JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 44, No. 6 AMERICAN WATER RESOURCES ASSOCIATION December 2008

GUIDELINES FOR RIPARIAN VEGETATIVE SHADE RESTORATION BASED UPON A THEORETICAL SHADED-STREAM MODEL[1]

David R. DeWalle[2]

ABSTRACT: Guidelines for riparian vegetative shade restoration were developed using a theoretical model of total daily radiation received by a shaded stream. The model assumed stream shading by nontransmitting, vertical or overhanging, solid vegetation planes in infinitely long reaches. Radiation components considered in the model were direct beam shortwave on the stream centerline, diffuse atmospheric shortwave, shortwave reflected by vegetation, atmospheric longwave, and longwave emitted by vegetation. Potential or extraterrestrial shortwave irradiation theory was used to compute beam shortwave radiation received at the stream centerline, and view factor theory was used to compute diffuse radiation exchange among stream, vegetation, and atmospheric planes. Model shade effects under clear skies were dominated by reductions in receipt of direct beam shortwave radiation. Model shade effects with cloudy skies were dominated by the "view factor effect" or the decreases in diffuse shortwave and longwave radiation from the atmosphere balanced against increases in longwave radiation from vegetation. Model shade effects on shortwave radiation reflected by vegetation were found to be negligible. The model was used to determine the vegetation height (H) to stream width (W) ratios needed to achieve 50, 75, and 90 % shade restoration for mid-latitude conditions on clear and cloudy days. Ratios of vegetation height to stream width, for dense nontransmitting vegetation, generally ranged from 1.4 to 2.3 for 75% shade restoration at a mid-latitude site (40°N). The model was used to show H/W needed for E-W *vs*. N-S stream azimuths, varying stream latitudes between 30° and 50°N, channels with overhanging vegetation, channels undergoing width changes, as well as the limits to shade restoration on very wide channels.

(KEY TERMS: restoration; stream temperature; riparian ecology; best management practices; modeling; radiation view factors; vegetation overhang angles; stream azimuth; extraterrestrial solar radiation.)

DeWalle, David R., 2008. Guidelines for Riparian Vegetative Shade Restoration Based Upon a Theoretical Shaded-Stream Model. *Journal of the American Water Resources Association* (JAWRA) 44(6):1373-1387. DOI: 10.1111/j.1752-1688.2008.00230.x

INTRODUCTION

Restoration of riparian vegetative shade to improve water temperature regimes and help rehabilitate aquatic ecosystems is becoming a common watershed management practice (Broadmeadow and Nisbet, 2004; Kauffman *et al.*, 1997; Poole and Berman, 2001; Roni *et al.*, 2002; Rutherford *et al.*, 1997a; Watanabe *et al.*, 2005). Many streams have lost riparian vegetation due to human disturbances (agriculture, forestry, urbanization, mining, etc.) or natural

[1]Paper No. JAWRA-07-0124-P of the *Journal of the American Water Resources Association* (JAWRA). Received August 31, 2007; accepted February 12, 2008. **Discussions are open until June 1, 2009**.

[2]Professor Emeritus of Forest Hydrology, School of Forest Resources, and Penn State Institutes for Energy and the Environment, 107 Land and Water Research Bldg., The Pennsylvania State University, University Park, Pennsylvania 16802 (E-mail/DeWalle: drdewalle@psu.edu).

disasters (high winds, fire, flooding, etc.) which has resulted in increased maximum daily stream temperatures and loss or modification of aquatic ecosystems (Bartholow, 2000; Borman and Larson, 2003; Brown, 1970; LeBlanc *et al.*, 1997; Lynch *et al.*, 1984; Moore *et al.*, 2005; Scarsbrook and Halliday, 1999; Swift and Messer, 1971; Wilkerson *et al.*, 2006; Zwieniecki and Newton, 1999). Shifts in aquatic macro- and microflora and fauna due to changing thermal regimes in streams caused by changes in shading have been reported in many regions (Whitledge *et al.*, 2006; Parkyn *et al.*, 2003; Sweeney, 1993; Harding *et al.*, 2006). Spring-fed headwater streams in karst terrain found in states like Pennsylvania have been partially converted from cold-water to warm-water fisheries by loss of shade (Grant, 2005), which provided further local incentive for this paper.

A major question that arises in re-establishing riparian shade is what amount and type of shade is necessary to significantly affect the heat balance of the stream. Other related questions are whether smaller headwater streams can be significantly shaded by short grass and shrub vegetation rather than taller trees, the benefits of using overhanging vegetation, effects of stream width changes during shade restoration, and the effectiveness of shade restoration on larger streams and rivers.

Small headwater channels with shade from relatively tall, dense trees, receive most of their radiation as longwave radiation from vegetation and a varying component of transmitted shortwave radiation. In these situations, emphasis can be placed on specification of the buffer zone width, height, leaf area index, tree crown diameter, and/or density to be maintained or cultivated. Forested buffer zone widths ranging from about 9-30 m width are generally considered adequate to maintain thermal regimes in such small streams (Beschta *et al.*, 1987; Sridhar *et al.*, 2004; Lanini *et al.*, 2004; Wilkerson *et al.*, 2006; Zwieniecki and Newton, 1999). An alternative approach for transmitted radiation is specification of the crown cover above the channel (Tate *et al.*, 2005) or the fraction of incoming shortwave radiation transmitted by vegetation (Amaranthus *et al.*, 1989; Davies-Colley and Payne, 1998). For example, forest streams may only naturally receive 10-20% of above-canopy solar radiation during summer when maximum temperatures occur, but receipt of only 30-50% of incoming solar after restoration is often considered desirable or acceptable (Davies-Colley and Quinn, 1998; Broadmeadow and Nisbet, 2004; Rutherford *et al.*, 1997a).

Transmission of shortwave radiation through vegetation is a complex process that depends upon an attenuation coefficient, the plant or leaf area index, arrangement and clumping of plant parts and the path length for radiation transmission within vegetation. Applicability of simple exponential Beer's Law models to transmission of shortwave radiation has been tested (Aubin *et al.*, 2000; Baldocchi *et al.*, 1984; Federer, 1971; Link *et al.*, 2004) and found primarily suited to relatively homogeneous vegetation layers. Transmission in more heterogeneous or discontinuous vegetation can be analyzed using more data-intensive simulation models (Li *et al.*, 1995) or hemispherical photography of the plant canopy along channels (Hardy *et al.*, 2004).

At the other extreme, where riparian vegetation is completely absent or very sparse, shading may be initially limited to that caused by stream banks and local topography. In this situation, the ultimate height and overhang of vegetation in relation to stream width and stream azimuth, which control shadow lengths and receipt of direct beam shortwave radiation, become more important variables. Ratios of vegetation height to stream width are proposed in this paper as a useful way to characterize shade. The greater importance of shade for smaller headwater channels, where the lower water depths can lead to more-rapid and greater heating of the stream, than for deeper, higher-order channels where heating is less rapid is well known (Poole and Berman, 2001; Chen *et al.*, 1998b; Rutherford *et al.*, 1997b). Experimental development of shade restoration guidelines is difficult due to the large number of controlling variables, and modeling is probably the best way to infer such guidelines.

Models vary in treatment of shortwave and longwave fluxes and effects of riparian shade. Models generally include a reduction in the receipt of shortwave radiation by shaded streams (Meier *et al.*, 2003; Sinokrot and Stefan, 1993) or separate reduction procedures for direct beam shortwave radiation with consideration of transmission by vegetation and diffuse shortwave radiation from the atmosphere (Bartholow, 2002; Chen *et al.*, 1998a; LeBlanc *et al.*, 1997; Quigley, 1981; Rutherford *et al.*, 1997b; Sridhar *et al.*, 2004; Welty *et al.*, 2002; Tung *et al.*, 2007). Topographic shading is considered separately from vegetative shading in some applications where transmission by vegetation is considered (Bartholow, 2002; Chen *et al.*, 1998a; Rutherford *et al.*, 1997b). Diffuse atmospheric shortwave radiation received by shaded streams is generally reduced by the view factor from the stream to atmosphere and in some applications view factors are also used to compute atmospheric longwave radiation (Bartholow, 2000; DeWalle, 1974; Quigley, 1981; Rutherford *et al.*, 1997b; Chen *et al.*, 1998a; LeBlanc *et al.*, 1997; O'Driscoll and DeWalle, 2006; Tung *et al.*, 2007). Longwave radiation exchange corrections with view factors become important when the radiating temperatures and emissivities of riparian vegetation are significantly different from that of the atmosphere. Shortwave radiation reflected to the stream by riparian vegetation has not generally been considered; DeWalle (1974) found negligible amounts of reflected shortwave radiation received by rivers in large valleys. View factors can be computed from measurements along shaded channels (Rutherford *et al.*, 1997b; Welty *et al.*, 2002) or by heat transfer theory (Holman, 1972) assuming simple geometric shapes for shaded stream cross-sections (DeWalle, 1974). Overhanging vegetation effects have been implicitly considered in a few models where crown diameter of trees is allowed to overlap the channel width (Chen *et al.*, 1998a; Quigley, 1981). As vegetative shading will affect direct beam and diffuse shortwave differently, shading effectiveness should also vary between clear and cloudy days. Overall, application of models to specific locations requires considerable site-specific data inputs.

Shade restoration in this paper is defined as the process of converting the incoming radiation regime of exposed streams, typically dominated by direct beam shortwave radiation and atmospheric diffuse shortwave and atmospheric longwave radiation, into the incoming radiation regime typical of heavily shaded streams dominated by longwave radiation from vegetation. Due to the lack of general guidelines for shade restoration for channels that initially have little to no shade, the major objective of this paper was to determine an index of shading needed to reduce all-wave radiation received by exposed streams to 50, 75, and 90% of that for fully shaded streams for various stream azimuths and latitudes, based upon vegetation height to stream width ratios. Other sub-objectives were to: (1) quantify the net impact of increased shading on direct beam solar radiation relative to other shortwave and longwave radiation fluxes to the stream, (2) estimate the relative importance of increased shade on shortwave radiation reflected to small streams by riparian vegetation, and (3) determine the impact of overhanging vegetation on stream radiation receipt in terms of an overhang angle.

SHADED STREAM MODEL

A shaded stream model was developed assuming an infinitely long, horizontal stream plane which was shaded by two adjoining, parallel, nontransmitting vegetation planes of equal height (Figure 1). Shading by both vertical and overhanging vegetation planes was considered. Direct beam shortwave radiation receipt on the stream centerline was computed using potential or extraterrestrial solar irradiation theory (Lee, 1978) for entire days. Diffuse shortwave and longwave radiation receipt by the stream plane was computed using radiation exchange view factor theory (Holman, 1972), which assumes isotropic diffuse radiation exchange.

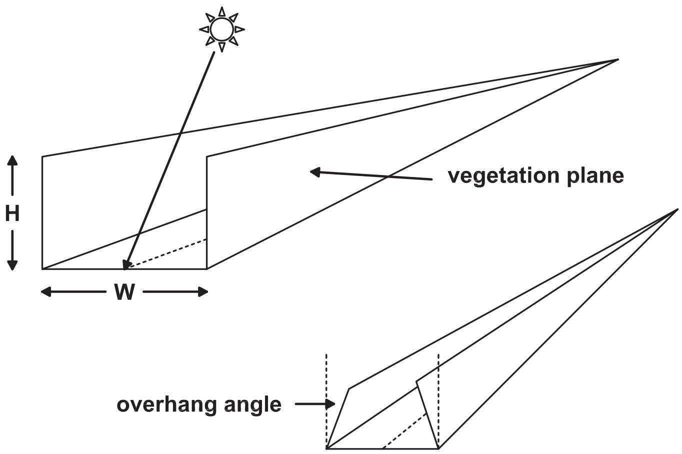

FIGURE 1. Model of an Infinitely Long Shaded Stream Section With and Without Vegetation Overhang Used in the Theoretical Analysis.

Shortwave Radiation

Shortwave radiation reaching a shaded stream surface was modeled as the sum of a direct beam solar ($K{\downarrow}_{\mathrm{beam}}$) and two diffuse shortwave radiation components; one diffuse component representing shortwave from the atmosphere ($K{\downarrow}_{\mathrm{atm\ diffuse}}$) and the other diffuse reflected by riparian vegetation ($K{\downarrow}_{\mathrm{refl\ diffuse}}$) as

$$K{\downarrow}_{\mathrm{stream}} = [\mathrm{FP} \cdot K{\downarrow}_{\mathrm{beam}}] + [F_{\mathrm{s-a}} \cdot K{\downarrow}_{\mathrm{atm\ diffuse}}] + [2F_{\mathrm{s-v}} \cdot K{\downarrow}_{\mathrm{refl\ diffuse}}], \quad (1)$$

where $K{\downarrow}_{\mathrm{stream}}$ is daily total incoming shortwave radiation at the stream surface, FP is the ratio of daily potential or extraterrestrial solar irradiance on the centerline of a shaded plane to that on an unobstructed plane at the top of the atmosphere, $K{\downarrow}_{\mathrm{beam}}$ is the incoming daily shortwave beam radiation reaching an unobstructed horizontal surface, $F_{\mathrm{s-a}}$ is the view factor from stream plane to atmosphere plane, $K{\downarrow}_{\mathrm{atm\ diffuse}}$ is the incoming daily shortwave atmospheric diffuse radiation reaching an unobstructed horizontal surface, $F_{\mathrm{s-v}}$ is the view factor from stream plane to vegetation plane on one bank, and $K{\downarrow}_{\mathrm{refl\ diffuse}}$ is the incoming daily shortwave diffuse radiation received and reflected by vegetation planes. FP can be determined by theoretical analysis of beam irradiation, ignoring atmospheric attenuation, at the stream center-line for a given *H/W* and stream azimuth, latitude and time of year (summer solstice assumed). The necessary view factors $F_{\mathrm{s-a}}$ and $F_{\mathrm{s-v}}$

were derived from heat transfer theory and shaded stream reach geometry. The incoming radiation totals $K{\downarrow}_{beam}$, $K{\downarrow}_{atm\ diffuse}$, and $K{\downarrow}_{refl\ diffuse}$ can be measured, extrapolated from published data, as in this analysis, or computed using theoretical relationships (Niemelä *et al.*, 2001; Iqbal, 1983).

Longwave Radiation

Longwave radiation received by shaded streams derives from atmospheric longwave emissions reaching the stream plane and longwave radiation emitted by vegetation along both banks as

$$L{\downarrow}_{stream} = [F_{s-a} \cdot L{\downarrow}_{atmos}] + [2F_{s-v} \cdot L{\downarrow}_{veg}], \tag{2}$$

where $L{\downarrow}_{stream}$ is the daytime total longwave radiation received by the stream surface, $L{\downarrow}_{atmos}$ is the daytime longwave radiation received from the atmosphere on an unobstructed surface, and $L{\downarrow}_{veg}$ is the daytime longwave radiation emitted by riparian vegetation. Longwave radiation fluxes from vegetation or the atmosphere can also be measured, extrapolated from published data or computed using the Stefan-Boltzmann law where

$$L{\downarrow} = \varepsilon \sigma T^4, \tag{3}$$

where $L{\downarrow}$ is the longwave flux density in W/m^2, ε is the emissivity of the radiator (atmosphere or vegetation), σ is the Stefan-Boltzmann constant or 5.67×10^{-8} W/m^2/K^4, and T is the absolute temperature (°K) of the radiator. Emissivity of clear sky varies mainly with water vapor content, whereas emissivity for cloudy sky is increased by cloud cover (see Duarte *et al.*, 2006; Crawford and Duchon, 1999). Emissivity for vegetation generally exceeds 0.95 (Oke, 1987). Given the low longwave reflectivity of vegetation and soil (<5%), reflection of longwave radiation to streams was ignored in this analysis.

METHODS

Fraction of Potential Solar Irradiation

Equations describing the solar altitude and solar azimuth angles for any latitude, time of year, and time of day (List, 1968) were used to establish times of sunrise and sunset on the shaded stream (Figure 1). Height of the vegetation (H), stream width (W), and stream azimuth were varied to simulate a range of conditions. Once the times of sunrise and sunset on the stream plane were established, the potential solar irradiation of the unshaded or shaded stream plane during a day was computed as (Frank and Lee, 1966)

$$I = (I_o/r^2)[(t_2 - t_1) \cdot \sin \text{lat} \cdot \sin d + 3.8197 \cdot \cos \text{lat} \cdot \cos d \cdot (\sin \omega t_2 - \sin \omega t_1)], \tag{4}$$

where I_o is the solar constant (1360 W/m^2), r is the radius vector which corrects for varying earth-sun distance, t_2 is the sunset time, t_1 is the sunrise time, lat is latitude, d is solar declination which varies with time of year, and ω is the daily angular velocity of the earth's rotation (2π radians per 24 hours).

The stream centerline was used as the point of reference for FP computations and stream azimuths were varied from N-S to E-W. Vegetative shade altitudes, or angle between the stream centerline and the top of the vegetation plane in the direction of the sun, were computed for incremental 0.1 hour time steps from sunrise to sunset on an unobstructed horizontal plane. Sunrise occurred on the stream centerline whenever the solar altitude exceeded the shade altitude and sunset on the stream occurred whenever solar altitude fell below shade altitude. Double sunrise and sunset times can occur particularly for E-W stream azimuths, where the stream centerline would be shaded at noon but illuminated for a period in the morning when the sun was in the East and for a period in the afternoon when the sun was from the West. Calculations were conducted for the summer solstice (June 21, solar declination = +23.5°) when the sun is at its maximum elevation during the year for a given latitude; shading would be greater at other times of year. Emphasis was given to computations for 40°N latitude, which generally represents conditions in the mid-latitudes of the United States (U.S.), but results for 30°N and 50°N latitudes are also shown.

Knowing the appropriate sunrise and sunset times for the unobstructed and shaded stream plane and values of r and d from ephemeris tables (List, 1968; Frank and Lee, 1966), the fraction of potential or extraterrestrial beam radiation received by the stream was computed as

$$\text{FP} = I_{stream}/I_{horizontal} \tag{5}$$

using Equation (4) for shaded (I_{stream}) and exposed ($I_{horizontal}$) stream conditions, respectively. FP was then be used to represent the fraction of beam shortwave radiation reaching the stream plane over a given day using Equation (1). Double sunrise and sunsets required two integrations to obtain FP and I_{stream} for a given day.

Effects of varying vegetation overhang angle on FP were computed from simple geometry within the shaded stream reach. Overhang angle was defined as the angle between the vertical and a line from the stream edge to the bottom edge of overhanging foliage (Figure 1). Effects of overhang angle were given as a family of curves (Figure 4), each for a different H/W without overhang, showing how the effective H/W ratios increase with increasing overhang angle. Overhang angle also affects the view factor from the stream to vegetation for a given H/W as described below.

View Factors

View factors were used to approximate exchange of diffuse radiation between plane surfaces in the stream-atmosphere-vegetation system. The view factor between two infinitely long parallel planes of width = W separated by distance H was computed (Hottel, 1931) and used to represent the view factor from the stream to the atmosphere as

$$F_{s-a} = [1 + (H/W)^2]^{1/2} - H/W \tag{6}$$

As the sum of view factors from a plane surface to all surfaces in the hemispherical view above the plane must add to unity, $1 - F_{s-a}$ represents the view factor from the stream to the vegetation along both banks ($2F_{s-v}$). Alternatively, the view factor between two infinitely long planes sharing a common edge with a 90° included angle can be computed (Siegel and Howell, 2001) and used to represent the view factor from the stream plane to vegetation along one bank as

$$F_{s-v-90} = 1/2\,\{1 + H/W - [1 + (H/W)^2]^{1/2}\} \tag{7}$$

The view factor from an infinitely long stream plane to an overhanging infinitely long vegetation plane with an included angle <90° (α) can be similarly computed (Schröder and Hanrahan, 1993) as

$$F_{s-v-<90} = 1/2\,\{A + 1 - [A^2 + 1 - 2A\cos\alpha]^{1/2}\}, \tag{8}$$

where $A = H/(W \sin \alpha)$ and $0 \geq F_{s-v-<90} \leq 1$. In Equations (6-8), the term W is analogous to the width of the stream plane and H to the vertical height of the vegetation plane. Equations (7) and (8) can also be used to compute view factors from stream to vegetation planes of unequal heights on opposing banks, although only symmetrically shaded stream sections are considered here.

Modeling Radiation Received by Streams

Radiation received by shaded streams using Equations (1) and (2) was computed for mid-latitude conditions (40°N) using representative radiation data from Pennsylvania (Table 1). Emphasis is placed upon clear-sky and the summer solstice conditions when maximum solar radiation and maximum stream heating are likely to occur, although results for cloudy conditions in summer are also given. Potential or extraterrestrial solar irradiation on a horizontal surface at the top of the atmosphere for the summer solstice (42.81 MJ/m^2/day at 40-42°N latitude) was used as a starting point (Frank and Lee, 1966). Clear-sky global radiation (direct beam plus diffuse shortwave) on this date of 29.54 MJ/m^2 was next computed using a June clear sky (<10% cloud cover) clearness index of 0.69 for northcentral Pennsylvania (NASA Surface Meteorology and Solar Energy Tables). The clearness index is the fraction of radiation at the top of the atmosphere which reaches the earth's surface as global radiation during clear-sky days (days with <10% cloud cover). Global radiation was apportioned to 80% solar beam ($K{\downarrow}_{beam}$ = 23.63 MJ/m^2) and 20% diffuse shortwave from the atmosphere ($K{\downarrow}_{atm}$ = 5.91 MJ/m^2) based upon analysis of the beam *vs*. diffuse fractions of clear-sky radiation days at the NOAA SURFRAD network Penn State station during June-July 2002-2006. Representative clear-sky, daytime, incoming longwave flux from the atmosphere ($L{\downarrow}_{atmos}$ = 16.4 MJ/m^2) was also based upon measurements at the Penn State SURFRAD site based upon a 14-hour daytime period.

TABLE 1. Daytime Radiation Totals for Clear and Cloudy Days Used to Model Effects of Riparian Vegetative Shade for Mid-Latitude (40°N) Conditions.

Radiation Component	Clear Day, MJ/m^2	Cloudy Day, MJ/m^2
Direct beam shortwave ($K{\downarrow}_{beam}$)	23.63	3.4
Diffuse atmospheric incoming shortwave ($K{\downarrow}_{atm\ diffuse}$)	5.91	13.7
Shortwave received by unobstructed vertical planes[1] ($K{\downarrow}_{vert}$)	3.27 E- and W-facing 1.52 N-facing 2.25 S-facing	2.18 1.02 1.48
Atmospheric incoming longwave radiation ($L{\downarrow}_{atmos}$)	16.4	19.7
Longwave radiation emitted by vegetation[2] ($L{\downarrow}_{veg}$)	20.66	20.66

[1]Used to compute $K{\downarrow}_{veg}$, source DOE NREL website for Williamsport PA, see text.
[2]Approximately 18°C average vegetation radiating temperature.

Blackbody radiating temperatures and fluxes of longwave radiation from riparian vegetation during clear days are not known. As a first approximation, longwave emitted from vegetation ($L\downarrow_{veg}$) was assumed equal to the June average outgoing radiation flux from the ground surface of unirrigated grass turf and row crops measured at the Penn State SURFRAD site ($L\downarrow_{veg} = 20.66$ MJ/m^2). Based upon Equation (3), this flux is approximately equal to a blackbody radiating temperature of 18°C for vegetation, which is probably a conservative estimate for clear days. Sunlit edges could radiate at much higher temperatures during parts of the day; for example, with E-W stream azimuths the South-facing vegetation could receive solar radiation at near normal incidence and heat at times to much higher temperatures than vegetation on the opposite bank which was facing North. Mean air temperatures during clear days in summer at the Penn State SURFRAD site averaged about 22°C and model results using a vegetation temperature of about 25°C (22.5 MJ/m^2) are also shown.

Shortwave radiation reflected from vegetation planes along streams also presented special problems, as no measurements of reflected radiation from vegetation along streams were available. Estimated clear-day shortwave radiation received on unobstructed vertical planes ($K\downarrow_{vert}$) facing N, E, S, and W at Williamsport, Pennsylvania for June (DOE National Renewable Energy Laboratory website) was used to approximate shortwave received by vertical vegetation planes. Fluxes for North- and South-facing vertical planes were associated with an E-W stream azimuth, while fluxes for East- and West-facing vertical planes, which were equal, were associated with a N-S stream azimuth (Table 1). These fluxes for unobstructed vertical planes were assumed to be entirely diffuse radiation and were corrected for the reduction in amount of radiation that could reach the vegetation from the atmosphere as shading increased using the view factor from the vegetation to atmosphere (F_{v-a}) and then multiplied by an assumed albedo for vegetation of 0.2 to estimate $K\downarrow_{refl\ diffuse}$. The view factor from vegetation to atmosphere, F_{v-a},was derived from other view factors previously discussed, since by symmetry in the shaded stream section, $F_{v-a} = F_{v-s}$ and by reciprocity $F_{v-s} = F_{s-v}\ W/H$ (Holman, 1972). Thus, the reflected shortwave radiation from vegetation for use in Equation (1) was

$$K\downarrow_{refl\ diffuse} = 0.2F_{s-v} \cdot W/H \cdot K\downarrow_{vert} \quad (9)$$

Substitution of Equation (9) into Equation (1), converts the third term in Equation (1) to

$$2F_{s-v} \cdot K\downarrow_{refl\ diffuse} = (2)(0.2)F_{s-v}^2 \cdot W/H \cdot K\downarrow_{vert}, \quad (10)$$

where the product $2F_{s-v}{}^2 \cdot W/H$ becomes the effective view factor from stream to vegetation along both banks controlling receipt of reflected shortwave radiation to the stream.

Cloudy days were also modeled where it was assumed that incoming shortwave to an unobstructed plane was only 0.4 of potential, with 80% being diffuse shortwave and 20% being direct beam shortwave, which was representative of partial to heavy cloud cover days in Pennsylvania. For cloudy-day modeling, shortwave radiation reaching vertical vegetative planes was reduced to two-thirds of that for clear days (based upon clear to average day ratios given on DOE NREL website for Williamsport), incoming atmospheric longwave was increased to 19.7 MJ/m^2 for the daytime period (based upon data at the Penn State SURFRAD site) and longwave emitted from vegetation was not changed.

RESULTS

Fraction of Potential Solar for Shaded Streams

Effects of stream shade on the daily fraction of direct beam solar radiation reaching the stream centerline are summarized in Figure 2 for E-W, N-S, and intermediate stream azimuths as a function of *H/W* for latitude of 40°N on the summer solstice.

Increasing shading or *H/W* produces a gradual curvilinear reduction in receipt of direct beam solar radiation as expected, but for E-W streams the curves shows a more complex pattern due to occurrence of double sunrises and sunsets. For E-W streams a threshold or inflection point exists where the fraction

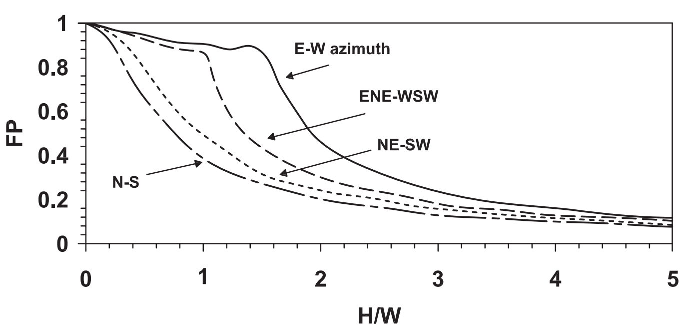

FIGURE 2. Fraction of Potential Extraterrestrial Solar Irradiation (FP) Received on a Shaded Stream Centerline on the Summer Solstice and a Latitude of 40°N as a Function of Stream Azimuth and the Ratio of Vegetation Height (*H*) to Stream Width (*W*). Vegetation overhang angle = 0°.

of beam radiation received begins to drop rapidly for increasing shade angles or *H/W* ratios, which represents the point where the maximum shade angle [arctan *H/*(*W/*2)] begins to exceed the maximum solar altitude for that day. This threshold also marks the initiation of double sunrise and sunsets on the stream centerline as vegetation height (*H*) increases relative to stream width (*W*). For dense shade (e.g., *H/W* = 5) FP is reduced to values less than 0.1, equivalent to 10% of beam solar radiation received.

Importance of stream azimuth in controlling effectiveness of riparian shading from shortwave radiation has been documented by several investigators. Ice (2004) described the varying shading effect of vegetation buffers through interactions with stream azimuth. Modeling studies have also shown that E-W azimuth streams can experience double sunrise and sunsets under certain shading conditions (University of Washington 2001).

Latitude can have a major influence on the direct beam radiation reaching the stream for E-W streams (Figure 3a), but has a smaller influence on the direct beam receipt for N-S streams (Figure 3b). Generally for a given *H/W*, the fraction of potential solar beam radiation received is greatest for 30°N latitude and least for 50°N latitude. The threshold for onset of double sunrises and sunsets exists at *H/W* = 1 for latitude of 50°N, and for a latitude of 30° the threshold occurs at *H/W* = 4. No similar threshold exists for N-S streams where the fraction of direct beam solar received for a given *H/W* is only slightly reduced with increasing latitude over the range of 30-50°N latitude.

Vegetation overhang can reduce the fraction of direct beam solar radiation that reaches the stream beyond that due to shading by vegetation without overhang (see Figure 4). An effective *H/W* ratio can be defined which accounts for shading by overhanging vegetation to compute changes in FP using Figures 1 and 2 for beam shortwave radiation received. For example, shading by vegetation with *H/W* = 1 with a 0° overhang angle can be increased to an effective *H/W* = 4 with just a 20° overhang angle. The effect of overhang angle can be great where *H/W* is initially larger, but has a very limited effect where *H/W* is initially lower (Figure 4). For example, for an initial *H/W* = 0.2 with 0° overhang, a 64° overhang angle is needed to achieve an effective *H/W* = 1; however, if the initial *H/W* = 0.6 with 0° overhang, only a 18° overhang angle is needed to achieve an effective *H/W* = 1.

View Factors for Shaded Streams

Radiation exchange view factors vary with the ratio of vegetation height to stream width and the amount of vegetation overhang. View factors from the stream to atmosphere without vegetation overhang vary from 100% view of the atmosphere at *H/W* = 0 to about 10% of the view at *H/W* = 6 (Figure 5). One minus this view factor gives the view factor from the stream to the vegetation along both banks used to compute longwave radiation receipt. The composite view factor expression used in Equation (10) to compute diffuse shortwave reflected by vegetation to the

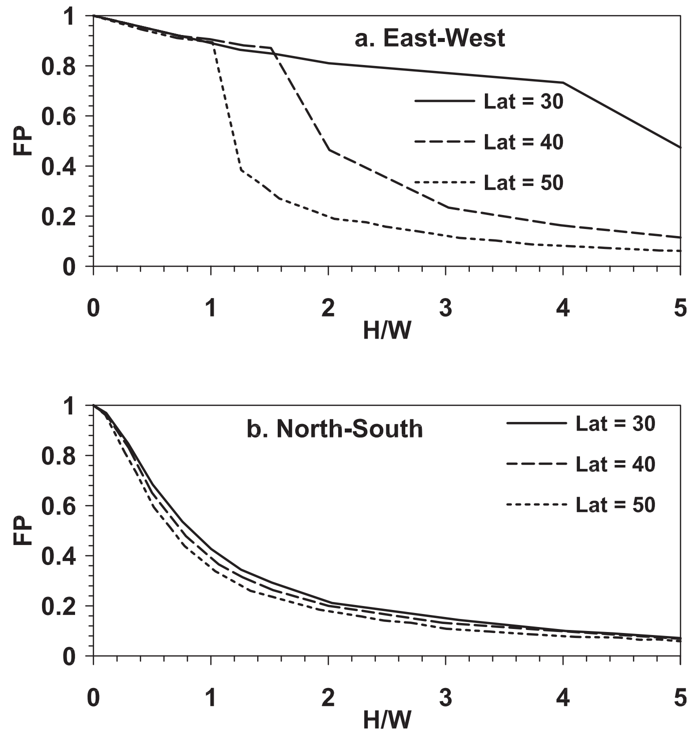

FIGURE 3. Effect of Latitude (30-50°N) on the Relationship Between Fraction of Potential Solar Irradiation (FP) Received on the Stream Centerline and the Ratio of Vegetation Height (*H*) to Stream Width (*W*). Upper graph (a) shows curves for E-W stream azimuths and the lower graph (b) shows N-S stream azimuths. Vegetation overhang angle = 0°, summer solstice.

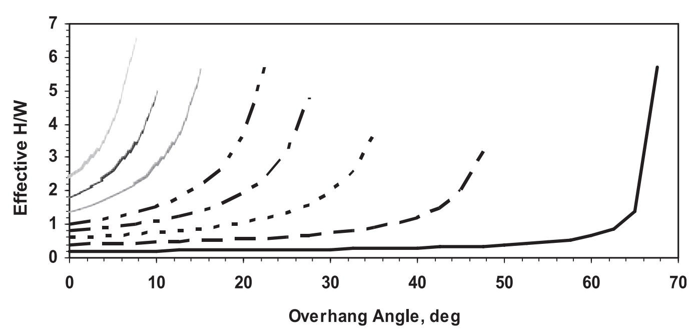

FIGURE 4. Overhang Angle Effects on the Effective Ratio of Vegetation Height (*H*) to Stream Width (*W*) to be Used to Determine FP for Direct Beam Shortwave Radiation Shading. Each Line Shows the Variation in Effective *H/W* With Overhang Angle, Beginning With a 0° Overhang Angle or Vertical Vegetation Plane.

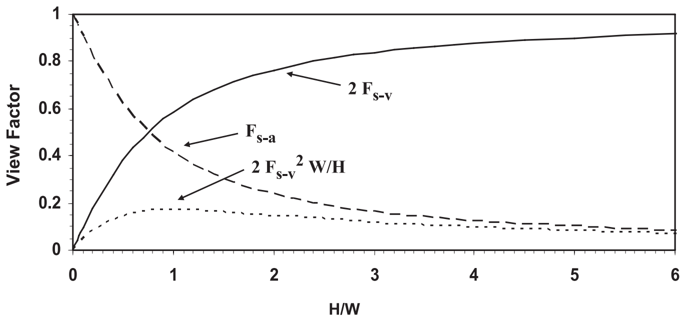

FIGURE 5. View Factors Used to Model Radiation Received by a Shaded Stream as a Function of Vegetation Height to Stream Width Ratio: F_{s-a} = View Factor From Stream Plane to Atmosphere, $2F_{s-v}$ = View Factor From Stream Plane to Vegetation Planes Along Both Banks, $2F_{s-v}^2W/H$ = Composite View Factor Derived to Compute Diffuse Reflected Shortwave Radiation From Both Vegetative Planes to the Stream. Vegetation overhang angle = 0°.

stream ($2{\cdot}F_{s-v}^2 \cdot W/H$) is also shown in Figure 5. As H/W and hence shading increases, this view factor for reflected shortwave initially increases because the increasing view from stream to vegetation dominates, reaches a peak of 18% at $H/W = 1$, and then decreases because the view factor from vegetation to atmosphere begins to dominate.

Vegetation overhang reduces the view from the stream to the atmosphere and increases the view to vegetation along the banks (Figure 6), which increases the importance of longwave emitted and shortwave reflected to the stream by vegetation. For example, the view factor from the stream to vegetation on both banks with $H/W = 1$ and zero overhang is about 0.6, but this view factor increases to about 0.72 with just a 10° overhang angle and to about 0.9 with 20° overhang angle. Note that a maximum view factor from the stream to vegetation along both banks of 1.00 is achieved relatively easily at small $H/W < 1$ with only 30° overhang angles. Long overhanging branches from trees and shrubs or stems from grasses which do not reach a very great height above the stream plane (H) may still be effective in altering the reflected shortwave and emitted longwave radiation received. Overhanging planes are also assumed to be nontransmitting and thus are solid planes in the model.

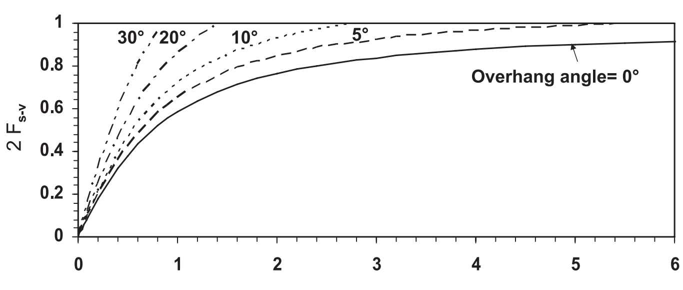

FIGURE 6. Overhanging Vegetation Effects on Radiation Exchange View Factor From Shaded Stream Plane to Vegetation Planes on Both Banks as a Function of Vegetation Height (H) to Stream Width Ratio (W) for Several Different Vegetation Overhang Angles.

Modeled Radiation Received by Shaded Streams

Modeled shortwave and longwave radiation components received by shaded streams based upon Equations (1) and (2) are shown in Figure 7 for a N-S stream azimuth and Figure 8 for an E-W azimuth, respectively. Results are based upon clear-sky mid-latitude conditions on the summer solstice without overhanging vegetation. Figure 7 shows total daytime radiation received on a N-S stream varied from about 46 MJ/m^2 with no shade to about 25 MJ/m^2 with $H/W = 5$. The reductions in total radiation received are largely caused by reductions of shortwave beam, with reduction in shortwave atmospheric and longwave atmospheric radiation being largely offset by increases in longwave radiation received from vegetation. Shortwave reflected to the stream by vegetation, based upon modeling assumptions, was negligible, but rose slightly and then declined as shading increased. At $H/W = 5$, which simulates heavy shade, radiation received was reduced by about 45% and dominated by longwave radiation (80% of the total) received from vegetation.

In Figure 8, analogous radiation components for an E-W stream azimuth are given for clear-sky, mid-latitude conditions. Patterns of changes of radiation components with increased shading on E-W streams are similar to those for a N-S stream except for the shortwave beam radiation, which differs according to FP with azimuth as shown in Figure 2,

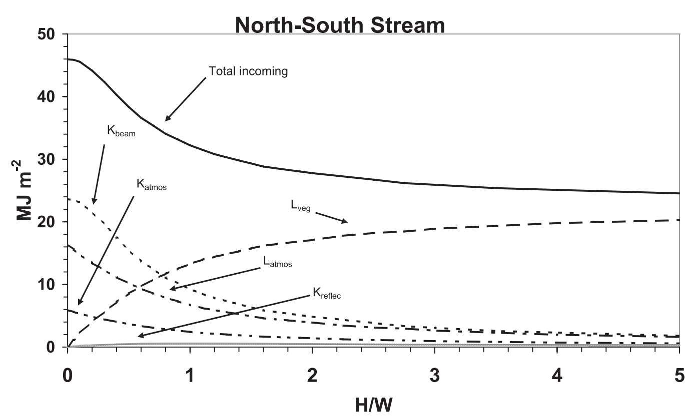

FIGURE 7. Modeled Daytime Components of Radiation Received by Shaded N-S Streams for Clear-Sky, Mid-Latitude (40°N) Conditions at Various Vegetation Height (H) to Stream Width (W) Ratios. Vegetation overhang angle = 0°.

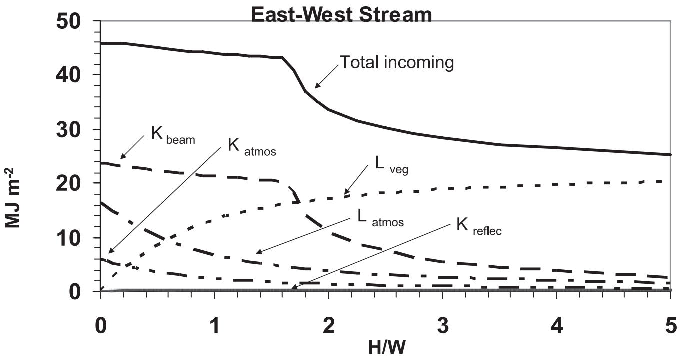

FIGURE 8. Modeled Daytime Totals of Radiation Received by Shaded E-W Streams for Clear-Sky, Mid-Latitude (40°N) Conditions at Various Vegetation Height (*H*) to Stream Width (*W*) Ratios. Vegetation overhang angle = 0°.

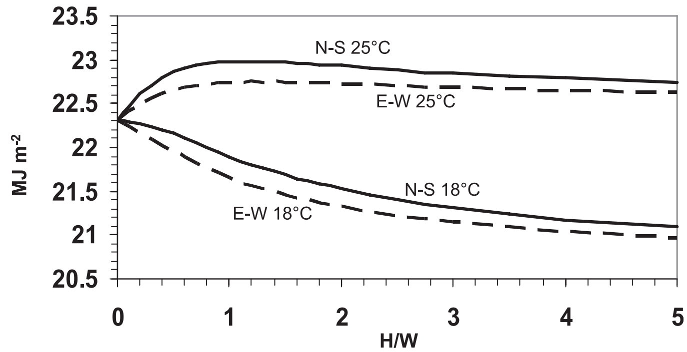

FIGURE 9. Modeled Variation in the Sum of Diffuse Shortwave and Longwave Radiation Components Received by a Shaded Stream With Varying Vegetation Height (*H*) to Stream Width (*W*) Ratios for Clear-Sky, Mid-Latitude (40°N) Conditions. Results are given for both N-S and E-W stream azimuths and for two assumed vegetation radiating temperatures (18°C and 25°C). Vegetation overhang angle = 0°.

and very slight differences in reflected shortwave radiation due to differences in shortwave received by vertical vegetation planes. Regardless of stream azimuth, vegetative shade effects on FP and receipt of shortwave beam radiation were most important during clear days.

The role of changes in diffuse shortwave and longwave radiation (total minus shortwave direct beam radiation) contributions to the stream with shade increases on clear days is shown in Figure 9. The changes in the sum of all diffuse fluxes with increased shading are negative and quite small, less than 1 MJ/m^2, thus it is clear that most changes in total radiation received are due to changes in shortwave beam radiation. Small differences in the sum of diffuse shortwave and longwave radiation fluxes with azimuth are due to minor differences in the amount of shortwave reflected from vegetation in the model. Increasing the assumed vegetation temperature from about 18°C to about 25°C, also shown in Figure 9, caused a minor peak at $H/W = 1$, but again the changes in the sum of diffuse components remained small and the overall effect of increased shading on diffuse shortwave and longwave radiation was generally negative. Even though the total diffuse flux does not change appreciably with increased shading, diffuse shortwave plus longwave radiation equals about 85% of the total received at $H/W = 5$ or heavy shade conditions and represents the minimum amount of radiation achievable by shade restoration programs.

Cloudy-day results showed that varying H/W could also be effective in reducing the radiant energy received by streams, but results varied little between N-S and E-W stream azimuths (Figure 10). Regardless of azimuth, maximum radiant energy received by the stream for cloudy days declined curvilinearly from a maximum of 37 MJ/m^2 at a $H/W = 0.0$ to a minimum of about 22 MJ/m^2 at $H/W = 5$. Radiation received without shading was dominated by diffuse atmospheric shortwave and atmospheric longwave radiation, while with heavy shade radiation received was dominated by longwave radiation emitted by vegetation. Under cloudy conditions, shade effects on view factors from the stream to atmosphere and vegetation played a dominant role.

APPLICATIONS

Shade Height Requirements

Modeled total radiation loads on shaded streams in Figures 7, 8, and 10 were used to estimate H/W needed for shade restoration in mid-latitude sites (40°N) in the U.S. with zero overhang (Table 2).

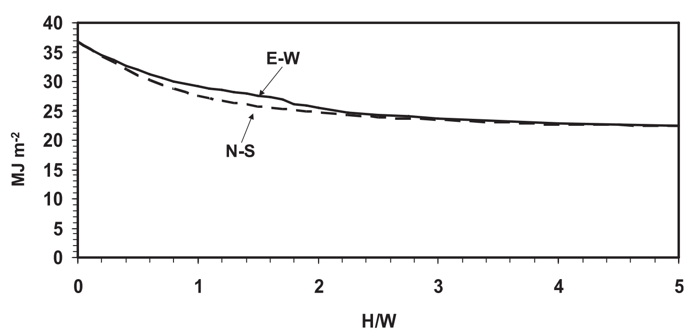

FIGURE 10. Modeled Variation in the Sum of Total Radiation Received by a Shaded Stream Under Cloudy-Sky, Mid-Latitude (40°N) Conditions as a Function of Vegetation Height (*H*) to Stream Width (*W*) Ratios for Both E-W and N-S Stream Azimuths. Vegetation overhang angle = 0°.

Ratios for three levels of shade restoration are given, 50, 75, and 90%, which might be relevant to those planning a shade restoration program. Based upon radiation totals in Figure 7 for N-S streams, restoration to 50, 75, and 90% of heavy shade can be achieved by vegetation height to stream width ratios of 0.7, 1.4 and 2.5, respectively. Restoration for E-W streams would require much greater *H/W* ratios of 1.8, 2.3 and 3.3, respectively (Figure 8). For example, if 50% shade restoration is desired, a 4-m wide stream would require vegetation height of about 2.8 m for a N-S stream azimuth, but about 7.2 m vegetation height for equivalent shading for an E-W stream azimuth. Shade heights of 2.8 m are possible with tall grass or shrub vegetation for N-S, but for E-W streams young, pole-sized woody vegetation would likely be needed. Blann *et al.* (2002) found that grasses and forbs could be as effective as taller woody vegetation in shading streams in Minnesota based upon modeling results. Whitledge *et al.* (2006) noted that potential for shade restoration was greater for narrower and N-S azimuth streams in the Missouri Ozarks based upon modeling results. Ratios needed for other stream azimuths would be intermediate to these values and in rough proportion to changes in FP with azimuth shown in Figure 2.

Stream bank height above the water surface is implicitly included in the vegetation height used in these examples. Entrenched streams may be partially shaded by banks and actual vegetation height from restoration efforts can be added to bank heights for purposes of this computation. Exposed stream banks will have a somewhat different albedo than vegetation, but as reflected shortwave is not a major component in shade computations, this effect should be negligible. Shading by topography can also be effective and the same *H/W* ratios in Figures 2 and 3 can be used to include topographic effects on direct beam radiation receipt by streams. The assumption of zero vegetation transmission in this analysis permits shading by stream banks and topography to be added with little error.

TABLE 2. Predicted Vegetation Height/Stream Width Ratios Needed to Achieve 50, 75, and 90% Shade Restoration for Clear and Cloudy Days for Mid-Latitude Conditions (40°N) Overhang Angle = 0°.

Sky Conditions/ Stream Azimuth	Vegetation Height to Stream Width Ratios for Shade Restoration		
	50% Restoration	75% Restoration	90% Restoration
Clear days/north-south	0.7	1.4	2.5
Clear days/east-west	1.8	2.3	3.3
Cloudy days/all azimuths	0.8	1.6	2.7

Cloudy day modeling results (Figure 10) were also used to infer impacts of shade restoration (Table 2). On cloudy days for all stream azimuths, model results suggest that 50, 75, and 90% of shade restoration could be achieved with *H/W* of 0.8, 1.6, and 2.7, respectively. Estimates for N-S and E-W streams differed only slightly and average ratios were used. These *H/W* ratios for cloudy days, where a larger fraction of diffuse shortwave radiation is received, are intermediate between clear-day estimates for N-S and E-W stream azimuths.

Grant (2005) studied the temperature increases in six stream reaches in Pennsylvania during summer in relation to FP and view factors to the atmosphere using a similar modeling strategy as used here based upon extrapolation of relationships for larger rivers from DeWalle (1974). He found that temperature increases were moderated by riparian vegetation where the view factor from stream to atmosphere (F_{s-a})was <0.40 and where the fraction of shortwave beam radiation reaching the stream centerline (FP) was <0.75.

Vegetation Overhang Effects

Vegetation overhang increases the effective *H/W* of vegetation and can be an important consideration in shade restoration programs for small streams, as shown in Figure 4. For example, 6-m high vegetation along a 4-m wide E-W azimuth stream would only give a ratio of vegetation height to stream width of 1.5, which is below the ratio of 2.3 needed to produce 75% shade restoration (Table 2). However, if this vegetation also had an overhang angle of 10° over the stream, then according to Figure 4, the effective *H/W* for direct beam shortwave would be increased to about *H/W* = 2.8, which is adequate to produce 75% shade restoration, as long as net changes in other radiation fluxes (e.g., reduced diffuse atmospheric shortwave and atmospheric longwave *vs*. increased longwave from vegetation) did not offset the change. Vegetation overhang of 10° with *H/W* = 1.5 essentially gives an increase in view factor from the stream to vegetation along both banks from 0.68 to about of 0.84 according to Figure 6; however, the sum of diffuse shortwave and longwave radiation received with this increased view was still only slightly less than that without overhang as was found in the model without overhang. Thus, impacts of overhanging vegetation on shading guidelines can be determined largely by analyzing effects on shortwave beam radiation using Figures 2 and 4 for clear sky conditions.

Analysis suggests that preference should be given to plant species that have overhanging foliage and branches to benefit the most from shade restoration programs. Rapidly growing overhanging grass and shrub vegetation can be used to provide quick shade, while slower growing woody vegetation becomes fully established. Planting riparian vegetation very close to the banks to get the most overhang could be very important in increasing the effective height of shorter grass and shrub vegetation for a given stream width. Planting near stream banks does increase the risk of loss of plant material due to bank collapse over time and the effect of channel width changes is considered below. Vegetation overhang in this analysis also assumes no transmission by foliage, thus only dense overhanging vegetation should be considered when using these guidelines.

Impacts of Stream Width Changes

Use of Figures 7, 8, and 10 and Table 2 implies that changes in width of channels over time can also cause significant changes in shading needs. For example, 90% shade restoration on a 1-m wide stream with N-S azimuth would require a $H/W = 2.5$ on clear days and $H/W = 2.7$ on cloudy days or a vegetation height range of 2.5-2.7 m. If the channel width increased to 2 m during shade restoration, the required vegetation height range needed for 90% shade restoration would double to a range of 5-5.4 m. If shade height were fixed, then such channel widening would effectively reduce the level of shade restoration that was obtained. Of course, channel narrowing during a shade restoration program could render the existing vegetation more effective than originally planned.

Restoration on Wide Streams

Given the natural limits on vegetation height that can be achieved with mature trees, Table 2 for 40°N latitude implies that there are some practical limits on the maximum stream width that can be appreciably affected by shade restoration programs. Assuming that if 30 m is the maximum vegetation height that can be achieved, then 50% shade restoration could only be achieved for E-W streams up to about 17-m wide ($H/W = 1.8$ needed) or N-S streams up to 43-m wide ($H/W = 0.7$ needed). Maximum stream widths that could be restored for other stream azimuths would fall within this range. In addition, as the time required for these maximum vegetation heights to be reached is significant, shade restoration programs on such wide streams would be a very long-term investment. There are many other good reasons for restoration of riparian vegetation along very wide streams, but lowering water temperatures by shading is probably not one of them.

Shading on wide streams would be somewhat more effective at higher latitudes and less effective at lower latitudes, at least for E-W stream azimuths. Based upon Figure 3, the maximum E-W stream width for 50% restoration by 30-m tall vegetation would be about 25-m at 50°N latitude compared to about 17-m width at 40°N latitude.

Latitude Effects

Effects of latitude on shade restoration requirements can be easily demonstrated using Figures 3a and 3b by considering only shortwave beam radiation reaching the stream, which is justified based upon modeling results. The vegetation height to stream width ratio (H/W) needed for 50% shade restoration (FP = 0.5) in Figure 3a for E-W stream azimuths is about 1.2, 1.9, and 4.8 for 50°, 40°, and 30°N latitudes, respectively. In Figure 3b for N-S streams, the H/W ratios needed to achieve 50% restoration with varying latitudes are about 0.66, 0.74, and 0.82 for 50°, 40°, and 30°N latitudes, respectively. Shading would be obviously much more effective at higher latitudes than lesser latitudes for E-W streams, but relatively unimportant for N-S streams.

Assumptions and Limitations

Analysis of stream shade involved several key assumptions that affect the application of results. Analysis was based upon the premise that daylight totals of radiation received by streams from sunrise to sunset provide a useful index to riparian vegetation shading. Results thus apply to idealized long channel reaches which are longer than the distance traveled by a slug of water during the daylight period. Analysis was also based upon daily direct beam shortwave radiation received on the stream centerline rather than radiation integrated over the entire width of the channel. Ultimately the effectiveness of radiation received in heating a stream will depend upon how discharge is distributed across the channel (e.g., whether the bulk of the flow occurs along one bank or near mid-stream). In this analysis, for the long straight channel reaches modeled, the stream centerline was simply used as the reference point. Impacts of shade on stream temperature regimes can depend upon many other factors such as water velocity, water depth, wind speed, humidity, air temperature, channel bed conductivity (Johnson, 2004), groundwater inputs (Story *et al.*, 2003; Mellina *et al.*, 2002), and vegetation characteristics including transmission and longitudinal distribution of vegetation along the channel (Burton and Likens, 1973; Scarsbrook and Halliday, 1999; Rutherford *et al.*, 2004), that cannot be easily generalized. Computation of shade restoration impacts on stream temperature would require case-specific calculations using one of the several available models including radiation components given in Equations (1) and (2).

Analysis also treated vegetation as nontransmitting planes, which means shading guidelines should only be applied to dense or wide vegetative riparian buffer zones or very dense overhanging vegetation. Transmission of solar radiation by vegetation would increase the amount of radiation reaching the stream and increase the *H/W* ratio shade restoration guidelines shown in this analysis as well as blur differences in shading guidelines due to stream azimuth. However, shade restoration guidelines also represent summer solstice conditions which would equate to greater shading at other times during the growing season, somewhat compensating for the nontransmitting assumption in this analysis. A definition of buffer zone characteristics needed for "nontransmitting" vegetation is not prescribed here, but reference can be made to the buffer widths typically recommended for restoring or maintaining shade; widths ranging from about 9-30 m width are generally considered adequate to maintain thermal regimes in small streams (Beschta *et al.*, 1987; Sridhar *et al.*, 2004; Wilkerson *et al.*, 2006; Zwieniecki and Newton, 1999). Other accommodations for effects of radiation transmission by vegetation would be to only use the larger *H/W* for 90% shade restoration given in Table 2 or to estimate transmission using Beer's law and apply the resulting increase in FP to Figure 2.

An estimate of increase in FP due to transmission of shortwave radiation by vegetation can be made based upon the Beer's Law in the form (Jarvis et al. 1976):

$$\Delta \mathrm{FP} = e^{-K\,\mathrm{LAI}} \qquad (Eq.II)$$

Where LAI is the leaf area index of the plant community and K is an extinction coefficient. LAI can be measured, but impacts of clumping and non-foliar components can be problematical (Bréda 2003). The attenuation coefficient (K) of plant stands varies with many factors including solar altitude and path length of radiation through the vegetation (Sridhar et al. 2004, Pomeroy and Dion 1996), which makes applications to buffer zones of finite dimensions (width, height, density) and varying stream-buffer geometries problematical. Regardless, as a rough approximation, if LAI = 5, representing dense vegetation and K = 0.47 representing mean broad-leaved forest (Bréda 2003), then ΔFP = 0.095. Pro-rating ΔFP by the fraction of the day when the stream is actually shaded (e.g. multiplying by 1−FP) is also needed. For example, given FP = 0.5 (H/W = 1) in Figure 2 for a NE-SW stream azimuth at 40°N latitude without transmission, this level of transmission increases FP received by 0.0475 (=ΔFP(1−FP)) and increases the solar beam radiation reaching the stream to FP = 0.5475 (H/W = 0.9). Viewed alternatively, shade requirements in Figure 2 would have to be increased from about H/W = 1.0 at FP = 0.5 without transmission to about H/W = 1.1 at FP = 0.4525 with consideration of transmission, to get the same shade restoration.

CONCLUSIONS

Vegetative shade effects on receipt of daily total shortwave beam radiation were found to dominate model results for clear weather conditions on the summer solstice. Increases in longwave radiation from vegetation due to increased shading were essentially offset by decreases in atmospheric diffuse shortwave and atmospheric longwave radiation based upon assumptions used in the model for clear weather. Consideration of view factors from the stream to vegetation and atmosphere and exchange of diffuse shortwave and longwave radiation were more important for cloudy weather conditions. Model results also indicated that shortwave radiation reflected by vegetation to the stream would be small and could be ignored. Measurements of all diffuse and direct and shortwave and longwave radiation fluxes received by shaded streams appear to be lacking, but are needed to support future modeling efforts.

Ratios of vegetation height to stream width for dense, nontransmitting riparian buffers are given as general guidelines for use by ecosystem managers to help plan shade restoration programs. For example, shade height to stream width ratios needed to reduce all-wave radiation received on the stream centerline to within 75% of that on a fully shaded stream ranged between 1.4 to 2.3 for mid-latitudes (40°N) depending on cloud conditions and stream azimuth. Ratios needed to achieve shade restoration will be greater for E-W than for N-S stream azimuths with clear sky, but stream azimuth would be relatively unimportant with cloudy weather. On small streams, shade restoration is possible with grass and shrub vegetation for N-S azimuths for some configurations, but taller woody vegetation may be needed for E-W azimuths depending upon stream width. Regardless, dense vegetation overhanging the stream can greatly enhance shading and measurements of overhang angles can be used to estimate this enhancement. Changing stream widths during shade restoration programs can also cause important shifts in ratios needed for restoration. Shade effects on E-W streams were especially effective for streams at higher latitudes. On larger streams, opportunities for shade restoration, with or without overhang, are limited to widths less than about 17 m for E-W azimuths and widths less than about 43 m for N-S streams for clear-day, mid-latitude conditions.

ACKNOWLEDGMENTS

Support for this research given by the School of Forest Resources and Penn State Institutes of Energy and the Environment at Penn State University are gratefully acknowledged.

LITERATURE CITED

Amaranthus, M., J. Jubas, and D. Arthur. 1989. Stream Shading, Summer Streamflow and Maximum Water Temperature Following Intense Wildfire in Headwater Streams. USDA, Forest Service, Gen. Tech. Rpt. PSW-109, Washington, DC.

Aubin, I., M. Beaudet, and C. Messier, 2000. Light Extinction Coefficients Specific to the Understory Vegetation of the Southern Boreal Forest, Quebec. Canadian Journal of Forest Research 30:168-177.

Baldocchi, D.B., D.R. Matt, B.A. Hutchison, and R.T. McMillen, 1984. Solar Radiation Within an oak-Hickory Forest: An Evaluation of the Extinction Coefficients for Several Radiation Components During Fully-Leafed and Leafless Periods. Agricultural and Forest Meteorology 32:307-322.

Bartholow, J.M., 2000. Estimating Cumulative Effects of Clearcutting on Stream Temperatures. Rivers 7(4):284-297.

Bartholow, J., 2002. Stream Segment Temperature Model (SSTEMP) Version 2.0, Revised August 2002. U. S. Geological Survey, Ft. Collins, Colorado, 29 pp.

Beschta, R.L., R.E. Bilby, R.E. Brown, G.W. Brown, L.B. Holtby, and T.D. Hofstra, 1987. Stream Temperatures and Aquatic Habitat: Fisheries and Forestry Interactions. *In:* Proceedings, Streamside Management: Forestry and Fishery Interaction, E.O. Salo and T.W. Cundy (Editors). Institute of Forest Resource, University of Washington, Seattle, pp. 191-232.

Blann, K., J.F. Nerbonne, and B. Vondracek, 2002. Relationship of Riparian Buffer Type to Water Temperature in the Driftless Area Ecoregion of Minnesota. North American Journal of Fisheries Management 22:441-451.

Borman, M.M. and L.L. Larson, 2003. A Case Study of River Temperature Response to Agricultural Land use and Environmental Thermal Patterns. Journal of Soil and Water Conservation 58(1):8-12.

Bréda, N.J.J., 2003. Ground-Based Measurements of Leaf Area Index: A Review of Methods, Instruments and Current Inventories. Journal of Experimental Botany 54(392):2403-2417.

Broadmeadow, S. and T.R. Nisbet, 2004. The Effects of Riparian Forest Management on the Freshwater Environment: A Literature Review of Best Management Practices. Hydrology and Earth System Sciences 8(3):286-305.

Brown, G.W., 1970. Predicting the Effect of Clearcutting on Stream Temperatures. Journal of Soil and Water Conservation 25:11-13.

Burton, T.M. and G.E. Likens, 1973. The Effect of Strip-Cutting on Stream Temperatures in the Hubbard Brook Experimental Forest, New Hampshire. BioScience 23(7):433-435.

Chen, Y.D., R.F. Carsel, S.C. McCutcheon, and W.L. Nutter, 1998a. Stream Temperature Simulation of Forested Riparian Areas: I. Watershed Scale Model Development. Journal of Environmental Engineering 124(4):304-315.

Chen, Y.D., S.C. McCutcheon, D.J. Norton, and W.L. Nutter, 1998b. Stream Temperature Simulation of Forested Riparian Areas: II Model Applications. Journal of Environmental Engineering 124(4):316-328.

Crawford, T.M. and C.E. Duchon, 1999. An Improved Parameterization for Estimating Effective Atmospheric Emissivity for use in Calculating Daytime Downwelling Longwave Radiation. Journal of Applied Meteorology 38(4):474-480.

Davies-Colley, R.J. and G.W. Payne, 1998. Measuring Stream Shade. Journal of North American Benthological Society 17:2.

Davies-Colley, R.J. and J.M. Quinn, 1998. Stream Lighting in Five Regions of North Island, New Zealand: Control by Channel Size and Riparian Vegetation. New Zealand Journal of Marine and Freshwater Research 32:591-605.

DeWalle, D.R., 1974. Effect of Partial Vegetation and Topographic Shade on Radiant Energy Exchange of Streams-With Applications to Thermal Loading Problems. Res. Publ. No. 82. Instit. Res Land and Water Resour., The Pennsylvania State University, University Park, PA, 105 pp.

DOE National Renewable Energy Laboratory Website. http://rredc.nrel.gov/solar/old_data/nsrdb/bluebook/data/14778.SBF, *accessed* on July 22, 2008.

Duarte, H.F., N.L. Dias, and S.R. Maggiotto, 2006. Assessing Daytime Downward Longwave Radiation Estimates for Clear and Cloudy Skies in Southern Brazil. Agricultural and Forest Meteorology 139(3-4):171-181.

Federer, C.A., 1971. Solar Radiation Absorption by a Leafless Hardwood Forest. Agricultural Meteorology 9:3-20.

Frank, E.C. and R. Lee, 1966. Potential Solar Beam Irradiation on Slopes. USDA, Forest Service, Research Paper RM-18, Washington, DC, 116 pp.

Grant, C.J., 2005. Relationships Between Riparian Buffers and Summer Stream Temperatures. M. S. Thesis, The Pennsylvania State University, University Park, Pennsylvania, 105 pp.

Harding, J.S., K. Claassen, and N. Evers, 2006. Can Forest Fragments Reset Physical and Water Quality Conditions in Agricultural Catchments and act as Refugia for Forest Stream Invertebrates? Hydrobiologia 568:391-402.

Hardy, J.P., R. Melloh, G. Koenig, D. Marks, A. Winstral, J.W. Pomeroy, and T. Link, 2004. Solar Radiation Transmission Through Conifer Canopies. Agricultural and Forest Meteorology 126:257-270.

Holman, J.P., 1972. Heat Transfer (Third Edition). McGraw-Hill Book Co., New York, 462 pp.

Hottel, H.C., 1931. Radiant Heat Transmission Between Surfaces Separated by non-Absorbing Media. Transactions. American Society of Mechanical Engineers 53:265-273, FSP-53-196.

Ice, G., 2004. How Direct Solar Radiation and Shade Influences Temperature in Forest Streams and Relaxation of Changes in Stream Temperature. National Council for Air and Stream Improvement, Misc. Doc., Research Triangle Park, 34 pp.

Iqbal, M., 1983. An Introduction to Solar Radiation. Academic Press, Toronto.

Jarvis, P.G., G.B. James, and J.J. Landsberg 1976. Chapter 7. Coniferous Forest. *In*: Vegetation and the Atmosphere, Vol. 2, Case Studies, J.L. Monteith (Editor). Academic Press, London, pp. 171-240.

Johnson, S.L., 2004. Factors Influencing Stream Temperatures in Small Streams: Substrate Effects and a Shading Experiment. Canadian Journal of Fisheries and Aquatic Sciences 61:913-923.

Kauffman, J.B., R.L. Beschta, N. Otting, and D. Lytjen, 1997. An Ecological Perspective of Riparian and Stream Restoration in the Western United States. Fisheries 22(5):12-24.

Lanini, J., V. Sridhar, A.L. Sansone, J. LaMarche, and D.P. Lettenmaier, 2004. Reply to Discussion by J. D. Fox Jr., Prediction of Stream Temperature in Forested Watersheds. Journal of American Water Resources Association 40(6):1661-1662.

LeBlanc, R.T., R.D. Brown, and J.E. FitzGibbon, 1997. Modeling the Effects of Land use Change on the Water Temperature in Unregulated Urban Streams. Journal of Environmental Management 49:445-469.

Lee, R., 1978. Forest Microclimatology. Columbia University Press, New York, 276 pp.

Li, X., A.H. Strahler, and C.E. Woodcock, 1995. A Hybrid Geometric Optical-Radiative Transfer Approach for Modeling Albedo and Directional Reflectance of Discontinuous Canopies. IEEE Transactions on Geoscience and Remote Sensing 33:466-480.

Link, T.E., D. Marks, and J.P. Hardy, 2004. A Deterministic Model to Characterize Canopy Radiative Transfer Properties. Hydrological Processes 18:3583-3594.

List, R.J., 1968. Smithsonian Meteorological Tables (Sixth Revised Edition). Smithsonian Institution, Misc. Collections, Volume 114, Washington, D.C., 527 pp.

Lynch, J.A., G.B. Rishel, and E.S. Corbett, 1984. Thermal Alteration of Streams Draining Clearcut Watersheds: Quantification and Biological Implications. Hydrobiologia 111(3):161-169.

Meier, W., C. Bonjour, A. Wüest, and P. Reichert, 2003. Modeling the Effect of Water Diversion on the Temperature of Mountain Streams. Journal of Environmental Engineering 129(8):755-764.

Mellina, E., R.D. Moore, S.G. Hinch, J.S. Macdonald, and G. Pearson, 2002. Stream Temperature Responses to Clearcut Logging in British Columbia: The Moderating Influences of Groundwater and Headwater Lakes. Canadian Journal of Fisheries and Aquatic Sciences 59:1886-1900.

Moore, R.D., D.L. Spittlehouse, and A. Story, 2005. Riparian Microclimate and Stream Temperature Response to Forest Harvesting: A Review. Journal of American Water Resources Association 41(4):813-834.

NASA Surface Meteorology and Solar Energy Website. http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/grid.cgi?email=grid@larc.nasa.gov, *accessed* July 22, 2008.

Niemelä, S., R. Räisänen, and H. Savijärvi, 2001. Comparison of Surface Radiative Flux Parameterizations Part II. Shortwave Radiation. Atmospheric Research 58(2):141-154.

NOAA SURFRAD Website. http://www.srrb.noaa.gov/surfrad/sitepage.html, *accessed* July 22, 2008.

O'Driscoll, M.A. and D.R. DeWalle, 2006. Stream-air Temperature Relations to Classify Stream-Ground Water Interactions. Journal of Hydrology 329(1-2):140-153.

Oke, T.R., 1987. Boundary Layer Climates (Second Edition). Methuen, London, 435 pp.

Parkyn, S.M., R.J. Davies-Colley, N.J. Halliday, K.J. Costley, and G.F. Croker, 2003. Planted Riparian Buffer Zones in New Zealand: Do They Live up to Expectations? Restoration Ecology 11(4):436-447.

Pomeroy, J.W. and K. Dion, 1996. Winter Radiation Extinction and Reflection in a Boreal Pine Canopy: Measurements and Modeling. Hydrological Processes 10:1591-1608.

Poole, G.C. and C.H. Berman, 2001. An Ecological Perspective on in-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human Caused Thermal Degradation. Environmental Management 27(6):782-802.

Quigley, T.M., 1981. Estimating Contribution of Overstory Vegetation to Stream Surface Shade. Wildlife Society Bulletin 9(1):22-27.

Roni, P., T.J. Beechie, R.E. Bilby, F.E. Leonetti, M.M. Pollock, and G.R. Pess, 2002. A Review of Stream Restoration Techniques and a Hierarchical Strategy for Prioritizing Restoration in Pacific Northwest Watersheds. North American Journal of Fisheries Management 22:1-20.

Rutherford, J.C., S. Blackett, C. Blackett, L. Saito, and R.J. Davies-Colley, 1997b. Predicting the Effects of Shade on Water Temperature in Small Streams. New Zealand Journal of Marine and Freshwater Research 31:707-721.

Rutherford, J.C., R.J. Davies-Colley, J.M. Quinn, M.J. Stroud, and A.B. Cooper 1997a. Stream Shade: Towards a Restoration Strategy. National Institute of Water and Atmospheric Research Ltd., Hamilton, New Zealand, NIWA Client Report DOC303, 159 pp.

Rutherford, J.C., N.A. Marsh, P.M. Davies, and S.E. Bunn, 2004. Effects of Patchy Shade on Stream Water Temperature: How Quickly do Small Streams Heat and Cool. Marine and Freshwater Research 55:737-748.

Scarsbrook, M.R. and J. Halliday, 1999. Transition From Pasture to Native Forest Land-use Along Stream Continua: Effects on Stream Ecosystems and Implications for Restoration. New Zealand Journal of Marine and Freshwater Research 33:292-310.

Schröder, P. and P. Hanrahan, 1993. On the Form Factor Between two Polygons. Computer Graphics, Assoc. Computing Machinery, Proc., Ann. Conf. Series. SIGGRAPH 93:163-164.

Siegel, R. and J.R. Howell, 2001. Thermal Radiation Heat Transfer (Forth Edition). Taylor and Francis, New York, 864 pp.

Sinokrot, B.A. and H.G. Stefan, 1993. Stream Temperature Dynamics: Measurements and Modeling. Water Resources Research 29(7):2299-2312.

Sridhar, V., A.L. Sansone, J. LaMarche, T. Dubin, and D.P. Lettenmaier, 2004. Prediction of Stream Temperature in Forested Watersheds. Journal of American Water Resources Association 40(1):197-213.

Story, A., R.D. Moore, and J.S. Macdonald, 2003. Stream Temperatures in two Shaded Reaches Below Cutblocks and Logging Roads: Downstream Cooling Linked to Subsurface Hydrology. Canadian Journal of Forest Research 33:1383-1396.

Sweeney, B.W., 1993. Effects of Streamside Vegetation on Macroinvertebrate Communities of White Clay Creek in Eastern North-America. Proceedings of the Academy of Natural Sciences of Philadelphia 144:291-340.

Swift, Jr., L.W. and J.B. Messer, 1971. Forest Cuttings Raise Temperatures of Small Streams in the Southern Appalachians. Journal of Soil and Water Conservation 26(3):111-116.

Tate, K.W., D.F. Lile, D.L. Lancaster, M.L. Porath, J.A. Morrison, and Y. Sado, 2005. Statistical Analysis of Monitoring Data Aids in Prediction of Stream Temperature. California Agriculture 59(3):161-167.

Tung, C.-P., Y.-C.E. Yang, T.-Y. Lee, and M.-H. Li, 2007. Modification of a Stream Temperature Model With Beer's Law and Application to GaoShan Creek in Taiwan. Ecological Modelling 200:217-224.

University of Washington, 2001. Fact Sheet #08: The Impact of Riparian Forest Management on Shade Production. University of Washington, College of Forest Resources, Seattle, WA, 5 pp. http://www.ruraltech.org/pubs/fact_sheets/fs008/index.asp, *accessed* August 27, 2007.

Watanabe, M., R.M. Adams, J. Wu, J.P. Belte, M.M. Cox, S.L. Johnson, W.J. Liss, W.G. Boggess, and J.L. Ebersole, 2005. Toward Efficient Riparian Restoration: Integrating Economic, Physical and Biological Models. Journal of Environmental Management 75(2):93-104.

Welty, J.J., T. Beechie, K. Sullivan, D.M. Hyink, R.E. Bilby, C. Andrus, and G. Pess, 2002. Riparian Aquatic Interaction Simulator (RAIS): a Model of Riparian Forest Dynamics for the Generation of Large Woody Debris and Shade. Forest Ecology and Management 162:299-318.

Whitledge, G.W., C.F. Rabeni, G. Annis, and S.P. Sowa, 2006. Riparian Shading and Groundwater Enhance Growth Potential for Smallmouth Bass in Ozark Streams. Ecological Application 16(4):1461-1473.

Wilkerson, E., J.M. Hagan, D. Siegel, and A.A. Whitman, 2006. The Effectiveness of Different Buffer Widths for Protecting Headwater Stream Temperature in Maine. Forest Science 52(3):221-231.

Zwieniecki, M.A. and M. Newton, 1999. Influence of Streamside Cover and Stream Features on Temperature Trends in Forested Streams of Western Oregon. Western Journal of Applied Forestry 14(2):106-113.