The effect of surrounding topography on receipt of solar radiation

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ABSTRACT Characteristics of radiation receipt in basins can be measured or modeled. The modeling approach is of particular value when site specific data are not available or when estimates are required for a large number of sites. This study was performed to assess annual solar radiation on sites in terrain where surrounding ridges and tall trees block both direct beam and sky diffuse short wave radiation. The model used here accounts for topographic blocking of direct beam radiation, anisotropic diffuse radiation and ground reflected radiation. Model results show the importance of various components of short wave radiation at a site. A procedure is outlined for using the model to calculate radiation receipt for an entire basin.

L'effet de la topographie avoisinante sur la réception de rayonnement solaire
RESUME Les caractéristiques de la réception en rayonnement de bassins peuvent être mesurées ou modélisées. La modélisation est utile quand les données spécifiques au site sont inexistantes, ou quand on a besoin d'estimations pour un grand nombre de sites. Le but de cette étude était l'évaluation du rayonnement annuel direct et diffus atteignant des sites à l'ombre d'arbres ou d'accidents de terrain. Le modèle utilisé tient compte du blocage topographique du rayonnement direct, du rayonnement diffus anisotropique et du rayonnement réfléchi par la surface du sol. Les résultats du modèle indiquent l'importance relative de chaque composante radiative de courte longueur d'onde sur le site. On présente aussi une procédure visant à utiliser le modèle pour calculer la réception de rayonnement sur un bassin entier.

INTRODUCTION

Solar radiation is a major factor controlling forest site productivity and tree growth. This radiation, the major component
of the energy budget for a site, supplies the energy for growth, evaporation, and environmental heating. Solar radiation can be either beneficial or detrimental to plant growth. In situations where plants grow in close proximity there is competition for photosynthetically active radiation, whereas abundant radiation can create excessive temperature or water demand.

Use of intensive field measurements may be preferred for evaluation of solar radiation but is seldom a viable option on a large scale. As a result, modeling approaches are used either without benefit of any measured data or as a tool to extrapolate measured results from a nearby site. Modeling the radiation environment is an attractive alternative because the cost of obtaining information is relatively low. The success of the modeling approach depends on the availability of the data required to execute the model and the quality of the predictions. In steep terrain, modeling procedures to extrapolate nearby data are complicated by the need for detailed knowledge about the surrounding topography and the skyview at a specific site.

There are techniques available to model radiation which range in accuracy and may be used depending on specific needs. These include calculation of potential direct beam solar radiation without correcting for effects of the atmosphere (e.g. Frank & Lee, 1966), calculation of direct and diffuse shortwave radiation components based on simple attenuation models of the atmosphere (e.g. Bristow et al., 1985) and detailed consideration of the nature of scattering in the atmosphere (e.g. Iqbal, 1983; Grant, 1985).

This paper uses a solar radiation calculation procedure developed to assess clear sky radiation on reforestation sites in steep terrain (Flint & Childs, 1987). The model accounts for the distribution of blocked direct beam radiation on sites in high relief topography; the anisotropic distribution of diffuse radiation, effects of topographic shading on total diffuse load and the fractions of ground reflected and sky radiation when the sky occupies less than 2π steradians of the hemisphere above a site. This report evaluates the influence of slope, aspect and irregular horizons on the annual radiation delivery to a site.

MODELING TECHNIQUE

Proper calculation of total solar radiation receipt on a specific site requires that three factors be treated: 1) position of the sun with respect to the location of a specific site on both daily and seasonal time scales; 2) atmospheric conditions that affect transmission, reflection and scattering of direct beam solar radiation (treatment of these conditions should allow calculation of the diffuse radiation in the sky); and 3) location and orientation of the receiving surface.

Atmospheric effects are the most difficult factors to determine in calculating the distribution of solar radiation. The intensity of direct beam radiation is reduced and diffuse radiation is increased as the solar beam passes through the atmosphere. Part of the direct beam is reflected at the top of the atmosphere, part is scattered as diffuse radiation, and part is absorbed by the
Effect of topography on solar radiation

Some models calculate diffuse radiation as a percentage of either potential direct beam (Beschta & Weatherred, 1984) or total potential radiation minus actual direct beam (List, 1971; Bristow et al., 1985). These techniques are subject to error when atmospheric conditions change with time or if the solar beam is blocked for significant periods of time by surrounding topography.

Another class of models separates measured values of radiation into direct and diffuse components (Bristow et al., 1985; Weiss & Norman, 1984; Harrington, 1984) so that components can be applied independently to other nearby sites. The separated direct beam radiation component is corrected to the new slope and the diffuse component is added back. Caution is necessary if the new site has a significantly different surrounding topography which affects diffuse radiation.

Another major consideration in modeling clear sky diffuse radiation is the anisotropic distribution in the sky with a large portion near the position of the sun (Stevens, 1977; McArthur & Hay, 1981; Grant, 1985; Klucher, 1979). Because radiation scattered by aerosols has a strong forward-scatter component, a substantial portion of the aerosol-scattered diffuse radiation appears to come from a small annular area around the sun. Flint & Childs (1987) adopted the simple procedure of separating diffuse radiation into two components: a circumsolar component of aerosol-scattered radiation and an isotropically distributed component consisting of Rayleigh scattered radiation, ground reflected radiation and the remaining aerosol scatter not attributed to circumsolar radiation.

The receiving surface also must be specifically evaluated before models can be directly applied. Latitude and longitude must be known but can usually be assumed constant for a basin. Elevation, slope, aspect, the height of surrounding ridges and albedo of the surrounding area are point specific factors which will vary significantly within a basin. These can be determined during a site visit with an altimeter, clinometer and compass. Flint & Childs (1987) recommended that the elevation of the effective horizon be measured every 10° around the compass. Similar information can also be obtained from topographic maps. Knowledge of the effective horizon is used to block direct beam solar and circumsolar diffuse radiation. It also allows separation of the "hemisphere" above a site (Fig.1) into sky (contributing isotropic diffuse radiation) and ground (contributing ground reflected radiation).

The model was run using a variety of receiving surface conditions to examine the effects of slope, aspect and horizon on radiation delivery. The horizon data at Wolf Creek, Oregon, USA and seasonal atmospheric conditions are given in Flint & Childs (1987).

RESULTS AND DISCUSSION

The steps to model the daily shortwave radiation for a site are shown in Fig.2. This series of graphs shows the major changes needed to correctly account for surrounding topography. In Fig.2a, the atmospheric portion of the model calculates solar radiation as 21% greater than the measured value with no corrections made for surrounding topography. In Fig.2b, the model blocks direct beam radiation according to the surrounding topography (Fig.1a) so that
only diffuse radiation reaches the site early and late in the day. Now, modeled radiation is only 5% greater than measured but there is still error in the diffuse radiation calculation. Fig. 2c demonstrates that blocking circumsolar diffuse radiation brings model calculation within 2% of measured values (a figure approaching the accuracy of our instrumentation). The magnitude of the effects shown in Fig. 2 will increase for sites deep in valleys or adjacent to tall ridges. Although the improvement in model results caused by accounting for circumsolar diffuse radiation is small (the difference between Figs 2b & 2c), this correction is important when extrapolating results in steep terrain.

FIG. 1 View of the sky dome from site at Wolf Creek, Oregon. The solar paths for the summer and winter solstice show topographic blockage (shaded area) of direct beam and circumsolar radiation. a) actual horizon, b) horizon elevated 10°, c) horizon elevated 30°.

The monthly contribution of four radiation components is shown in Fig. 3. Ground reflected radiation averages 8% throughout the year but makes a larger contribution (15%) in winter when snow cover increases ground albedo. Circumsolar diffuse radiation comprises about 7% of the total radiation but is as large as 15% during the summer months when increased atmospheric turbidity increases aerosol-scattered radiation. The decline in direct beam radiation during the summer is due to decreased atmospheric transmission. Although direct beam radiation is the major component it only
Effect of topography on solar radiation contributes about half of the total radiation in January when isotropic diffuse and ground reflected radiation components are large.

![Graph](image)

**FIG. 2** Measured shortwave radiation (dots) with modeled diffuse and direct beam radiation (solid lines): (a) standard calculations without correction for surrounding topography, (b) incorporation of surrounding topography to block direct beam radiation and (c) incorporation of surrounding topography to block both direct beam and circumsolar diffuse radiation. (Fig. after Flint & Childs, 1987).

![Graph](image)

**FIG. 3** Seasonal contribution of radiation components: direct beam, circumsolar diffuse, isotropic diffuse, and ground reflected radiation. Atmospheric conditions are for Wolf Creek, OR, 1983.
The contribution of ground reflected and isotropic diffuse radiation is important in steep terrain when direct beam and circumsolar diffuse radiation is blocked. This model calculates these components to be larger than more simplified models of diffuse radiation. As a result, comparisons among sites are less dramatic than those made with models that do not account for changing atmospheric and ground albedo conditions. This observation has been made by others working in mountainous terrain (e.g. Olyphant, 1986) but in general, more variation in radiation environment is seen in steep terrain where slope and sky view effects are important.

The atmospheric conditions for Wolf Creek, Oregon, USA, 1983 (Flint & Childs, 1987), were used in model calculations of the seasonal influence of slope. By mid-June, the highest daily radiation load is on a 15° slope with a south aspect (Fig.4). At this longitude (42°N) the sun reaches a maximum zenith angle of 71° (19° slope would have a 90° zenith angle at this time). As the slope increases beyond 15° (19° actually) the maximum radiation is reduced in the summer but increases in the winter when the zenith angle is lower and radiation is more direct on the steeply sloping surfaces.

![Graph](image)

**FIG.4** Radiation received on south-facing sites with different slopes.

A striking effect of slope to the south is the change in timing of peak radiation loads. The more constant daily radiation on south-facing slopes between 45 and 75° can have beneficial effects on site climate. In February and March, increased radiation receipt hastens soil warming. This is an advantage in situations where
sites are dry during the summer months. Lower daily radiation at the end of the summer (when plants on dry sites experience water or heat stress) may also be advantageous.

In the northern hemisphere, increasing slope to the north always causes a reduction in total radiation (Fig.5). The curves do not resemble those of south aspects; they always have a midsummer peak and the peak decreases with increasing slope. On slopes greater than 30°, there are portions of the winter when there is no direct beam radiation. During these periods, total radiation can be between 1 and 5 MJ m⁻² day⁻¹ depending on atmospheric conditions and ground albedo. The range in radiation shown in Figs 4 and 5 demonstrates that slope to the north has a larger effect on radiation climate than slope to the south.

![Graph showing radiation received on north-facing sites with different slopes.](image)

**FIG. 5** Radiation received on north-facing sites with different slopes.

The effect of topography surrounding a site can be as dramatic as the effect of slope to the north. This influence was assessed by modifying the effective horizon used in model calculations. This was simulated by adding 10° increments to the blocking ridges (Fig.1). The sun is low enough in the winter sky so that increasing the height of the ridges by 30° or more blocks all direct beam radiation (Fig.6). The effect of increased horizon elevation is an overall decrease in radiation and the duration of peak radiation is intermediate between the short peaks of north slopes and the broad peaks of steep south slopes. The pattern of reduction in radiation with increasing elevation of surrounding topography is strongly
dependent on the specific conditions at a site. In the case shown, the first increments in elevation are less important than the succeeding ones. At elevations greater than 30°, there is also a large reduction in isotropic diffuse radiation because the sky view is small. As a result, there can be as little as 2 MJ m\(^{-2}\) day\(^{-1}\) on these sites. That is, topography can create lower radiation environments on south slopes than those occurring on north slopes (Fig. 5).

![Diagram of radiation received on a south-facing slope](image)

**FIG. 6** Radiation received on a south-facing slope with the surrounding ridges (Fig. 1) increased in height by 10° increments.

This technique of simulating topographic effects on radiation is of value for basin studies because it is quite simple. The site specific parameters required for input are basic and simple to acquire. Although the atmospheric portion of the model is complex, published values of atmospheric conditions and a series of empirical equations can be used to adequately predict clear sky radiation (Flint & Childs, 1987). The technique of increasing the elevation of surrounding topography to simulate increased distance into a valley is very simple and could be replaced by more sophisticated models. Nevertheless, total radiation load in a basin can be calculated using slope, aspect and ridge-height classes weighted by the percentage of total area in each class. Another application of this model would be prediction of radiation at sites near to a radiation measuring station. The model would allow extrapolation with good accuracy because a measured dataset could be used to calibrate the model and it would also identify cloudy and partly cloudy days.
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REFERENCES


