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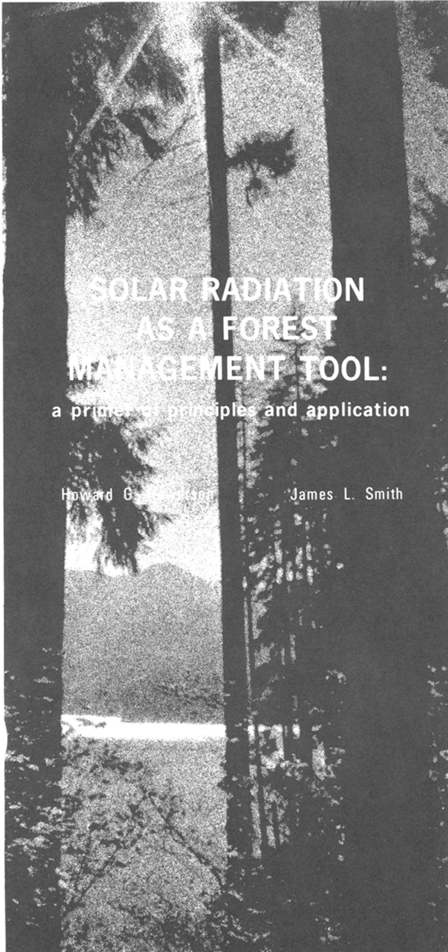

SOLAR RADIATION AS A FOREST MANAGEMENT TOOL:
a primer of principles and application

Howard G. Halverson   James L. Smith

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Forests are products of solar radiation use. The sun also drives the hydrologic cycle on forested watersheds. Some basic concepts of climatology and solar radiation are summarized including earth-sun relations, polar tilt, solar energy, terrestrial energy, energy balance, and local energy. An example shows how these principles can be applied in resource management. This paper is designed to be used with an earlier report on controlling solar light and heat in a forest by managing shadow sources.

Retrieval Terms: forest management; solar radiation; hydrologic cycle; climatology; energy exchange.

INTRODUCTION

The sun is the primary source of energy for the earth and its atmosphere. Solar energy drives the biologic, hydrologic, and atmospheric processes. The second largest energy source is the heat flux from the interior of the earth. This second source accounts for only about 0.02 percent of the total. Other sources contribute even smaller quantities of energy.

Our forests are products of solar radiation use. Insolation is used to combine elements found near the surface of the earth so that essential physiological processes necessary for forest growth and maturity can be completed. The sun also drives the hydrologic cycle on our forested watersheds. As land managers, we are interesed in both the forest growth cycle and the hydrologic cycle because wood and water are tangible products of forest land.

We cannot manage or control the incident solar radiation received by large land areas; however, forest management can exert significant effect on local insolation in small areas. Harvest and regeneration patterns can be designed to increase or decrease the radiation level at many sites. The objectives of the management plan can determine the level of insolation desirable. Previously, management of such matters as reproduction and snow water yield considered solar radiation levels broadly or qualitatively before any activity started, but made no specific plan based upon a detailed examination. This paper discusses basic relationships usable to more quantitatively evaluate how solar radiation and shadows can be integrated at specific sites to achieve a management goal.

This paper summarizes some basic concepts of applied climatology and solar radiation. Although the principles are well known to those trained in micrometeorology, they may be less familiar to those working in resource management and planning. An example is included to show how these principles can be used in resource management. The paper is designed to be used with an earlier report *Controlling solar light and heat in a forest by managing shadow sources* (Halverson and Smith 1974a). That report has been supplemented by a series of tables on a tree-shadow length for 2° latitude increments spanning latitudes 30° to 50° N.

Requests for copies of the earlier report—Research Paper PSW-102—and of the shadow-length tables should be directed to: Pacific Southwest Forest and Range Experiment Station, P.O. Box 245, Berkeley, California 94701, Attn: Publications Distribution.

EARTH-SUN RELATIONS

The Sun Affects Our Forests

Several properties of the sun help explain the energy relations of the forest. The sun is our most prominent neighbor in the solar system. In relation to the earth, it is stationary; however, it appears to trace a path across the sky because the earth is rotating on its axis.

The sun, which is at the center of our solar system, has a diameter more than 100 times larger than that of the earth. The sun is 93 million miles (150 million km) from the earth. The solar radiation which reaches the earth arrives in parallel rays because of solar size and distance. If the sun were smaller than the earth, solar radiation would appear as diverging rays. Because the rays are parallel, shadows appear as a direct image of the source projected along the rays to the surface of the earth. Parallelism of solar radiation makes it possible to calculate shadow locations, sun location, and sun times with reasonable accuracy.

Although the sun looks small because of earth-to-sun separation, it contains most of the mass of our solar system, about 99 percent. The sun generates energy through nuclear fusion, creating helium from hydrogen. In the process it converts some mass to energy at a relatively constant rate. The sun should last about another 30 billion years. Much of the nuclear radiation emitted by the sun is screened by distance and atmosphere before it reaches the earth.

The energy emitted from the sun arrives in parallel rays. Because of the fixed and predictable relation of earth to sun one may precisely determine the position and angle at which these rays will strike any portion of the earth on any given day, as well as the energy which arrives at that point unless it has been modified by cloud cover. Arrangements or rearrangement of the spatial distribution of tree boles and crowns can prevent or allow solar radiation reaching any spot of ground. Thus, timber harvest and tree planting can be managed to change the amount of solar radiation reaching the surface. This change in solar radiation amount can be used to increase heat to snowpacks to create melt, to prevent thermal pollution in trout streams, and in other ways.

Polar Tilt Defines Our Seasons

The earth rotates on an axis extending through the polar latitudes and completes one rotation every 24 hours. A variation of about 2 seconds in day length does not significantly affect our purposes. The polar axis tilts 23° 27′ from normal alinement with the plane of the elliptical orbit around the sun and this tilt is responsible for the seasons. Summer occurs when our hemisphere is tipped toward the sun; winter results when we are angled away from the sun.

Our orientation toward or away from the sun is related to the earth's location on an orbit around the sun (*fig. 1*). The earth completes one revolution every 365.25 days, or each year. The sun appears displaced north of the equator during summer and south during winter. The angular displacement is called the solar declination. The points of maximum displacement are referred to as the summer and winter solstice and occur about June 22 and December 22. The vernal and autumnal equinoxes occur about March 22 and September 22 when the earth's orbit crosses the solar equator. The reference plane used to describe the declination of the sun is defined by the earth's equator. As the earth revolves about the sun, the solar disk appears to move below, south of the equator in winter, and above, north of it in summer. The maximum displacement is the same as the tilt of the earth's axis, 23° 27′, and is defined as positive on June 22 and negative on December 22. Latitude is also defined by the same plane through the equator. The tropics—Cancer and Capricorn—are at the same latitude as the maximum declination of the sun; the sun is directly overhead on the appropriate solstice. At the equinox, the sun is in the plane of the earth's equator and declination is zero.

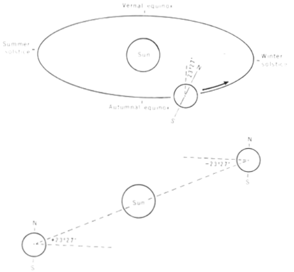


Figure 1. The earth rotates on its axis in an elliptical orbit around the sun. The polar axis tilts 23° 27′ from normal alinement with the plane of the elliptical orbit around the sun.

As the earth progresses through one rotation on its axis every 24 hours, the sun appears to trace a path in the sky and that path completes a circle around the globe each day. This translates to 360° in 24 hours, or 15° per hour. This quantity, 15°, is defined as the *hour angle*, the spherical angle the sun position must traverse per hour so that it will appear in the same place 24 hours hence. It is referenced to noon, true solar time, when the sun is due south of the observer, and is positive before noon and negative after. (It is more precise to say the earth must revolve through an arc of 15° per hour, but manner of presentation does not affect the calculations of sun position.)

The location of the sun in the sky can be described by two angles when the declination, latitude, and hour angle are known. The following equations define the sun *elevation* above the horizontal and the sun *azimuth*. The sun azimuth is the arc of the horizon measured between south and the vertical circle passing through the center of the point of observation and extending to the sun.

Elevation of the sun is given by the equation:

$$\text{sine } e = \sin L \sin d + \cos L \cos d \cos h$$

in which

- e = altitude of the sun (angular elevation above the horizon)
- L = latitude of the site
- d = declination angle of the sun
- h = hour angle

The azimuth of the sun is defined as

$$\sin a = \frac{\cos d \sin h}{\cos e}$$

in which a = azimuth of the sun measured eastward (+) or westward (−) from south. The algebraic signs of the two trigonometric functions in the various quadrants are:

Function	*Range in Degrees*			
	0-90	90-180	180-270	270-360
Sine	+	+	−	−
Cosine	+	−	−	+

Another angle frequently encountered in calculation of sun position is the *zenith* angle (Z), the angular separation of the sun from vertical at the site. Therefore,

$$Z = 90° - e$$

and from trigonometric identities

$$\cos Z = \sin e$$

The relationships of the various angles can be diagrammed (*fig. 2*).

These equations give rise to the following facts.

1. At any latitude at solar noon, the hour angle is 0° and Z = L − d.
2. The half-day length (H) at all but polar latitudes is cos H = tan L tan d. The half-day length will be 6 hours (90°) when tan L is 0—that is to say, all days on the equator. The half-day length will also be 6 hours when tan d equals 0, the equinoxes at all but the polar latitudes.
3. In polar latitudes cos L is 0, sin L is 1, and sin a = sin d, from the equation for solar elevation. Then the elevation angle of the sun at the poles equals the declination angle.
4. The day is always symmetrical about solar noon on a level surface; that is, sunrise and sunset occur the same number of hours before and after solar noon. The azimuth and elevation angles are the same for equivalent numbers of hours before and after solar noon. Also, the azimuth west of south at sunset is equivalent to the sunrise azimuth east of south. Calculations for the first or second half of a day can be transposed across solar noon to describe the remaining half day.

The calculations described are all based on *true solar time*—sometimes called sun time. Solar time is calculated from solar noon, when the sun is due south, along the meridian, of the observer. Solar time is preferred over standard time because standard time, though based on solar time at the time zone meridians, has been subjected to several modifications. Daylight saving time is now common. Time-zone boundaries

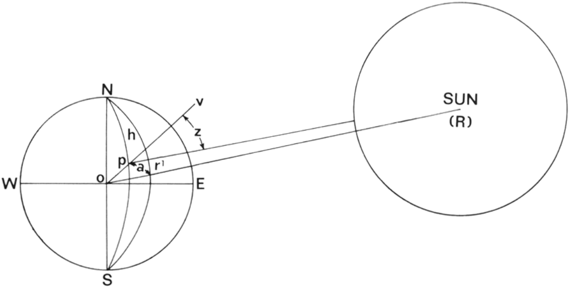


Figure 2. At a given latitude, relationships among the hour angle, zenith angle, and solar elevation can be shown. (R) = the endpoint of a line from the center of the earth (o) to the center of the sun (R), o = center of the earth, p = position of observer, line opv is the vertical at the position of the observer, r′ = line from observer to sun, or ′R = line from the center of the earth to the sun. The various angles are: z = *zenith* angle between center of the sun and the vertical at the position of the observer, h = *hour* angle between NpS and Nr′S, a = *azimuth* of the sun, and 90°-z = *elevation* of the sun.

have been modified also by political entities to place entire States within a single time zone. Local time may vary considerably from solar time in different regions. Using solar time as a base avoids the necessity to consider these variations.

Solar time is referenced to the center of the solar disk. Apparent sunrise occurs slightly before sunrise in true solar time because the edge of the solar hemisphere appears before the center of the sun and because atmospheric refraction makes the solar disk appear slightly earlier. The same two effects also delay sunset. The deviation lasts about 4 minutes at midlatitudes, and increases in time with increasing latitude.

SOLAR ENERGY RELATIONS

The various laws which govern the generation and flux of radiations are well established. These laws, which we apply, date back to the 19th century and earlier, and reached their maturity during "the thirty years that shook physics," from 1900 to 1930.[1] Because these laws are important to the manipulation of solar radiation data for management purposes, they will be reviewed.

The basic unit of energy is the 15° gram-calorie (cal); this is the amount of heat required to raise the temperature of 1 gram of water 1°C. When this energy is expressed on an area basis the unit area is cm^2. The langley (ly) is 1 g calorie cm^{-2}. The kilolangley (kly) is, by convention, 1000 ly. The langley unit is convenient for use in forest science because processes such as evaporation and snowmelt use the calorie as the basic unit. Other disciplines use other units, such as the watt, erg, joule, or British thermal unit (BTU). These quantities are all interchangeable with conversion factors such as

$$
\begin{aligned}
\text{One } 15^\circ \text{ g cal cm}^{-2} &= 1 \text{ cal cm}^{-2} \\
&= 1 \text{ ly} \\
1000 \text{ ly} &= 1 \text{ kly} \\
\text{One cal cm}^{-2}\text{min}^{-1} &= 4.1855 \text{ joules cm}^{-2}\text{min}^{-1} \\
&= 4.1855 \times 10^7 \text{ergs cm}^{-2}\text{min}^{-1} \\
&= 69.75 \text{ milliwatts cm}^{-2} \\
&= 3.6855 \text{ BTU ft}^2 \text{ min}^{-1}
\end{aligned}
$$

The addition of the time unit, minutes, converts the energy terms to *flux*. Flux is the quantity of radiant energy of all wavelengths (cal) crossing a unit area of surface (cm^2) per unit time (min). Minutes are chosen rather than seconds to prevent negative exponents from appearing with the equivalent energy quantities.

The energy emitted from the sun is about 56×10^{26} ly min^{-1}, and the earth is a mean distance of 1.5×10^{13} cm away from the sun. The energy received per unit area on a sphere with a radius equal to the average distance from the sun to the earth is thus:

$$S = \frac{56 \times 10^{26} \text{ ly min}^{-1}}{4\pi(1.5 \times 10^{13})^2} = 2.0 \text{ ly min}^{-1}$$

in which S is the solar constant.

The solar constant is the energy flux passing through a square centimeter surface normal to the sun's rays per minute. The surface is located at the top of the atmosphere, so that energy actually incident at the ground depends on transmission losses in the atmosphere and the sine of the angle between the earth surface and the rays from the sun. Because of variations in energy output from the sun and differing distances of earth-sun separation, the solar constant varies by about 1.5 percent around the mean value. (Values of the solar constant reported in the literature also vary between 1.94 and 2 ly min^{-1}, but for most purposes, the value 2 ly min^{-1} is acceptable.)

The emission and absorption of radiation by the sun are described by a number of fundamental relations. Different objects emit radiation as a function of their absolute temperature. Kirchhoff (1824-1887) gave us a law which states that the radiating powers of all bodies at a given temperature must be in exactly the same ratio as their absorbing powers, or they could never attain temperature equality. Qualitatively, therefore, Kirchhoff's Law says that good absorbers of energy are also good emitters. A *black body* is an object that emits and absorbs radiation in all wavelengths. The term "black body" is a physical one—it may not describe the color that we see, although generally, objects that appear black to us are also good radiation absorbers and emitters.

If the sun is assumed to be a black body we can calculate its radiation temperature. In 1879, Josef Stefan (1835-1893) deduced that the total emission of a black body for all wavelengths together is proportional

[1]Details of these laws can be gleaned from any basic college-level text on physics should the reader be interested in pursuing the subject for new knowledge, or for review.

to the fourth power of the absolute temperature. Five years later, in 1884, Ludwig Boltzmann proved the law on the basis of thermodynamics. From the Boltzmann experiments we have the Stefan-Boltzmann equation:

$$\text{Flux} = \sigma T^4$$

in which σ is the Stefan-Boltzmann constant (8.14×10^{-11} ly min^{-1} T^{-4}). The sun flux is equal to 56×10^{26} ly min^{-1} divided by the surface area of the sun (6.093×10^{22} cm^2). Solving the equation and extracting the fourth root of the temperature variable yields a radiation temperature of 5800° K.

Black body radiation characteristics were not explained by the wave theory of light. It remained for Max Planck (1858-1947), a theoretical physicist, to determine that all radiant energy comes to us in the form of electromagnetic waves and only in "chunks" or discrete energy packets. These chunks are called *quanta*. Planck, in the early part of this century, discovered that the energy, I, emitted per second per unit area per unit of frequency into a sphere was described by the equation:

$$I = \frac{8\pi h v^3}{C^2 \left[e^{\frac{hv}{\sigma T}} - 1 \right]}$$

in which h is Planck's constant (6.6252×10^{-27} erg sec), v is frequency of radiation, and e is the base of the natural log. The Boltzmann constant is expressed in consistent units (1.3805×10^{-16} erg deg^{-1}) and C is the speed of light (3×10^{10} cm sec^{-1}). To derive the energy emitted in a single direction, Planck's equation is divided by 4π. Planck's law led to modern physics: quantum mechanics and the electromagnetic theory of light.

Planck also assumed that the energy per unit, or quantum of light, is given by the equation:

$$E = hv$$

in which

E = Energy
h = a constant
v = frequency of vibration

This equation can be written also as $E = nhv$, in which n is a whole number and is called a *quantum number* and hv is called a *quantum of energy*.

The number of quanta emitted in a large-scale process, such as solar radiation, is so great that individual quanta cannot be distinguished. Such a process, therefore, appears to be continuous. Planck's assumption, later proved correct, gave a method to determine the relative energy of radiation of different frequencies.

Black bodies radiate at several frequencies centered about a maximum. Wilhelm Wien (1864-1928) proved that maximum energy radiated by a hot body shifts to shorter and shorter waves as the temperature rises.

The maximum in terms of frequency can be derived from the relationship

$$v = \frac{C}{\lambda}$$

Using the measured wavelength of maximum radiation we can determine the absolute temperature of an object by solving the equation which approximates Wien's Law. In the general case, Wien's Law is

$$\lambda T = w$$

in which

λ = wavelength
T = absolute temperature
w = Wien's displacement constant

An approximation of Wien's Law, with w determined experimentally is

$$\lambda = 0.2897\ T^{-1}$$

Solving Planck's equation for each frequency is tedious. Using Wien's Law, however, we find that solar radiation is centered about a wavelength near

$$\lambda = 0.2897/5800°\text{K}$$
$$= 0.5 \times 10^{-4}\ \text{cm}$$

Currently, the preferred units for wavelength are *nanometers*. The wavelength of maximum radiation energy is 500 nanometers. About 99 percent of solar radiation is contained in wavelengths defined as shortwave or solar radiation between 150 and 4000 nanometers. Of this, about 9 percent is ultraviolet (150 to 400 nanometers), 45 percent is visible to the human eye (400 to about 740 nanometers), and 46 percent is infrared (740 to 4000 nanometers) (*fig. 3*).

Terrestrial Energy Relations

A little reflection on the nature of Planck's work and Wien's Law tells us that any object whose temperature

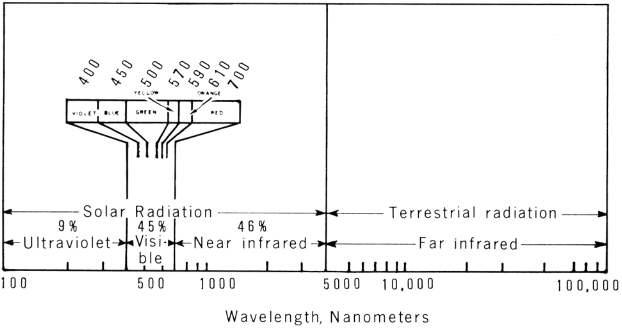


Figure 3. A portion of the electromagnetic spectrum is shown, separated into solar and terrestrial radiation. Visible, ultraviolet, and infrared light waves do not represent all of the known kinds of electromagnetic radiation. Beyond the visible and infrared toward longer wavelengths would be heat waves; beyond the shorter wavelength would be X-rays and gamma rays.

is greater than absolute zero must radiate energy in some wavelength spectrum. This is true for terrestrial objects whose temperature is much below that of solar temperature. If we consider temperatures in the range 273° to 335° Absolute (0°C to 62°C), we find the wavelength of maximum radiation to approximate from 8500 to 11,500 nanometers. These are temperatures we might expect in the forest and at soil surfaces during the year. The wavelengths are not visible, are longer than solar wavelengths and, by convention, are designated longwave or terrestrial radiation (*fig. 3*). Gases like those of the atmosphere emit radiation as well as solid objects and vegetation.

We have treated radiation from sources of various temperatures as discrete quantities, assuming each source is a perfect *black body* which absorbs and emits energy as a function of temperature. A perfect *white body* would absorb and emit nothing and, theoretically, would have a temperature of absolute zero. Most objects fall somewhere in between; that is, they do not absorb all incident energy, emit something less than the flux indicated by the Stefan-Boltzmann Law, and are referred to as *gray bodies*. The ratio of actual to theoretical emission is called *emissivity*. Emissivity is always less than unity. Gray bodies react exactly as black bodies, except that the radiation flux is lowered by a factor equal to emissivity equally in all wavelengths. The term gray body describes radiation properties and not the visible color that we see. If these imperfect absorbers and emitters also function differently at different wavelenghts, that is, if they have a spectral response, they are called *natural* bodies. Spectral responses are usually measured in bands of from 10 to perhaps 100 nanometers. Emissivity is calculated from reflectance and transmissivity of the target in the wavelength band.

Natural bodies reflect some of the energy received. If we speak of a comparatively narrow band or single wavelength, the property is usually termed *reflectivity*. A broader wavelength, such as the entire visible band, shows an integrated reflection called *albedo*. The albedo of new snow in short wavelengths may exceed 90 percent: in other words, only about 10 percent of the solar energy impinging on a snow surface is absorbed.

As solar energy is absorbed, an object warms and emits an increasing flux of longwave energy. One process that occurs naturally is the conversion of solar energy into longwave energy by all the components of the earth-atmosphere system. Since natural bodies are imperfect emitters, the law of conservation of energy implies that some absorbed solar energy is used for another purpose, or transmitted through the body and not emitted. The Stefan-Boltzmann Law can be applied to a gray body when modified by the emittance (ϵ):

$$\text{Flux} = \epsilon \delta T^4$$

The Stefan-Boltzmann Law applies also to natural bodies, but the wavelength or band must be specified as the factor ϵ may vary in different wavelength bands. We usually separate the energy spectrum into short and long wavelengths and use an integrated emissivity.

Snow serves to point out another interesting facet of energy relations. Snow has a high albedo in short wavelengths. However, in the long wavelengths it acts almost as a perfect black body. It absorbs and emits longwave energy close to the theoretical value. The same may hold true for various vegetation types and other natural features of the forest. The example of snow points out the broadband spectral nature that many natural radiation sources exhibit. When discussing energy relations we should specify the wavelength band of interest. Most natural emitters approximate gray bodies over the total longwave spectrum. Soils, vegetation, and snow properties can be approximated with the gray body equations.

ENERGY BALANCE

Of the various energy sources for the earth, the dominant one is the sun. Energy from the sun reaches the earth as shortwave radiation; some is converted to longwave radiation within the earth-atmosphere. Some energy is converted to another form within the biosphere, through chemical reactions or transpiration; some in the atmosphere, through heating; and some within the hydrologic cycle, through snowmelt and evaporation. The energy, however, is eventually released within the earth and atmosphere system because these reactions are all reversible.

Reasonably then, the earth must lose as much energy annually as it receives from the sun. Otherwise the earth and atmosphere would be getting rapidly warmer or colder. But the earth does not get rapidly warmer or colder, at least not permanently, although episodes such as the ice ages indicate there can be geologically short-term alterations.

The earth receives about 263 kly per year at the top of the atmosphere. From there, energy is distributed in the following general proportions. Considering incident shortwave solar radiation first, a reasonable distribution is:

	kly
Solar energy incident at the top of the atmosphere	263
Reflected by clouds	63
Reflected by other atmosphere constituents	15
Reflected from the surface of the earth	16
Total reflection (albedo)	94
Absorbed by clouds	7
Absorbed by other atmospheric constituents	38
Absorbed by the surface of the earth	124
Total absorption	169

One of the processes going on is the conversion of shortwave energy to longwave so that the earth can exist in an energy-balanced state. Therefore, we must lose the equivalent of 169 kly per year in longwave radiation. An approximation of the loss is:

	kly
Longwave radiation emitted by the surface of the earth	258
Lost beyond the atmosphere	20
Absorbed by the atmosphere	238
Longwave radiation emitted by the atmosphere	355
Lost beyond the atmosphere	149
Reabsorbed by the earth's surface	206
Sum of radiation lost from the surface of the earth	52
Sum of radiation lost from the atmosphere	117
Total loss	169

So the earth enjoys an energy balance, emitting as much energy as it receives. This energy is not distributed evenly, however, and varies by geographic location and date (declination). The energy surplus in areas like the tropics is transferred poleward by atmospheric and ocean currents to areas where deficits occur. Each area, then, has a "typical climate." Local climate certainly shows large annual variations—but these are variations about a mean and not simply random total changes in climate.

Although the earth as a whole is in balance, the earth's surface and atmosphere show an energy discrepancy. Examination of annual radiation fluxes shows that the earth's surface absorbs 124 kly per year and radiates 52 kly so the earth's surface gains 72 kly. The atmosphere absorbs 45 kly and radiates 117 kly per year for a negative balance of 72 kly. Energy must be transferred from the ground to the atmosphere. This occurs mainly by absorbing heat through evaporation from the surface and releasing heat by condensation in the atmosphere. Heat transfers upward by convective currents in the air. Air is warmed by conduction when in contact with warm soil and is carried upward by turbulent air movement.

LOCAL ENERGY RELATIONS

Energy fluxes at a single site may not exactly balance during a short time span, one season, for example. Over several years, however, a balance will occur such that energy received and energy lost are equal. The sun is still the primary energy source although horizontal energy transfer by atmospheric motion and ocean currents is necessary to the energy balance over the earth's surface.

Forests can be managed to take advantage of solar energy because the sun provides a predictable flux of energy from a given position. It is difficult, and sometimes impossible, to manage forests to respond to infrequent meteorological events. Solar radiation that reaches the forest is modified in several respects. Atmospheric absorption removes some energy, clouds reflect some back to space, water vapor scatters some and this reaches the earth in a diffuse form, and the incident angle of radiation serves to reduce the flux. At midlatitudes, about half of the solar radiation incident at the top of the atmosphere reaches the surface. This varies considerably depending on atmospheric conditions, elevation, and solar angle at a given site. Predicting incident solar radiation at a site is difficult because of local weather variations, but potential insolation can be estimated (Buffo and others 1972, Frank and Lee 1966).

Some incident shortwave radiation is reflected from the surface on which it falls. The albedos for surfaces we might find are:

Surface:	Albedo *Percent*
Water	6 to 21
Snow	40 to 95
Ice	30 to 40
Soil, dry	20 to 45
Soil, wet	5 to 20
Sand	35 to 45
Desert	25 to 30
Chaparral	15 to 20
Meadow	10 to 20
Forest, deciduous	10 to 20
Forest, coniferous	5 to 15

Longwave radiation is a function of atmospheric and local temperature. The geometry of the sources and sinks at the site also affects the flux of longwave radiation. Any part of the total site can act as a net source or sink of longwave radiation, depending on the effective radiating temperature. The atmosphere above the site also acts as a source or sink for energy in most of the longwave frequency band. Atmospheric components are very poor absorbers of radiation in wavelengths between 8500 and 11,000 nanometers. This "atmospheric window," so named because it is transparent to radiation, allows radiation to escape from the earth-atmosphere system. Thus the atmospheric window in the wavelength band 8500 to 11,000 nanometers shows almost complete transmission of longwave radiation. These are the wavelengths corresponding to radiation at ambient temperatures. About 9 percent of the emitted energy goes directly out of the earth-atmosphere system. Certain atmospheric components absorb longwave radiation in specific radiation wavelengths. The absorbers include water vapor (5300 to 7700 nanometers and beyond 20,000 nanometers), ozone (9400 to 9800 nanometers), carbon dioxide (13,100 to 16,900 nanometers) and clouds (all wavelengths). Absorbed radiation is reradiated in all directions, and some returns to the surface of the earth.

Energy relations at a site depend on the nature of surfaces exposed in long as well as short wavelengths. The emissivity and absorptivity of some terrestrial radiation sources are approximately:

Source:	Emissivity *Percent*
Water	92 to 96
Snow	89 to 99.5
Ice	96
Soil, wet	95 to 98
Soil, dry	90
Sand	89 to 95
Desert	90 to 91
Meadow	90
Forest, deciduous	90
Forest, coniferous	90

Albedo and emissivity will vary; therefore the tabulated values above are in the range that may be expected. Albedo increases as the incident angle of radiation decreases. The values for albedo assume the sun is near zenith, so albedos in early morning and late afternoon would be higher. Emissivity does not vary as much because it is a property of the radiating body. Emissivity, however, may vary slightly with temperature. The emissivity variance is so slight for a given natural body that it is usually ignored, except when working with narrow wavelength bands.

If we use the basic information about the sun and the radiation properties of the various surfaces in the forest, we can draw some general conclusions.

Direct solar radiation is the best variable to manage because solar location and flux are predictable. Diffused solar radiation is scattered downward from all parts of the sky and vegetation management would have small effect.

Longwave radiation fluxes occur when parts of the site absorb direct insolation. We can exert some control over longwave radiation levels by controlling the parts of a site which are exposed to solar radiation. In general, a site exposed to solar radiation shows secondary effects including increased soil temperature, maximum air temperature, evaporation, and transpiration. Heat fluxes are greatest at the ground surface, but maximum temperatures will be attained in air immediately above the ground which is receiving radiation from both the atmosphere and the ground. If streams or snow are present, the water temperature will rise, or snowmelt will be faster in the spring.

Radiation flux into the site will be greatest during midday because albedo is lowest when the sun is near zenith. Forest components are not theoretical gray bodies but have a spectral response. Soils and growing vegetation, however, absorb radiation in almost all wavelengths so they warm rapidly and emit large fluxes of longwave radiation when exposed to the sun. Snow and water are reflective in the shortwave portion of the spectrum, but are nearly perfect absorbers and emitters of longwave radiation.

MANAGEMENT TECHNIQUES

Solar radiation adds some 263 kly of energy to the earth and atmosphere each year. Although this energy is reflected or eventually emitted by the earth, some is retained and used to drive the various physiological and biological processes with which we are familiar.

The value of total incident radiation does not tell us much about the level of energy at forest sites. Tables of solar beam irradiation are available for the mid-latitudes, however. The tables published by Frank and Lee (1966) list the potential solar radiation levels for various aspects at several different dates. If we consider a level site at 40°N latitude as an example, the potential solar radiation ranges from a low of 328.9 to a high of 1022.7 ly per day. Assuming 50 percent atmospheric attenuation, the soil, snow, or vegetation receives 164.4 to 511.4 ly per day of direct beam solar radiation. If all this energy were absorbed it could, each day, melt from 2 to 6.5 cm of ice, evaporate approximately 0.3 to 0.8 cm of water, or raise the temperature of 100-cm depth of water from 1.6° to 5.1°C. Although some of this energy is converted to longwave at the site, it is all incident, and must be lost from the site in some manner. Longwave emittance, evaporation, and air movement all help dissipate the energy.

Shortwave radiation may arise from direct beam insolation or it may be reflected into a site by clouds, snow-covered slopes, or other objects. Incident shortwave radiation may exceed expected levels if additional reflected energy supplements direct solar radiation. In one case, measurements of incident shortwave radiation on a tree stem showed the highest radiation level at the north side. The source was reflected energy from a snow-covered south aspect located north of the tree.

Longwave radiation plays other important roles in forest site-energy relations. Most parts of a forest absorb longwave radiation better than shortwave; consequently, heat from longwave radiation remains within a site longer than energy from shortwave. Shielding the site from shortwave energy also lowers the longwave radiation level. Shading should include not only the soil or snow surface but also the trunks of boundary trees. Tree trunks emit high levels of longwave radiation after exposure to the sun. The snow can be shaded from both longwave and shortwave radiation by using tree shadows to shield tree trunks and the snow from direct and reradiated energy.

Managing a site to utilize tree shadows requires some new considerations. Various site conditions, such as bordering mountains, slope, aspect, latitude, and solar declination must be considered. These factors are not subject to any management scheme. Forest vegetation, however, *is* subject to management and shadows are the best tool we have to affect direct solar radiation and emitted longwave radiation. In developing management plans we have to consider both the fixed factors and those subject to management. The desired result may be reached by maintaining minimum solar exposure or by exposing an area to both direct and reradiated energy. Minimum exposure, for example, would result in lower soil temperature, delayed snowmelt, lower stream temperatures, reduced evapotranspiration, and reduced levels of other energy-dependent processes.

There are situations where maximizing solar exposure is desirable. These include clearing snow from roads or buildings, warming campsites earlier in the season, and generally increased rates of energy-dependent processes, such as organic matter oxidation.

Encouraging reproduction is a special case, with the silvicultural requirements of the desired species setting the solar energy requirements.

Modern forestry is based on a multiple-use concept. In each area we must balance our management of energy in the forest to accommodate all the uses of the land. Evaluating all variables and developing the final management plan is still the responsibility of the land manager. The management objectives determine how shadows should be used. Management plans might also indicate that only certain seasons of the year are important. For example, snowmelt occurs at the greatest rate in late spring. April and May might be considered critical and a goal of delaying snowmelt and runoff can be reached by shading the snow surface and the boles of trees surrounding small openings or strips.

Developing a set of shadow length calculations for each application would be tedious. In some situations a specific table for an area might be necessary. A computer program that completes all the necessary calculations is available (Halverson and Smith 1974a). Input data include latitude, date, east and south slope components, and the time interval needed between shadow calculations. Output information includes total, north and west shadow extent, and the sun azimuth for each time interval after sunrise.

For more general applications, tables are available for alternate latitudes between 36° and 50°N (Halverson and Smith 1974b). Seven dates between the longest and shortest day are included. Slopes are varied in both north-south and east-west dimensions to a maximum of 40°. Selection of the proper table includes determining the site latitude, dates of interest, and the slope and aspect measured in cardinal directions. Tabulated information includes the shadow vectors in cardinal directions, and the shadow length and sun azimuth for each hour after sunrise. Interpolation for intermediate latitudes, slopes, or dates will give acceptable results.

EXAMPLE: A MANAGEMENT PROBLEM

A land manager wants to harvest part of an old-growth red fir stand on a 5 to 15 percent north-facing slope at latitude 40°N at 7000-feet elevation in the Sierra Nevada of California. His objective is to delay snowmelt as late in the season as possible for late season streamflow increase, and to delay onset of the summer soils drought for increased seedling survival. He has determined that a strip-cut form of harvest in which strips would be clearcut in widths of 132 feet would be silviculturally desirable. He now must determine the optimum direction for strip orientation to achieve his objective.

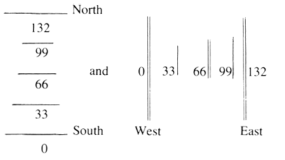
Drawing from an example used in our earlier publication (Halverson and Smith 1974a), let us assume we are interested in the distribution of energy across two long, narrow openings which are usually covered with snow in the winter. But we also need to know the energy distribution during the day and at several points in the opening.

Let us assume:

1. Latitude 40°N
2. The openings are 2 chains wide (132 feet), one is oriented N-S, the other E-W
3. The slope is 9°N
4. The date of interest is April 1
5. Border trees are 100 feet tall

We assemble some necessary information: The shadow table is available in an earlier publication (Halverson and Smith 1974b). But we need information on potential solar radiation. The tables by Frank and Lee (1966) list only *daily totals* and will not give us *distribution during the day*. Diagrams by Buffo and others (1972), however, give hourly radiation fluxes for a variety of dates and slopes, so we decide to use these tables. As often happens, the solar radiation tables do not list the exact date and slope of interest. And Buffo and others (1972) assumed an atmospheric transmission of 0.9. Transmission of solar radiation through the atmosphere varies because of changing cloud cover, turbidity, and atmospheric thickness above the site (determined by site elevation). At mid-latitudes, atmospheric transmission usually varies from about 0.5 to 0.9, with an average near 0.6. An atmospheric transmission of 0.9 might not be applicable for our purposes because of unusual local conditions, such as air pollution. Local meteorologists will be able to supply an estimate of atmospheric transmission. Difficulties are often encountered because of the extensive range of slopes and numerous dates for which transmission coefficients would yield an almost infinite number of combinations. If the site is very critical, corrections would be required. But for most purposes we can accept some approximations. We will assume:

1. Use the solar radiation isogram for March 21 (Buffo and others 1972).
2. Divide the openings by half chain intervals as shown in the following drawing.



East-West orientation North-South orientation

3. Use 1-hour intervals, starting at 05.78 hours, sunrise, to 17.78 hours, just before sunset.
4. A—in the data column indicates the point is in the shade, and 100 percent of the solar beam irradiation was intercepted by the border vegetation.

The calculations done hourly from sunrise to sunset would yield an insolation profile *(table 1)*.

We can check our calculations by noting that radiation total at a point exposed all day, about 540 ly, falls within the range given by Buffo and others (1972) which is 564 for a slope of 0 and 420 for a slope of 15 percent. Also, we need to note the uneven radiation distribution evident in the opening oriented east and west.

Table 1. Hourly insolation profile ($ly\ hr^{-1}$) for March 21 across a 132-foot-wide clearcut strip at 39.5° N latitude

Time	East-West Orientation					North-South Orientation				
	0	33	66	99	132	0	33	66	99	132
05.78	--	--	--	--	--	--	--	--	--	--
06.78	--	--	10	10	10	--	--	--	--	--
07.78	--	--	--	30	30	--	--	--	--	--
08.78	--	--	--	50	50	--	--	--	--	--
09.78	--	--	--	60	60	60	60	--	--	--
10.78	--	--	--	77	77	77	77	77	--	--
11.78	--	--	--	77	77	77	77	77	77	--
12.78	--	--	--	77	77	--	77	77	77	77
13.78	--	--	--	60	60	--	--	60	60	60
14.78	--	--	--	50	50	--	--	--	--	50
15.78	--	--	--	30	30	--	--	--	--	--
16.78	--	--	--	20	20	--	--	--	--	--
17.78	5	5	5	5	--	--	--	--	--	--
Total	5	5	15	546	541	214	291	291	214	187

It is evident that from about 9 a.m. to about 4 p.m., the north wall of timber and the last 35+ feet of snow in the east-west cut strips were subjected to large amounts of solar radiation. The north wall of timber heated up from this constant radiation would, in turn, radiate heat to the pack.

In the north-south oriented strip, the snow across the strip was subjected to direct radiation only for a 3 to 4 hour period at any point rather than for the entire day, as shown in the east-west strip situation.

The snowmelt pattern which resulted was such that, on May 4, 1966 when only 2 area inches of water were left in the snowpack next to the south wall of timber in the east-west strips, there was a complete cover of snow over the north-south strip. It contained 10 inches of water *(figs. 4 and 5)*.

Conifer seed germination and seedling survival were abundant and uniformly distributed across the north-south oriented strips. The abundant number of seedlings found near the south side of the east-west oriented strips decreased significantly in direct relation to nearness to the north wall of timber.

Number of seedlings surviving the dry summer on this transect were in direct relation to the length of time snow remained on the soil. Snow disappeared early enough along the north wall of the east-west strip so that low, night air temperatures caused freezing of the exposed soil and the seedlings frost-heaved. Because the soil in this area was subjected to more heat, it dried out earlier and the seedlings were desiccated. A successful seedling crop was established only after a spring in which massive winter snows did not melt until mid-June. At this time danger of frost-heave had ceased, the summer drought was short enough to prevent massive early season desiccation of the soil, and the more vertical sun did not heat up the north wall of timber to the extent possible in April and May.

Although this illustration relates to soil moisture and seedling survival, one may control solar radiation with shadows, or their lack, for many purposes. Stream temperatures may be ameliorated, snow covered campgrounds opened up sooner, snow covered roads may be opened sooner or kept closed longer, and many other goals may be achieved by using the sun's energy both as direct radiation and as absorbed and reradiated heat.

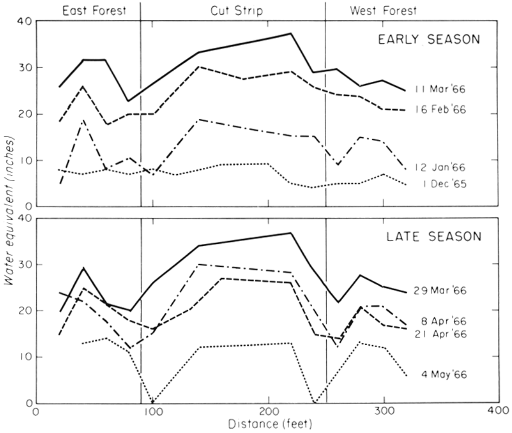


Figure 4. Water content of the snowpack varied by location across a 166-foot wide east-west oriented clearcut strip and in the adjacent forest to north and south.

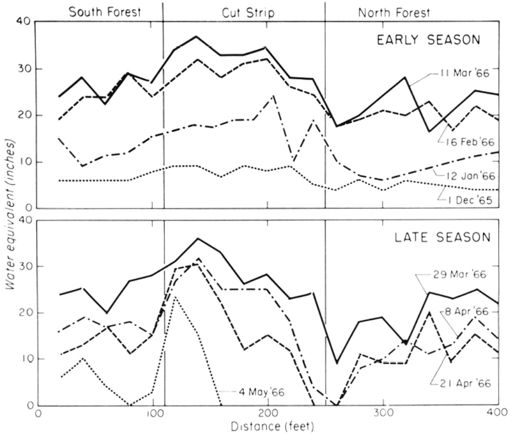


Figure 5. Water content and location of the snowpack across a 166-foot wide north-south oriented clearcut strip and in the adjacent forest to the east and west.

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