each time interval, as well as the azimuth of the sun. With this information the shadow pattern from a residual stand can be determined before the harvest.

Examination of snow accumulation and ablation patterns in a group of cut strips in California illustrates how shadows can be used in snow management. Two-chain wide cut strips extending north-south and east-west were compared during a snow season. Accumulation patterns were similar. Snow and tree boles at the north boundary were exposed to solar radiation throughout the day on the east-west strips. The exposure to shortwave and reradiated longwave resulted in accelerated snowmelt along the north boundary. On the strips oriented north-south, the snowmelt pattern across the strip was more even, with less melt near the borders than was evident near the north border of the east-west strip. When the snow water content was reduced to 2 inches concentrated along the south boundary of the east-west strip, there were 10 inches of water evenly distributed on the north-south opening. The snow study showed that the energy regime was more uniform across the openings oriented north-south, and that the reduced radiation level delayed snowmelt.

Snow management is only one of several applications of shadow information. The size, shape, and orientation of openings can be designed to encourage reproduction, prevent changes in stream temperature, control soil surface temperature, and control other processes dependent on solar light and heat.

Shadow length tables can be developed for a specific site by the resource manager. A series of eight sets of shadow length tables is available as a supplement to this report. The tables are issued for even latitudes between 36° and 50° N. Slope inclinations up to 40° in both north-south and east-west directions are covered for each latitude. Interpolation for intermediate latitudes and slopes will make these tables applicable to most forest situations.

For optimum growth, a forest needs the right amount of solar light and heat. Solar radiation affects transpiration, evaporation, temperature, soil moisture, oxidation of organic matter, plant growth, and snow ablation. If the forest manager could control solar light and heat, he might be able to develop a more favorable growth environment. Through silvicultural practices, he could favor certain tree species over others. Available browse could be increased for wildlife. Fish habitat could be enhanced by regulating stream temperatures. Soil moisture and snow accumulation or ablation could be altered by cultural patterns.

The amount of direct sunlight allowed to reach the soil or snow surface and tree boles will vary according to the timber harvest method used. Clearcutting large areas results in maximum exposure to shortwave radiation. Selection cutting results in minimum increase in solar energy below the remaining canopy. Strip or small-patch cutting can be designed to control light exposure and subsequent heat exposure in the openings and near the border. Size and shape of cuttings can be varied so as to fully expose or fully shade the soil or snow surface in an opening and tree boles on the sides of the opening.

Timber harvests of various forms, sizes, and orientations have been proposed to meet snow management needs (Anderson 1963, Berndt 1965, Church 1933, Kittredge 1953). But most harvests are designed without full consideration of how the resultant opening will affect the radiation level in the opening and in the forest near the borders.

Shadows cast by surrounding trees partially control the amount of heat and light reaching the surface or tree boles. Length of shadows at the time maximum control is desired largely determines the size of a harvest opening. Shadow length and direction for trees of the same height vary according to aspect, slope, latitude, time of day, and time of year. By knowing in advance the shading patterns and light conditions in openings, the forest manager can plan more effectively for reaching a specific management objective.

This paper describes a computerized technique for determining the shadow length and direction for a tree of any height in any location between 23.45° N. latitude and 50° N. latitude. The method is applicable to any aspect, slope, time of day, and time of year.

For those who do not wish to develop their own, a set of eight tables has been prepared. These "Shadow Length Tables for Environmental Planning" are available for individual latitudes – 36, 38, 40, 42, 44, 46, 48, and 50 – or as a complete set and may be secured upon request to: Director, Pacific Southwest Forest and Range Experiment Station, P.O. Box 245, Berkeley, California 94701, Attention: Publications. The tables cover the contiguous United States from 36° N. latitude to 50° N. latitude in 2-degree increments.

Each set of the eight tables consists of 175 individual tables. By extrapolation, they can be used from the Mexican to the Canadian border. Each table lists shadow lengths for latitude by seven monthly intervals – beginning on December 22 (shortest day of the year) and ending June 22 (longest day of the year). The tables can also be used to determine shadow lengths for the period June 22 to December 22 by reversing the dates, because the sun paths are the same moving south in summer and moving north in winter. Slopes covered in the tables are 0°, 20°, and 40° in 25 combinations of north-south and east-west aspects for each date.

SOLAR RADIATION

Several conditions regulate the amount of direct solar radiation and the reradiated longwave energy from tree boles. These include latitude of the site, date translated into position of the sun, aspect, slope angle, and vegetation present. Four conditions are fixed: latitude, date, aspect, and slope angle. The vegetation can be managed to control partially the amount of radiation reaching the soil or snow surface and to alter the microclimate in a desired direction.

The radiation reaching the soil or snow surface is a combination of direct and scattered shortwave radiation from the sun, atmospherically diffused shortwave radiation, and longwave radiation from tree boles or other nearby objects. When exposed to radiant solar energy, these objects are warmed and emit longwave radiation. The greater the mass of trees or other objects heated, the greater the radiation. Effects of accelerated snowmelt from this form of radiation have been observed as far as 200 feet south of a wall of timber.

Longwave radiation is an important energy source in the early melt season because snow is a black body in long wavelengths. Shortwave radiation is less important owing to the high reflectivity (albedo) of the snow surface – especially at low sun elevations.

Later in the melt season, albedo decreases as the snow structure changes, and as airborne detritus and plant debris accumulate on the surface. At that time, shortwave radiation also assumes a major role in snowmelt. Since the amount of light and heat reaching the forest floor or snow surface under forest cover is directly related to the amount of cover, changes in cover pattern and amount alter the heat-light regime.

PROCEDURE

The equations for calculating the total shadow length, north and east length components, and the sun azimuth were programmed in FORTRAN IV language. The computer program (Appendix) determines the time of sunrise, then begins listing three shadow components and sun azimuth. Computations continue at time intervals specified by the operator until sunset. Southerly vectors of the shadows (between March 22 and September 21) are listed as negative, and northerly shadow vectors are positive. Likewise, westerly shadow vectors (before noon) are positive and easterly shadow vectors are negative. A reversal of either sign convention means the sun is not visible from the site at the time, and all shadows should be considered infinite. The times listed on the program output are true solar times; the Appendix includes a procedure to convert to local standard time.

The program and three data cards are required to generate shadow information for any combination of date, aspect, and latitude within the program limits. Aspect is used here for a value that combines aspect and slope. The first data card transmits the following information:

Columns:	
1-10	Latitude of the site in degrees
11-20	Day number of the year (Julian date)
21-30	South slope angle in degrees
31-40	East slope angle in degrees
41-50	Time interval between shadow computations in hours

The time interval, in hours and decimal fractions, determines how frequently during the day the shadow length will be computed. The time interval must be listed, and although it is unlimited, intervals of one-half or 1 hour appear most useful. In every case, a decimal point must be included or the data punched in fields of 10.4.

The second data card – a title card – is printed directly on the output sheet. Up to 80 alphanumeric characters may be keypunched and will appear at the top of the output. This card may be left blank if desired, but a card must be in the deck. If more than one computation is to be made at the same time, several pairs of data cards in the proper order may be inserted.

The last data card lists an impossible latitude, 95°, to terminate calculations.

The latitude of the observer or site is listed in degrees and decimal fractions. The program is limited to 23.45° to 50° N. This coverage includes all of the United States except Alaska and Hawaii. The day number of the year (Julian date) follows and may range from 1 to 365. (The dates have been fitted to a mean year within each leap year cycle.) The year 1950 is used for general meteorological purposes (List 1958).

Any slope and aspect can be described by two angles, one in the north-south direction and the other in an east-west direction. The south slope angle, in degrees and decimal fractions, corrects for the north or south component of aspect. A positive angle is a northerly component; a negative angle is a southerly component. A similar angle system exists to correct for east and west components; a positive angle is a west component; a negative angle is an east component. Slope angles are limited to 90°.

The slope angles can be estimated from topographic snaps or measured on the site. However, if estimating is not practical and general slope and aspect data are on hand, the information in the Appendix can be used to convert slope inclinations in percent to slope in degrees. A method is included to convert the azimuth and inclination for the slope into the south and east vectors that will describe the slope and aspect of the site in the proper form for the shadow length program.

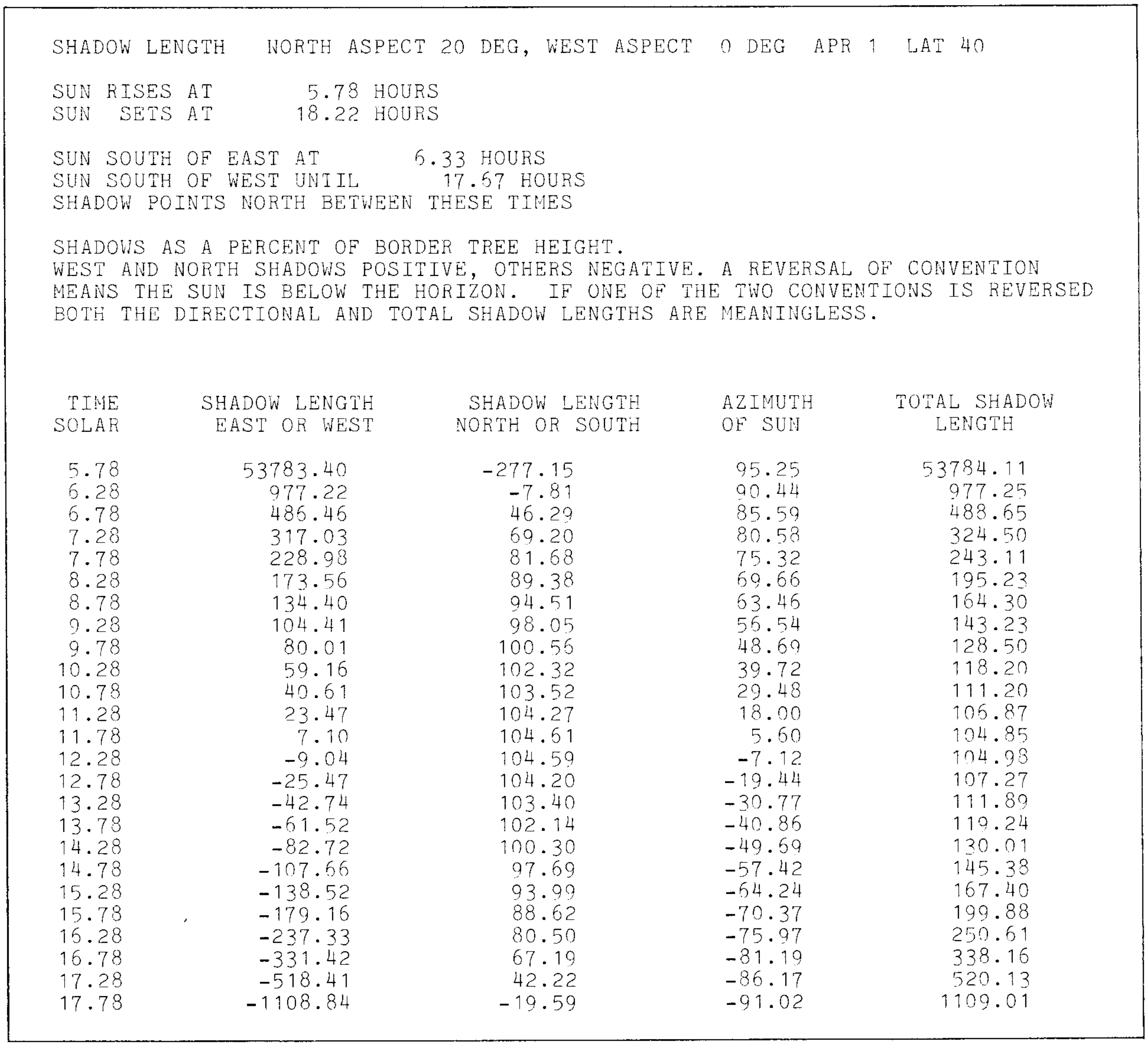
PROGRAM OUTPUT

The program output is a series of tables listing shadow length of objects for varying aspects, latitudes, and seasons of the year. The shadow lengths in the tables are a percent of the height, *above the soil or snow surface* of the shadow source. North-south and east-west shadows are calculated, as well as the total shadow length and the azimuth of the sun measured eastward from the south. The direction of the shadow is the reverse of the azimuth.

To illustrate the utility of these shadow lengths, let us consider the shading effect of trees along the borders of timber harvests.

Only on extreme northern aspects *(fig. 1)* does the shadow extend beyond the north boundary of an east-west oriented cut strip 2 chains (132 feet) wide. On southerly aspects, during early spring, from 100 percent to approximately 65 percent of the surface of such a strip and all tree boles at the north boundary are not shaded at any time.

Coupled with direct insolation is the effect of longwave radiation from the trees bordering the northern boundary of the cut strip. Their combined effects may increase the net radiation received inside the opening. Snow is a black body for longwave radia-



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SHADOW LENGTH   NORTH ASPECT 20 DEG, WEST ASPECT  0 DEG  APR 1  LAT 40

SUN RISES AT       5.78 HOURS
SUN  SETS AT      18.22 HOURS

SUN SOUTH OF EAST AT       6.33 HOURS
SUN SOUTH OF WEST UNTIL      17.67 HOURS
SHADOW POINTS NORTH BETWEEN THESE TIMES

SHADOWS AS A PERCENT OF BORDER TREE HEIGHT.
WEST AND NORTH SHADOWS POSITIVE, OTHERS NEGATIVE. A REVERSAL OF CONVENTION
MEANS THE SUN IS BELOW THE HORIZON.  IF ONE OF THE TWO CONVENTIONS IS REVERSED
BOTH THE DIRECTIONAL AND TOTAL SHADOW LENGTHS ARE MEANINGLESS.


 TIME       SHADOW LENGTH     SHADOW LENGTH      AZIMUTH      TOTAL SHADOW
SOLAR        EAST OR WEST    NORTH OR SOUTH      OF SUN          LENGTH

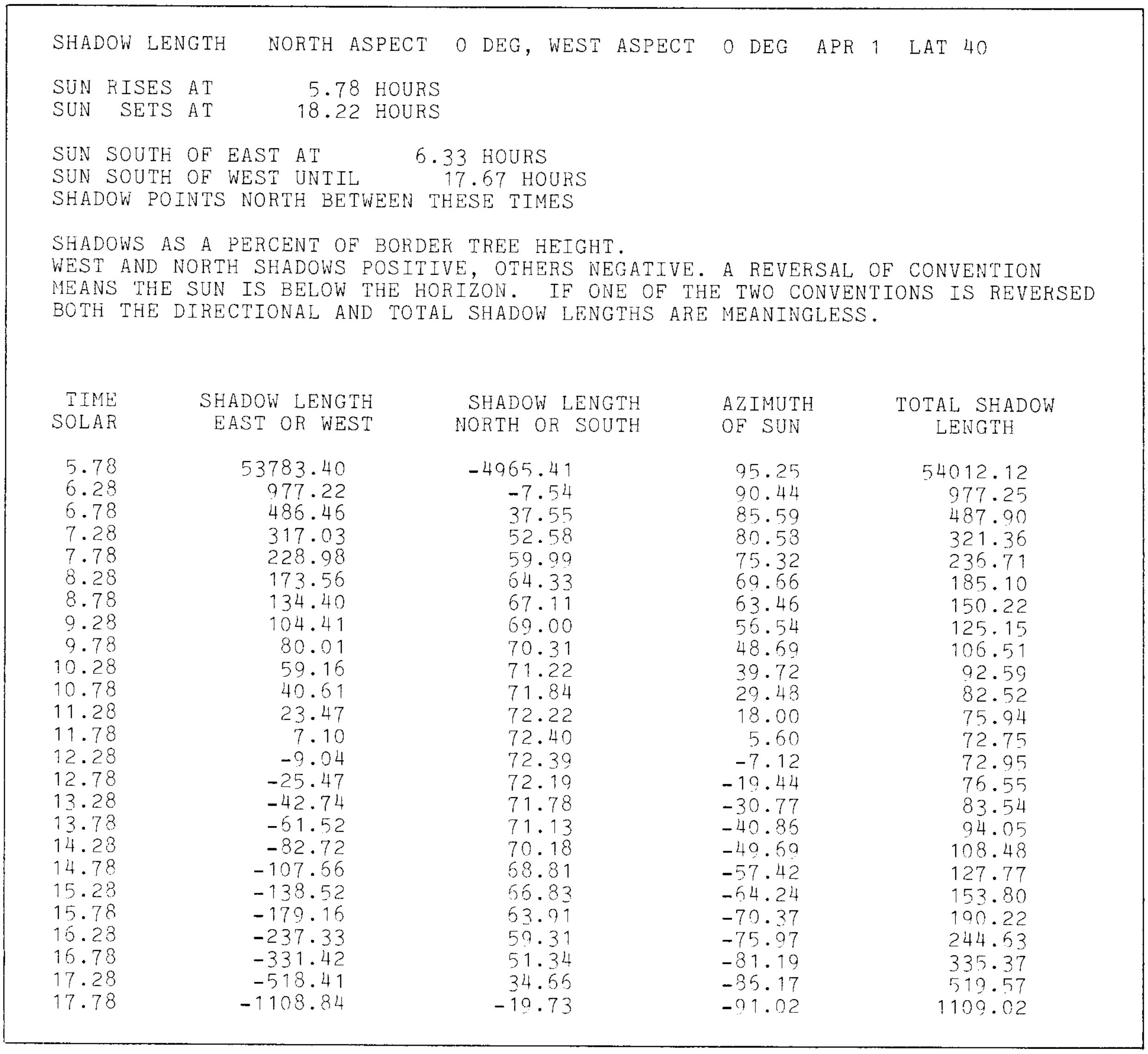
 5.78        53783.40          -277.15          95.25         53784.11
 6.28          977.22            -7.81          90.44           977.25
 6.78          486.46            46.29          85.59           488.65
 7.28          317.03            69.20          80.58           324.50
 7.78          228.98            81.68          75.32           243.11
 8.28          173.56            89.38          69.66           195.23
 8.78          134.40            94.51          63.46           164.30
 9.28          104.41            98.05          56.54           143.23
 9.78           80.01           100.56          48.69           128.50
10.28           59.16           102.32          39.72           118.20
10.78           40.61           103.52          29.48           111.20
11.28           23.47           104.27          18.00           106.87
11.78            7.10           104.61           5.60           104.85
12.28           -9.04           104.59          -7.12           104.98
12.78          -25.47           104.20         -19.44           107.27
13.28          -42.74           103.40         -30.77           111.89
13.78          -61.52           102.14         -40.86           119.24
14.28          -82.72           100.30         -49.69           130.01
14.78         -107.66            97.69         -57.42           145.38
15.28         -138.52            93.99         -64.24           167.40
15.78         -179.16            88.62         -70.37           199.88
16.28         -237.33            80.50         -75.97           250.61
16.78         -331.42            67.19         -81.19           338.16
17.28         -518.41            42.22         -86.17           520.13
17.78        -1108.84           -19.59         -91.02          1109.01
```

Figure 1—The relation of the shadow length of border trees on a cut strip to the strip width can be determined from these tables. They show shadow lengths as a percent of source height for a north aspect, 20^0 slope on April 1 at latitude 40° N.

tion and so shading tree boles would reduce the net radiation to the snow and delay melt.

Shadow-length effects can be evaluated by estimating the incident solar radiation received by a surface. At 40° N. latitude on a level site on April 1, the shadow extent is a maximum of 72.4 percent of the bordering tree height on an east-west clearcut strip *(fig. 2).* If bordering trees tower 100 feet above the snow and the strip is 2 chains wide, then 60 feet of the snowpack and the wall of timber at the north border of the strip are exposed for the 11.34 hours between the east-west crossings of the sun. The snow and the north boundary trees exposed to direct solar radiation could receive as much as 786.3 Langleys/day according to potential solar radiation tabulations (Frank and Lee 1966). The radiation becomes progressively greater as the aspect becomes more southerly and shadows become shorter. Solar radiation increases to 890 ly/day on a 45° S. slope. A 45° N. slope receives 225.8 ly/day. East and west slope components change the time of sunrise and sunset, but affect direct solar radiation only slightly. A 45° E. or 45° W. aspect reduces the potential solar radiation from 786.3 to 721.6 ly/day.

Data from a snow study serve to illustrate the effects of orientation upon the microclimate and subsequent melt of snow in 2-chains-wide openings created by a strip cut timber harvest pattern. The site



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SHADOW LENGTH   NORTH ASPECT  0 DEG, WEST ASPECT  0 DEG  APR 1  LAT 40

SUN RISES AT       5.78 HOURS
SUN  SETS AT      18.22 HOURS

SUN SOUTH OF EAST AT        6.33 HOURS
SUN SOUTH OF WEST UNTIL      17.67 HOURS
SHADOW POINTS NORTH BETWEEN THESE TIMES

SHADOWS AS A PERCENT OF BORDER TREE HEIGHT.
WEST AND NORTH SHADOWS POSITIVE, OTHERS NEGATIVE. A REVERSAL OF CONVENTION
MEANS THE SUN IS BELOW THE HORIZON.  IF ONE OF THE TWO CONVENTIONS IS REVERSED
BOTH THE DIRECTIONAL AND TOTAL SHADOW LENGTHS ARE MEANINGLESS.



 TIME       SHADOW LENGTH       SHADOW LENGTH       AZIMUTH       TOTAL SHADOW
SOLAR        EAST OR WEST      NORTH OR SOUTH       OF SUN           LENGTH

 5.78         53783.40           -4965.41           95.25          54012.12
 6.28           977.22              -7.54           90.44            977.25
 6.78           486.46              37.55           85.59            487.90
 7.28           317.03              52.58           80.58            321.36
 7.78           228.98              59.99           75.32            236.71
 8.28           173.56              64.33           69.66            185.10
 8.78           134.40              67.11           63.46            150.22
 9.28           104.41              69.00           56.54            125.15
 9.78            80.01              70.31           48.69            106.51
10.28            59.16              71.22           39.72             92.59
10.78            40.61              71.84           29.48             82.52
11.28            23.47              72.22           18.00             75.94
11.78             7.10              72.40            5.60             72.75
12.28            -9.04              72.39           -7.12             72.95
12.78           -25.47              72.19          -19.44             76.55
13.28           -42.74              71.78          -30.77             83.54
13.78           -61.52              71.13          -40.86             94.05
14.28           -82.72              70.18          -49.69            108.48
14.78          -107.66              68.81          -57.42            127.77
15.28          -138.52              66.83          -64.24            153.80
15.78          -179.16              63.91          -70.37            190.22
16.28          -237.33              59.31          -75.97            244.63
16.78          -331.42              51.34          -81.19            335.37
17.28          -518.41              34.66          -86.17            519.57
17.78         -1108.84             -19.73          -91.02           1109.02
```

Figure 2—Shadow length effects on a cut strip can be evaluated from the appropriate tables. These show shadow lengths for a north aspect, level plain, on April 1 at latitude 40° N.

of the study was at about 40° N. latitude, on a 9° N. slope at 7,000 feet elevation in the Sierra Nevada of California. Border timber was about 100 feet above the snow on April 1.

The effect of the lack of tree shadow was evident *(fig. 3)*. Snow water equivalent measured across an east-west-oriented cut strip at several times during a snow season showed wide fluctuations. Each part of the opening received about the same amount of precipitation, but the ablation pattern varied across the opening. Ablation rate increased toward the north boundary. Late in the season snow was retained only at the south boundary. The snow and then the soil near the north border were exposed to both direct solar radiation and energy reradiated from exposed tree trunks.

These effects show how the environment changes progressively across the opening in relation to shadow length *(fig. 4)*. Toward the north boundary, the microclimate includes more energy and becomes hotter and drier. The changing microclimate accelerates snowmelt in selected areas.

Conversely, in 2-chain strips cut north and south through timber 100 feet tall, the opening is exposed to the sun for about 7 hours before shadows falling eastward or westward again cover the entire strip *(fig. 4)*. In such cuts, any one point within the cut strip is exposed to direct solar radiation for only half this time before shadows again cover it. Direct solar radiation may fall below 240 ly/day upon the surface. Easterly and westerly aspects receive about the same radiation; only the times of sunrise and sunset change. North and south aspects change the direct solar radiation as received on a plain in a range from 89 ly/day on 45° N. aspects to 290 ly/day on 45° S. aspects.

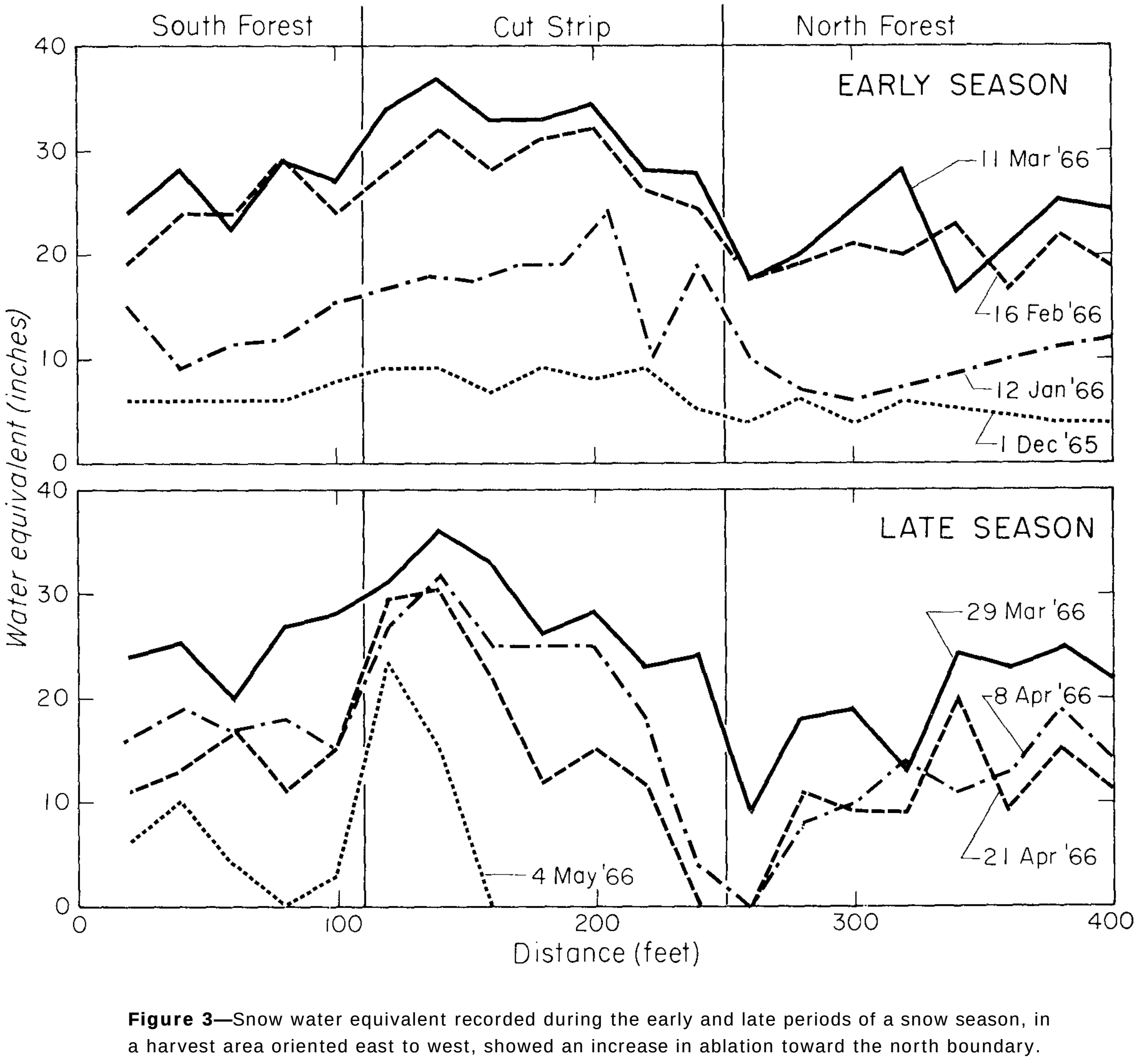

Figure 3—Snow water equivalent recorded during the early and late periods of a snow season, in a harvest area oriented east to west, showed an increase in ablation toward the north boundary.

The study data for accumulation in an open area oriented north-to-south showed that the pattern was uniform across the strip *(fig. 5).* The late season surveys showed that ablation was also uniform. Only a small differential increase appeared at either boundary. Ten inches of water remained in the snow across the north-south oriented strip at a time when only 2 inches remained on the east-west oriented strip. The snow information showed that the environment was more uniform across the opening. The strip received less energy and therefore was cooler.

The study illustrates that on strips oriented in a north-south direction, the cut area receives more shade, and the boundary trees themselves are more shaded than on strips oriented east-west. The shaded trees reradiate less energy to the snowpack, thus delaying the date and reducing the rate of snowmelt, and producing a generally milder microclimate. Only on extreme north exposures does the boundary orientation fail to affect the radiation to the opening.

Although the utility of shadow length information has been illustrated with data from snow water equivalent, applications could be drawn from other types of management data. The silvicultural requirements of different species dictate whether an opening should be designed to admit maximum or minimum solar radiation and reradiation. Roads and other

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SHADOW LENGTH   NORTH ASPECT  9 DEG, WEST ASPECT  0 DEG   APR 1  LAT 40

SUN RISES AT       5.78 HOURS
SUN  SETS AT      18.22 HOURS

SUN SOUTH OF EAST AT        6.33 HOURS
SUN SOUTH OF WEST UNTIL      17.67 HOURS
SHADOW POINTS NORTH BETWEEN THESE TIMES

SHADOWS AS A PERCENT OF BORDER TREE HEIGHT.
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  TIME        SHADOW LENGTH        SHADOW LENGTH        AZIMUTH        TOTAL SHADOW
 SOLAR         EAST OR WEST        NORTH OR SOUTH        OF SUN           LENGTH

  5.78          53783.40             -567.31             95.25          53786.39
  6.28            977.22               -7.54             90.44            977.25
  6.78            486.46               40.42             85.59            488.13
  7.28            317.03               58.08             80.58            322.31
  7.78            228.98               67.12             75.32            238.62
  8.28            173.56               72.52             69.66            188.10
  8.78            134.40               76.03             63.46            154.41
  9.28            104.41               78.43             56.54            130.58
  9.78             80.01               80.11             48.69            113.22
 10.28             59.16               81.28             39.72            100.53
 10.78             40.61               82.08             29.48             91.57
 11.28             23.47               82.57             18.00             85.84
 11.78              7.10               82.80              5.60             83.10
 12.28             -9.04               82.78             -7.12             83.27
 12.78            -25.47               82.52            -19.44             86.37
 13.28            -42.74               82.00            -30.77             92.47
 13.78            -61.52               81.16            -40.86            101.85
 14.28            -82.72               79.94            -49.69            115.03
 14.78           -107.66               78.19            -57.42            133.06
 15.28           -138.52               75.68            -64.24            157.84
 15.78           -179.16               71.99            -70.37            193.08
 16.28           -237.33               66.28            -75.97            246.42
 16.78           -331.42               56.58            -81.19            336.22
 17.28           -518.41               37.14            -86.17            519.74
 17.78          -1108.84              -19.37            -91.02           1109.01
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Figure 4—Shadow length effects on the cut strip studied are evident from these tables for a north aspect, 9° slope, on April 1 at latitude 40° N.

physical facilities can be cleared of snow earlier than normal by increasing heat into a location, or kept closed later into the season by maintaining a heavy total cover or by removing back-radiating vegetation on the border. Stream temperatures can be regulated increased by removal of vegetation on the south bank or held relatively constant by removal of vegetation from the north bank. In each case, the management goal may be attained more readily by evaluation of the effect of changed solar radiation before the harvest begins. Many other uses can be made of this type of information.

APPLICATION

Before the resource manager can use this technique, he must develop a series of tables for the major combinations of slope, aspect, sun angle, and times of year that are of interest to him. In a timber harvest, for example, he would determine the basic objective of his timber manipulation, and then the desirable shadow length for each combination of slope-aspect conditions at the date he most desires to exercise control. These decisions determine the width and length of the opening to be harvested. The actual harvest pattern width will vary, depending on slope angle and aspect. Thus if timber is harvested in a cut

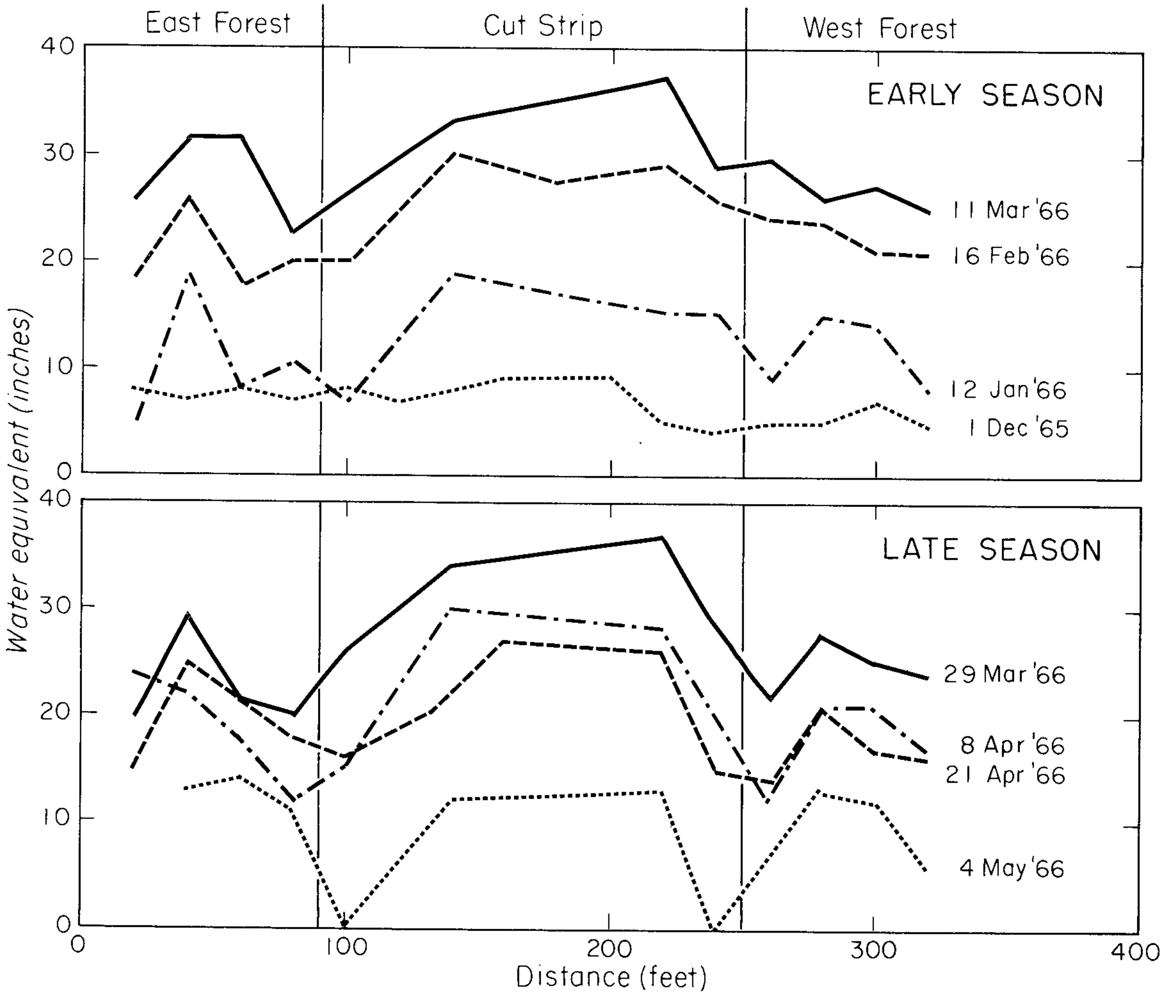

Figure 5—Snow water equivalent data for a harvest area oriented north to south showed a uniform pattern across the opening.

strip, width of the cut strip will vary, as cutting proceeds across a slope. This pattern relieves the monotonous visual effect of a strip having straight sides. In a patch harvest, the opening size will also vary with slope angle and aspect changes.

From the direction of the shadow and the length of shadow cast by the boundary trees at any given time of year, it is possible to estimate the increase or decrease in heat and light to the snow surface resulting from management. By shadow length manipulation, maximum control over the forest environment can be achieved. However, good planning and application on the ground is required to achieve the desired results.

APPENDIX

Shadow Length Program

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          PROGRAM SHDW (INPUT,OUTPUT)
     C    THIS PROGRAM COMPUTES THE LENGTH OF A TREE SHADOW AS A PERCENT
     C    OF TREE HEIGHT.  THE SHADOW IS GIVEN IN EACH OF THE CARDINAL
     C    DIRECTIONS.  THE LENGTH IN TOTAL IS ALSO CALCULATED.  THE
     C    AZIMUTH OF THE SUN AT EACH TIME IS GIVEN.   INPUT DATA REQUIRED
     C    INCLUDE THE LATITUDE, DATE NUMBER, SOUTH SLOPE COMPONENT IN
     C    DEGREES, EAST SLOPE COMPONENT IN DEGREES, AND THE TIME INTERVAL
     C    BETWEEN CALCULATIONS DESIRED.  ALL DATA ARE ENTERED IN FIELDS OF
     C    10.4.  THE SECOND DATA CARD IS A TITLE CARD FOR IDENTIFICATION.
          DIMENSION TITLE(14)
          REAL NSHAD
        1 READ 1000,XLAT,DTNO,SSLP,ESLP,DLTT
20        IF(XLAT.GE.90.) GO TO 6000
23        READ 1001,(TITLE(J),J=1,14)
     C    COMPUTERS USE RADIANS, NOT DEGREES.  THIS SEQUENCE CONVERTS.
31        CDR=6.2832/360.
32        XLTR=XLAT*CDR
33        DTR=(DTNO+10.5)*CDR*360./365.25
36        SSLP=SSLP*CDR
40        ESLP=ESLP*CDR
41        DECL=-23.45*COS(DTR)*CDR
45     10 T=4.0
     C     CALCULATE THE TIME OF SUNRISE.
47     11 DO 13 I=1,450
51        H=(12.-T)*15.*CDR
54        SINA=SIN(XLTR)*SIN(DECL)+COS(XLTR)*COS(DECL)*COS(H)
72        IF(SINA)12,14,14
74     12 T=T+.01
76     13 CONTINUE
100    14 TSR=T
     C    CALCULATE WHEN SUN IS DUE EAST OF SITE.
102    20 SINAPL=0.0
103    21 H=(12.-T)*15.*CDR
106       SINA=SIN(XLTR)*SIN(DECL)+COS(XLTR)*COS(DECL)*COS(H)
124       A= ASIN(SINA)
126       SINAP=COS(DECL)*SIN(H)/COS(A)
136       IF(SINAPL.GE.SINAP)GO TO 22
141       SINAPL=SINAP
142       T=T+.01
144       GO TO 21
     C    CALCULATE WHEN SUN IS DUE WEST AND SUNSET.
145    22 TSHDW=T-.01
146       TEND=24.-TSR
150       TQT=24.-TSHDW
152       TDW=24.-TSHDW
153       T=TSR
154       PRINT 1002,(TITLE(J),J=1,14)
161       PRINT 1003,TSR
167       PRINT 1004,TEND
175       PRINT 1005,TSHDW
```

```
203         PRINT 1006,TDW
211         PRINT 1007
215         PRINT 1008
221         PRINT 1009
225         PRINT 1010
231         PRINT 1011
235      31 IF(T.GE.12.)GO TO 60
240         H=(12.-T)*15.*CDR
242         SINA=SIN(XLTR)*SIN(DECL)+COS(XLTR)*COS(DECL)*COS(H)
260         A= ASIN(SINA)
262         SINAP=COS(DECL)*SIN(H)/COS(A)
272         AP= ASIN(SINAP)
274         XLOS=100./TAN(A)
277         XKLL=XLOS*SIN(AP)
302         Y=ATAN(100./XKLL)
306         IF(ESLP.GE.0.0)GO TO 68
310         SHAD=XKLL*SIN(Y)/SIN(3.1416-Y+ESLP)
321         GO TO 70
321      60 IF(T.GE.TEND)GO TO 1
324         H=(12.-T)*15.*CDR
326         SINA=SIN(XLTR)*SIN(DECL)+COS(XLTR)*COS(DECL)*COS(H)
344         A= ASIN(SINA)
346         SINAP=COS(DECL)*SIN(H)/COS(A)
356         AP= ASIN(SINAP)
360         XLOS=100./TAN(A)
363         XKLL=XLOS*SIN(AP)
366         Y=ATAN(-100./XKLL)
372         IF(ESLP.GE.0.0) GO TO 69
374         SHAD=XKLL*SIN(3.1416-Y)/SIN(Y+ESLP)
406         GO TO 70
406      68 SHAD=XKLL*SIN(3.1416-Y)/SIN(Y-ESLP)
421         GO TO 70
421      69 SHAD=XKLL*SIN(Y)/SIN(3.1416-Y-ESLP)
433      70 IF(T.LE.TSHDW) GO TO 59
436         IF(T.LE.TQT) GO TO 61
440         AP=0.0-3.1416-AP
443         GO TO 61
443      59 AP=3.1416-AP
445      61 XKL=XLOS*COS(AP)
450         Z=ATAN(100./XKL)
454         IF(SSLP.GE.0.0) GO TO 41
456         NSHAD=XKL*SIN(Z)/SIN(3.1416-Z+SSLP)
467         GO TO 90
467      41 NSHAD=XKL*SIN(3.1416-Z)/SIN(Z-SSLP)
502      90 TSHAD=SQRT(SHAD**2 + NSHAD**2)
506         AP=AP*57.296
510      93 PRINT 1012,T,SHAD,NSHAD,AP,TSHAD
526         T=T+DLTT
530         GO TO 31
       1000 FORMAT(5F10.4)
       1001 FORMAT(13A6,A2)
       1002 FORMAT(1H1,///,13A6,A2)
       1003 FORMAT(/,5X13HSUN RISES AT ,F10.2,6H HOURS)
       1004 FORMAT(5X13HSUN  SETS AT ,F10.2,6H HOURS)
       1005 FORMAT(/,5X21HSUN SOUTH OF EAST AT ,F10.2,6H HOURS)
       1006 FORMAT(5X,24HSUN SOUTH OF WEST UNTIL ,F10.2,6H HOURS)
       1007 FORMAT(5X,*SHADOW POINTS NORTH BETWEEN THESE TIMES*)
       1008 FORMAT(/5X*SHADOWS AS A PERCENT OF BORDER TREE HEIGHT.*)
       1009 FORMAT(5X,*WEST AND NORTH SHADOWS POSITIVE, OTHERS NEGATIVE. A REV
           1ERSAL OF CONVENTION*,/,5X,*MEANS THE SUN IS BELOW THE HORIZON.  IF
           2 ONE OF THE TWO CONVENTIONS IS REVERSED*,/,5X,*BOTH THE DIRECTIONA
           3L AND TOTAL SHADOW LENGTHS ARE MEANINGLESS.*)
       1010 FORMAT(///,6X4HTIME,6X13HSHADOW LENGTH,7X13HSHADOW LENGTH,6X7HAZIM
           2UTH,6X13HTOTAL SHADOW )
       1011 FORMAT(5X5HSOLAR,7X12HEAST OR WEST,6X14HNORTH OR SOUTH,6X6HOF SUN,
           210X6HLENGTH,/)
       1012 FORMAT(F10.2,4F17.2)
531    6000 CONTINUE
531         RETURN
533         END
```

Calculations of Shadows, Time, and Aspect

Computer Calculations of Shadows

The shading pattern created by trees on the edges of openings cut through the forest in a north-south or east-west direction is calculated in the program from standard formulas. They may be expressed as:

$$\sin \alpha = \frac{\cos \sigma \sin h}{\cos a} \qquad (1)$$

$$\sin a = \sin \delta \sin \sigma + \cos \delta \cos h \cos \sigma \qquad (2)$$

$$s = \frac{100}{\tan a} \qquad (3)$$

in which

a = altitude of the sun (angular elevation above the horizon)
δ = latitude of the observer
σ = declination of the sun
h = hour angle of the sun (angular distance from the meridian of the observer)
α = azimuth of the sun (measured eastward from south)
s = horizontal shadow length as a percentage of tree height above the snow

The altitude and azimuth of the sun are functions of the latitude of the observer, time of day or hour angle, and the date expressed as declination of the sun. Hour angle is the difference between time of observation and true solar noon; 1 hour is equivalent to 15°.

The program first calculates the sun azimuth and altitude of the sun above a horizontal plane through the site. Equation 3 is used to calculate the horizontal shadow length. To convert the horizontal shadow length into a south or east vector, an additional calculation is performed. The north component, NV, is computed from the cosine of the sun azimuth and the shadow length, s, from equation 3. The east vector EV, is computed from sine function:

$$NV = s \cos \alpha \qquad (4)$$

$$EV = s \sin \alpha \qquad (5)$$

To correct for slope, the total length and the south and east vectors are projected upon the plane of the slope as supplied on the first input data card. The projection is made along a path governed by the altitude and azimuth of the sun, and the three shadow lengths on the slope are then computed with the sine law.

Time Conversion

The time values used are true solar time. The true solar day is defined as the interval between two consecutive transits of the sun across any given meridian. True solar time is based on true solar noon, when the geometric center of the sun crosses the longitude of the observer. However, the revolution of the earth around the sun and the rotation of the earth on its axis are not precisely synchronous.

The mean solar day was adopted to gain the advantage of regularity. Mean solar time assumes a sun moving on the equatorial plane with a uniform velocity equivalent to the average velocity of the sun. The equation of time, which is obtained from a solar ephemeris (List 1958) is the difference between true and mean solar time and equals zero at four times during the year:

Date:	*Minutes*	*Hours*
Jan. 10	- 7.2	- 0.12
24	- 12.0	- .20
Feb. 7	- 14.2	- .24
20	- 13.9	- .23
Mar. 7	- 11.3	- .19
21	- 7.5	- .13
Apr. 4	- 3.3	- .05
19	+ 0.5	+ .01
May 3	+ 3.1	+ .05
18	+ 3.7	+ .06
June 1	+ 2.4	+ .04
22	- 1.6	- .03
July 12	- 5.4	- .09
27	- 6.4	- .11
Aug. 10	- 5.4	- .09
25	- 2.3	- .04
Sept. 9	+ 2.4	+ .04
23	+ 7.3	+ .12
Oct. 8	+ 12.1	+ .20
22	+ 15.3	+ .26
Nov. 5	+ 16.4	+ .27
19	+ 14.7	+ .25
Dec. 3	+ 10.5	+ .18
22	+ 1.8	+ .03

Local standard time (LST) is based on 15° longitudinal time zones. Noon in local standard time occurs when the sun in a mean solar day crosses the time zone meridian. To determine true solar time, add 4 minutes to the local standard time (not daylight saving time) for each degree of longitude the station is east of the standard meridian, or subtract 4 minutes for each degree west of the standard meridian.

This first calculation results in local mean solar time. True solar time is then obtained by adding algebraically the equation of time from the table.

Local standard time can be determined from true solar time through the reverse of the procedure just described. That is, the appropriate equation of time is algebraically subtracted from any time value given by the shadow length program. Then 4 minutes is subtracted (added) for each degree of longitude the station is east (west) of a standard meridian. Standard meridians for the 48 contiguous States, by time zones, are:

	Standard meridian degrees west longitude
Time zone:	
Eastern	75°
Central	90°
Mountain	105°
Pacific	120°

Standard meridians for the world can be determined from a time zone map as published by the U.S. Navy (1960).

Slope and Aspect Corrections

Site aspect is often described as the direction perpendicular to the contour, and slope by the inclination in percent. These data can be converted to the form required by the shadow program, although measurement on the site is desirable.

To convert to aspect, the azimuth of the perpendicular to the contour, measured eastward from south, must be determined. With this method, a south aspect has an azimuth of 0°, east has an azimuth of 90°, north is 180°, and west is 270°. Then:

$$\mathrm{ESLP} = -\arcsin\left[\frac{\sin\phi\ \sin\theta}{+\sqrt{\cos^2\phi + \sin^2\phi\ \sin^2\theta}}\right] \qquad (6)$$

$$\mathrm{SSLP} = -\arcsin\left[\frac{\sin\phi\ \cos\theta}{+\sqrt{\cos^2\phi + \sin^2\phi\ \cos^2\theta}}\right] \qquad (7)$$

in which

ESLP = east slope vector in degrees

Φ = slope in degrees

θ = azimuth from south toward east in degrees

SSLP = south slope vector in degrees

Note that the absolute value for slope is used in these calculations. The algebraic sign for azimuth, when carried in the numerator, gives the correct sign for the south slope and east slope values for use on the input data card. Signs of the functions are:

	Range in degrees			
	0-90	*90-180*	*180-270*	*270-360*
Function:				
Sine	+	+	-	-
Cosine	+	-	-	+

To convert percent slope to degrees and decimal parts required by the program, this tabulation is useful:

	Slope inclination
	Degrees
Slope (percent):	
0	0.00
10	5.72
20	11.32
30	16.70
40	21.80
50	26.57
60	30.97
70	35.00
80	38.67
90	41.98
100	45.00

Alternatively, more precise degree values for a percent slope can be calculated by the relation:

$$\tan\Phi = \frac{x}{100} \qquad (8)$$

in which Φ = slope angle in degrees and minutes and x = percent slope (elevational difference between two points 100 feet apart in horizontal distance).

Any minutes of angle must be converted to decimal form for program use by dividing by 60'/°. For example, a 20 percent slope may be expressed as $\tan\Phi = 20/100 = 0.20$. From a table of trigonometric functions, the angle Φ is 11°19' or 11° plus 19' divided by 60'/°, or 11.32°.

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Control of solar light and heat to develop the proper growth environment is a desirable goal in forest management. The amount of sunlight and heat reaching the surface is affected by shadows cast by nearby objects, including trees. In timbered areas, the type of forest management practiced can help develop desired microclimates. The results depend on the size and orientation of openings created and on the shade cast by surrounding vegetation. A computerized method to calculate the extent of boundary shading for any combination of date, slope, and aspect between 23.45° N. latitude and 50° N. latitude is described. For those who do not wish to develop their own, a set of shadow-length tables is available upon request. These may be secured as an entire set or by individual latitudes. They provide coverage for the contiguous United States in increments of 2° from 36° N. latitude to 50° N. latitude. By extrapolation, the tables can be used from the Mexican to the Canadian border.

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