Estimating the Effects of Understory Removal From a Douglas Fir Forest Using a Two-Layer Canopy Evapotranspiration Model

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W. J. Shuttleworth's (1979) development of the Penman-Monteith evaporation equation for multilayer, partially wet forest canopies was modified for application to the hypostomatous canopies of Douglas fir and salal. This theory was combined with standard hourly micrometeorological measurements, eddy diffusive, boundary layer and stomatal resistance functions, and canopy and root zone water balance equations to calculate evapotranspiration rates (E) from a Douglas fir forest with salal understory over extended periods during two growing seasons. Calculated values of E agreed to within 0.2 mm d⁻¹ of values determined using Bowen ratio-energy balance measurements. The courses of average root zone volumetric water content (θ) calculated for two extended periods agreed well with neutron probe measurements. Salal understory removal resulted in measured values of θ being only 0.01-0.03 m³ m⁻³ higher over the two periods, in close agreement with calculations. This corresponded to calculated tree transpiration rates being 0.4 mm d⁻¹ higher on average, during the second half of both periods. These higher rates were confirmed by stomatal resistance measurements.

INTRODUCTION

The Penman-Monteith equation [Monteith, 1965] has provided useful insight into the physical and physiological factors affecting forest evapotranspiration [Stewart and Thom, 1973; Tan and Black, 1976]. A further development of the equation for multilayer, partially wet forest canopies has provided a practical one-dimensional model [Shuttleworth, 1978, 1979], despite the simplifying assumptions regarding within canopy turbulent transfer [Jarvis et al., 1976; Raupach and Thom, 1981; Finnegan, 1985]. With standard hourly micrometeorological measurements and stomatal resistance characteristics, the model can be combined with a root zone water balance model [e.g., Spittlehouse and Black, 1982] to provide estimates of forest evapotranspiration over extended periods. This paper describes the evapotranspiration model as modified for use in hypostomatous canopies, tests the model using energy and water balance measurements, and uses the model to explain the effects of salal (Gaultheria shallon Pursh.) understory removal on tree transpiration rates in a Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) forest.

THEORY

Using Shuttleworth's [1979] evapotranspiration theory, assuming the similarity of sensible heat and water vapor aerodynamic transfer resistances and neglecting canopy energy storage, it can be shown that the water vapor flux density from layer i(Eᵢ') with leaf area (one side) index (aᵢ) within a multilayer forest canopy of hypostomatous leaves can be expressed as (see the appendix)

\[ Eᵢ' = \frac{s(Rᵢ - G) + \rho cᵥDᵢ}{L[s + γ(1 + rᵢ/rₛ)]} \]  

where Eᵢ' is the difference between the water vapor flux density above and below the layer (i.e., Eᵢ - Eᵢ₋₁), Rᵢ and Dᵢ are the net radiation flux density and vapor pressure deficit above layer i, respectively; G is the soil heat flux density; L is the latent heat of vaporization; \( \rho \) is the density of air; \( cᵥ \) is specific heat of air; \( s \) is the slope of the saturation vapour pressure curve; \( γ \) is the psychrometric constant, and

\[ δᵢ = \frac{[s(Rᵢ₋₁ - G)(aᵢ/(2aᵢ)) + (s + γ)L(Eᵢ₋₁ - rₛ)](ρcᵥ)}{L[s + γ(1 + rᵢ/rₛ)]} \]  

The total aerodynamic resistance (rₐᵢ) [Thom, 1972] is given by

\[ rₐᵢ = rₛᵢ + rₛ/(2aᵢ) \]  

and the canopy resistance of layer i (rᵢ) is expressed as

\[ rᵢ = \left( \frac{Wᵢ}{(1 + s/γ)rₛ/(2aᵢ)} + \frac{1 - Wᵢ}{rₛ/(2aᵢ) + (2 + s/γ)rₛ/(2aᵢ)} \right)^{-1} \]  

where rₛᵢ is the eddy diffusive resistance above layer i, rₛ and rᵢ are the boundary layer and stomatal resistances of one side of the leaves in layer i, respectively, and Wᵢ is the fraction of leaf area in layer i that is completely wet. Stomatal resistances of hypostomatous leaves of Douglas fir and salal on a one-sided basis have been related to light, leaf and soil water potential, and vapor pressure deficit [Tan et al., 1977, 1978].

Equation (1) is recognized as the Penman-Monteith equation with an additional term which accounts for the net radiation, latent and sensible heat flux densities below layer i. Black et al. [1970] used (1) as an evapotranspiration model for a dry snap bean canopy where rₛᵢ ≪ rₛ was assumed so that δᵢ was equal to the soil evaporation rate multiplied by rₛᵢ/(s + γ)/(ρcᵥ). If rₛᵢ is assumed to be zero, then (1) reduces to the Penman-Monteith equation applied to the layer (i.e., using the vapor pressure deficit and the available energy flux density (Rᵢ - Rᵢ₋₁) within the layer). Equation (4) gives the canopy
zones of all eight trees were isolated by a vertical plastic bar-tation above the stand were made throughout the 1981 and extending down to bedrock [Kelliher, 1985; Price et al., 1986]. Scientific Inc., Logan, Utah).

averages or totals using a data logger (model CR21, Campbell

Micrometeorological Measurements

measurement made in 1981 and 1982 in four circular plots on May 21, 1981. Each subplot contained one tree which was salal understory present and the other with it cut and removed about 6 and 3, respectively, in 1982. The soil, an Orthic Humo

METHODS

Site Description

The site was a 31-year-old Douglas fir stand with about 800 trees ha⁻¹, approximately 27 km northwest of Courtenay on the eastern coast of Vancouver Island (49° 50'N, 125° 14'W, 150 m above sea level). At the end of the 1982 growing season, stand (including understory) basal area was 16 m² ha⁻¹, and average tree height was 14 m. Average tree and salal understory leaf area indices on a one-sided leaf area basis, were about 6 and 3, respectively, in 1982. The soil, an Orthic Humo Ferric Podzol, is a gravelly sandy loam with a volumetric coarse fragment (> 2 mm diameter) content of 10–45%. It is covered with a layer of organic forest floor material 10–20 mm thick and is about 700 mm deep over sandstone bedrock. The site is on a slope of less than 10%, with a northeast aspect.

The model was tested using stand energy balance measurements made in 1982 and soil water content and potential measurements made in 1981 and 1982 in four circular plots about 7 m in diameter, each containing two subplots, one with salal understory present and the other with it cut and removed on May 21, 1981. Each subplot contained one tree which was similar in size to the one in the adjacent subplot. The root zones of all eight trees were isolated by a vertical plastic barrier consisting of two sheets of 0.15-mm-thick polyethylene extending down to bedrock [Kelliher, 1985; Price et al., 1986].

Micrometeorological Measurements

Routine measurements of solar irradiance above the stand, air temperature, and relative humidity in a Stevenson screen at the 6 m height, wind speed at the 15 m height, and precipitation above the stand were made throughout the 1981 and 1982 growing seasons. Data were recorded as one hour averages or totals using a data logger (model CR21, Campbell Scientific Inc., Logan, Utah).

In 1981, Rₙ above the forest (Rₙₑ) was measured using a model S-1 radiometer (Swissteco Pty. Ltd., Victoria, Australia), while Rₙ below the tree canopy (Rₙₐ) was measured in one plot using one net radiometer above the salal canopy and another above the forest floor surface, where salal had been removed. In 1982, Rₙₐ was estimated, prior to August, from solar irradiance measurements following Gates [1980]. During August 1982, Rₙₐ was measured as in 1981, but Rₙₐ was measured using an S-1 net radiometer mounted on a tram traveling at the 1-m height along a 10-m path where salal along one half of the path had been removed [Kelliher, 1985]. The tram traveled at 0.5 m min⁻¹ and automatically reversed when it reached each end. The net radiometer output voltage was measured every 10 s. These results showed that Rₙₐ was approximately 0.16 Rₙₐ and 0.14 Rₙₐ for uncut and cut subplots, respectively. In 1982, these relationships were used to estimate Rₙₐ prior to August. In both years, Rₙₐ below the salal canopy was estimated using Rₙₐ = (lₜ + γ/8)LE₀ + G where LE₀ was 2 W m⁻² (measured using small lysimeters described later). The soil heat flux density at the 50-mm depth in each subplot of one plot was measured during 1981 and in August 1982 using three soil heat flux plates (100 mm long x 25 mm wide x 3 mm thick), made following the design of Fuchs and Tanner [1968], connected in series and corrected for the rate of change of heat storage in the upper 50 mm of soil. On the basis of these measurements, G was estimated as 0.02 Rₙₐ and 0.03 Rₙₐ for uncut and cut subplots, respectively, in 1982.

In both years, air temperature (Tₐ) and vapor pressure deficit (D) were estimated below the tree canopy using hourly average values at the 6-m height with the relationships Tₐ (°C) (0.5 m height) = 0.93Tₐ (°C)(6 m height) + 1.2 and D(kPa) (0.5 m height) = 0.89 D(kPa) (6 m height) – 0.03 (based on 33 hourly average measurements of Tₐ and D at both heights on July 24 and 25, 1981). Hourly Assmann psychrometer measurements confirmed the validity of these relationships on several days in August 1981 and June 1982.

Diffusive Resistance Functions

Stomatal resistances (rₛ) of Douglas fir and salal were estimated using average root zone soil water potential (Ψₚ) and D for the layer following interpolation of the functions in Tan et al. [1978] [Kelliher, 1985]. When Rₙₐ was negative (i.e., 1900–700 hours PST), rₛ of both species was set to 10⁵ s m⁻¹. Boundary layer resistances (rₐ) were estimated using a function for artificial leaves in the work by Spittlehouse and Black [1982] and a shelter factor of two [Landsberg and Powell, 1973; Jarvis et al., 1976]. The function rₛ(x m⁻¹) = 2 × 184 (dₙ/u)⁰·⁵ was used, where dₙ is leaf diameter (m) (0.001 m for Douglas fir and 0.06 m for salal) and u is the wind speed (m s⁻¹) near the leaf (0.5 u₁₅₅ for Douglas fir and 0.13 u₁₅₅ for salal, where u₁₅₅ is the wind speed at the 15-m height). In 1982 (prior to August), u₁₅₅ was estimated to be 3 m s⁻¹ for 1100–2000 hours PST and 1.5 m s⁻¹ for the rest of the day. Dividing these values by 2a gave mean boundary layer resistances similar to those estimated following the relationships given by Garratt and Hicks [1973]. The eddy diffusive resistance above the Douglas fir layer, required when the air temperature and relative humidity measured at the 15-m height in August 1982 were used, was estimated assuming a logarithmic wind profile [Jarvis et al., 1976] with a zero-plane displacement height of 8.5 m [Szeicz et al., 1969] and a roughness length of 1.5 m [Stanhill, 1969]. The corresponding resistance above the salal layer was roughly estimated assuming an ex-
ponential eddy diffusivity profile from the top of the trees to the salal layer [Thom, 1975; Shuttleworth and Wallace, 1982] with an attenuation coefficient of 2. This value was based on the ratio of the below to above canopy windspeeds being about 0.13. Daytime eddy diffusive resistances above the salal layer were calculated to be about 40 s m$^{-1}$ compared to approximately 20 s m$^{-1}$ for the 600 trees ha$^{-1}$. The eddy diffusivity of the salal layer was determined by plotting 24-hour throughfall data against the prevailing wind direction. These measurements were used to determine the eddy diffusivity profile from the top of the trees to the salal layer [Thom, 1975; Shuttleworth and Wallace, 1985].

The value of $C$ was calculated for each time $j$ using the following water balance equation applied to the stand and its single-layer root zone:

$$
\theta_j = \theta_{j-1} + (P_j - E_j - F_j) \Delta t / \zeta
$$

where $P_j$, $E_j$, and $F_j$ are the rates of rainfall, evapotranspiration, and root zone drainage at time $k$, respectively; $\Delta t$ is the time interval between $k$ and $k-1$ (1 hour except for when $W_c > 0$ and then $\Delta t$ is 15 min); and $\zeta$ is root zone depth. Evapotranspiration rates were calculated using (1) through (7) with the canopy divided into two layers (tree and understory). Drainage from the root zone was calculated as a function of $\theta$ ($F(m \cdot d^{-1}) = 100(0.3)^{\theta-1}$) [Spittlehouse and Black, 1981]. During most of the summer, drainage was a small term in the root zone water balance equation so that $\theta$ was largely determined by rainfall and evapotranspiration.

**Testing the Evapotranspiration and Root Zone Water Balance Equations**

During July to September 1981 and May to July 1982, $\theta$ was measured at 1- to 2-week intervals using the neutron moderation technique with a calibrated [Kelliher, 1985] probe (model CPN 503, Campbell Pacific Nuclear Corp., Pacheco, Calif.) being lowered into aluminum access tubes. There were 3 or 4 tubes in each subplot. Thermocouple psychrometers and tensiometers were used to measure $\Psi$, every 2-7 days. A pair of psychrometers and a tensiometer were installed at 150 mm depth intervals down to bedrock in each subplot of plot 2. Measured values of $\theta$ and $\Psi$, were compared during the two summer periods with calculated values obtained using (8) and a soil water retention curve determined using neutron probe, tensiometer, and thermocouple psychrometer measurements at the site ($\Psi(MPa) = -0.005(0.3)^{\theta-0.5}$).

Forest evapotranspiration was measured on 4 days in August 1982 using the Bowen ratio-energy balance technique. Half-hourly measurements of the Bowen ratio ($\beta$) were made using a dc-powered rotating psychrometric apparatus described by Spittlehouse and Black [1981a]. The apparatus was located at the top of a 15-m-tall tower adjacent to the four plots, with the vertical separation between the two psychrometers being 3 m. The lower psychrometer was about 1 m above the tops of the trees. Forest evapotranspiration was calculated using

$$
E = (R_w - G - M)/(1 + \beta)
$$

where $M$ is the rate of canopy heat storage estimated following Stewart and Thom [1973]. This measurement of $E$ was considered to include tree and understory transpiration and soil evaporation, since the area where understory had been removed was small and 20 m from the tower in a direction at right angles to the prevailing wind direction. These measurements of $E$ were compared to calculated values obtained using (1)-(8) ($W_c = 0$) applied to a two-layer canopy (trees and understory) plus soil evaporation.

Stomatal resistance measurements were made using a ventilated diffusion porometer described by Tan et al. [1977]. Hourly measurements were made on the two trees and salal in one plot from sunrise until late afternoon on August 12 and 20, 1981, and on the two trees only on June 9, 17, 23, and 30, 1982. These measurements were used to check the applicability of the $r_s$ functions mentioned earlier to the trees and salal in 1981 and 1982 and to assess the accuracy of the rates of tree and understory transpiration calculated using (1).
TABLE 1. Daily (24-hour) Net Radiation Flux Density Above the Forest (R_{na}) and Daily Measured and Calculated Values of Evapotranspiration Rate (E) Following Initialization of Calculations on August 20, 1982, When Measured \( \theta \) was 0.16 m \(^3\) m \(^{-3}\) (\( \Psi_p = -0.3 \) MPa) 

<table>
<thead>
<tr>
<th>Date (August, 1982)</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{na} )</td>
<td>11.5</td>
<td>11.6</td>
<td>12.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Measured E</td>
<td>1.8</td>
<td>2.2</td>
<td>1.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Calculated E</td>
<td>1.9</td>
<td>2.0</td>
<td>2.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\( R_{na} \) are given in MJ m \(^{-2}\) d \(^{-1}\) and \( E \) in mm d \(^{-1}\). Root mean square errors in measured and calculated \( E \) were approximately 0.2-0.3 mm d \(^{-1}\) for August 24-26 and 0.1 mm d \(^{-1}\) for August 27.

### Results and Discussion

#### Measured and Calculated Daytime Evapotranspiration Rates

There was generally good agreement between daily values of \( E \) measured during the 4-day test period using the energy balance-Bowen ratio and values calculated for the stand with understory present (Table 1). Agreement was not as good when comparing the daytime courses of measured and calculated \( E \) (Figure 1). However, both measured and calculated \( E \) was highest for the 2-hour period prior to noon on August 25, 1982. Calculated Douglas fir \( r_s \) increased markedly after 1400 hours (>6000 s m \(^{-1}\)) owing to the high values of \( D \), and calculated salal \( E \) was highest for the period 1100-1400 hours (≈0.1 mm h \(^{-1}\)). Measurement error accounts for some of the disagreement, since Bowen ratios were high (≥2) on August 24-26 and wet and dry bulb gradients small on August 27 [Spittlehouse and Black, 1980].

#### Forest Floor Evaporation After Salal Removal

For \( \theta \) less than 0.185, forest floor diffusive resistance was linearly related to \( \theta \) (Figure 2). On 3 days when \( \theta > 0.185 \), \( r_{co} \) was 0.16 m \(^3\) m \(^{-3}\) (\( \Psi_p = -0.3 \) MPa). Errors in measured \( E \) were approximately 0.02-0.04 mm h \(^{-1}\) (Table 1). Agreement was not as good when comparing the daytime courses of measured and calculated \( E \) (Figure 1). However, both measured and calculated \( E \) was highest for the 2-hour period prior to noon on August 25, 1982. Calculated Douglas fir \( r_s \) increased markedly after 1400 hours (>6000 s m \(^{-1}\)) owing to the high values of \( D \), and calculated salal \( E \) was highest for the period 1100-1400 hours (≈0.1 mm h \(^{-1}\)). Measurement error accounts for some of the disagreement, since Bowen ratios were high (≥2) on August 24-26 and wet and dry bulb gradients small on August 27 [Spittlehouse and Black, 1980].

Fig. 1. Courses of net radiation flux density and vapor pressure deficit above the forest (\( R_{na} \) (solid lines) and \( D \) (dashed lines), respectively) and measured (solid lines) and calculated (dashed lines) forest evapotranspiration rate (\( E \)) (with understory) on August 25, 1982, a clear day when average zone soil water potential (\( \Psi_p \)) was about -0.7 MPa. Errors in measured \( E \) were approximately 0.02-0.04 mm h \(^{-1}\) [Spittlehouse and Black, 1980]. Root-mean-square errors in calculated \( E \) were 0.04-0.06 mm h \(^{-1}\) as determined by differentiation of (1) applied to two layers and soil. A 10% error was assumed for \( D_p \), a 20% error for \( (R_{na} - G) \), and a 30% error for the transfer resistances, \( LE_o \) and \( R_{co} \).

Fig. 2. Relationship between forest floor diffusive resistance (\( r_{co} \)) and average root zone soil water content (\( \theta \)) in the cut subplot of plot 2 for 10 days in July and August 1981. For \( \theta \) less than 0.185, \( r_{co} \) was 800 s m \(^{-1}\) (0 = 0.189), and 900 s m \(^{-1}\) (\( \theta = 0.200 \) and 0.203). This meant that \( E_o \) was limited by a dry surface layer whose thickness (\( l_s \)) can be related to \( r_{co} \) using [Denmead, 1984; Novak and Black, 1985]

\[ l_s = r_{co}/(6\theta_0 - \theta_0k_w) \quad (10) \]

where \( f \) is a "tortuosity" factor (0.66); \( \theta_0 \) and \( \theta_0 \) are the porosity and volumetric water content of the dry layer; and \( k_w \) is the molecular diffusivity for water vapor (24.9 \times 10 \(^{-6}\) m \(^2\) s \(^{-1}\) at 25°C). For the forest floor, \( \theta_0 \) and \( \theta_0 \) were taken from Plaamon [1972] as 0.88 (i.e., bulk density = 150 kg m \(^{-3}\)), organic matter density = 1300 kg m \(^{-3}\) [Van Wijk and De Vries, 1963], and 0.20 (i.e., matric potential = -1.5 MPa). Using these values and \( r_{co} = 700 \) s m \(^{-1}\) in (10) results in \( l_s = 8 \) mm. Field observations support this calculation. At about midday on the day following an evening irrigation equivalent to 100 mm of rain, the forest floor surface of a cut area (i.e., salal cut and removed) adjacent to the four plots was observed to be dry. The above value of \( l_s \) suggests that the top 8 mm of forest floor consisted of rapidly draining litter (i.e., undecomposed leaves and twigs), while the bottom 2–12 mm was humidified with some water storage capacity. The interface between the organic layer and mineral soil was moist until \( r_{co} \) reached
Table 2. Average Values of the Minimum Measured and Calculated Average Root Zone Water Content (m³ m⁻³) in the Cut (C) and Uncut (U) Subplots

<table>
<thead>
<tr>
<th>Subplot</th>
<th>August 27, 1981</th>
<th>June 25, 1982</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Calculated</td>
</tr>
<tr>
<td>1U</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>1C</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>2U</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>2C</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>3U</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>3C</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>4U</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>4C</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>

For plots 2 and 3 (but not plots 1 and 4) the difference between measured values in cut and uncut subplots was statistically significant (95% probability) in both years.

Calculated differences in \( \theta \) between paired subplots. Salal understory removal resulted in slightly higher values of \( \theta \) and much higher values of \( \Psi_r \). Because of the large value of \( \Delta \Psi_r/\Delta \theta \) for this gravelly sandy loam soil at low values of \( \theta \), a small decrease in \( \theta \) corresponded to a large decrease in \( \Psi_r \) (Figures 4 and 5).

**Effect of assuming \( r_{ai} = 0 \) and \( r_{li} = 0 \).** Considerable simplification of the evapotranspiration theory is achieved when \( W = 0 \) by using the limit \( r_{ai} \rightarrow 0 \) in the theory so that \( E_l' = \rho c_p D_i/r_{li} \), where \( r_{ai} = r_{al}/a_i \). Working in the same stand as in this study, Tan et al. [1978] obtained good agreement between energy balance–Bowen ratio evapotranspiration measurements and values calculated using the above procedure in 1975 following heavy thinning of the stand. Use of this procedure in the cut subplot of plot 2 (salal understory cut and removed) for the rainless period July 30 to August 18,
was for the period August 6–19, 1981, in plot 2 when the water balance values of $E$ were 2.4 and 1.1 mm d$^{-1}$ for the uncut and cut subplots, respectively, compared to calculated average values of 1.7 and 1.5 mm d$^{-1}$ respectively.

Calculated transpiration rates of the trees in the cut subplots were slightly higher than those in the uncut subplots for the first 19 days of the 1981 period and first 11 days of the 1982 period but were considerably higher during the rest of the respective periods (Figure 7). On August 12, 1981, calculated tree transpiration rates were 1.5 and 1.1 mm d$^{-1}$ in the cut and uncut subplots of plot 2 (leaf area index was 5 for both trees) respectively. The corresponding values on August 20 were 1.1 and 0.5 mm d$^{-1}$. Using (1) and $r_s$ measurements made at about the midcrown height of the trees in plot 2, tree transpiration rates were estimated to be 1.4 and 1.1 mm d$^{-1}$ on August 12 and 0.8 and 0.6 on August 20, 1981, in cut and uncut subplots, respectively. There was not as good agreement between calculated and estimated tree transpiration rates in plot 2 for June 9, 17, 23, and 30, 1982; however, the differences between the cut and uncut subplots were in good agreement. During the 1981 and 1982 periods, salal removal resulted in an average increase in calculated tree transpiration rate of 31% and 52%, respectively, in the four plots. Calculations indicated that the increase in tree transpiration rate was greatest in plot 3 where salal leaf area index (3 and 2.4 in 1981 and 1982, respectively) was highest and was least in plot 4 where salal leaf area index was lowest (2.1 and 1.7 in 1981 and 1982).

Calculated values of total salal transpiration plus forest floor evaporation below the salal were about twice those of forest floor evaporation after salal removal in the 1981 and 1982 periods. This largely accounts for the increased tree transpiration following salal removal, since Douglas fir interception in adjacent subplots was identical and salal interception was a small term in the water balance. McNaughton and Jarvis [1983] expressed the evapotranspiration rate in terms of the equilibrium evaporation rate ($E_{eq} = [s/(s + \gamma)](R_n - G)/p$) and the equilibrium vapor pressure deficit ($D_{eq} = [s/(s + \gamma)]T_v(R_n - G)/pc$). For the salal, small canopy resistances [Tan et al., 1978] resulted in $D_{eq} < D$ above the salal canopy and the ratio of the 24-hour average salal transpiration...
tion and forest floor evaporation rate to the corresponding value of \( E_{eq} \) being 2.0–2.7 during the period July 24 to August 20, 1981. For the forest floor after salal removal, large surface diffusive resistances generally resulted in \( D_{eq} > D \) above the forest floor and the ratio of the 24-hour average evaporation rate to \( E_{eq} \) being 0.5–1.0 during the same period.

The evapotranspiration theory was developed for extensive homogeneous surfaces so that its application in the cut subplots included the use of below-tree canopy values of \( D \) and \( T_{air} \), largely determined by the presence of salal in the surrounding forest. Values of below-tree canopy \( D \) and \( T_{air} \) would be expected to be higher following extensive salal removal; however, it is difficult to estimate the magnitude of the increase. McNaughton and Jarvis [1983] show that the \( D \) above a conifer forest canopy is likely to be well coupled to the outer mixed portion of the planetary boundary layer. Consequently, they argue that a 50% reduction in forest leaf area index would not result in an increase in above-forest \( D \) and therefore would result in a significant reduction in forest evapotranspiration. Since \( D \) below the tree canopy in this study was well correlated to that above (in agreement with the results reported by Stewart [1984] for Thetford forest), it is likely that only a slight increase in below-tree canopy \( D \) would result from extensive salal removal. Further research involving understory removal over an extensive area is required to answer this question.

**CONCLUSIONS**

Shuttleworth’s [1979] evapotranspiration theory with canopy and root zone water balance models proved to be reasonably accurate and practical in calculating the courses of \( \theta \), \( \Psi_p \), and tree transpiration during extended periods in the growing season. The difficulty in using the theory is in estimating the transfer resistances \( r_{st} \), \( r_{ai} \), \( r_{m} \), and forest floor diffusive resistance, although \( r_{m} \) is often available from physiological studies. Simplifying the evapotranspiration theory by neglecting \( r_{ai} \) above and within the canopy resulted in very small decreases in the courses of \( \theta \) and tree transpiration rate. Further simplification for dry canopy conditions (\( W = 0 \)) by assuming \( r_{at} = 0 \) caused an overestimation of understory evaporation which resulted in an underestimation of the courses of \( \theta \) and \( \Psi_p \) and tree transpiration in uncut subplots. This simplification resulted in little change in cut subplots, since \( r_{at} \) is much smaller than \( r_{m} \) for Douglas fir.

Calculations showed that the slightly higher values of \( \theta \) as a result of understory removal corresponded to higher tree transpiration rates. During early (June 1982) and late (August 1981) growing season drying periods, most of the difference in tree transpiration occurred during the second half of the period due to the large value of \( \Delta \Psi_p/\Delta \theta \) of the soil water retention curve for low values of \( \theta \) and stomatal closure by Douglas fir where salal remained. Increase in tree transpiration as a result of understory removal was greatest where understory leaf area index was highest.

**APPENDIX: DERIVATION OF EQUATIONS**

(A1), (4), and (5)

The Penman-Monteith equation for a canopy layer \( i \) neglecting energy storage is

\[
E_i = \frac{s(R_{at} - R_{ai-1}) + \rho_c \Delta D_{i-1}/\Delta H_i}{Ls + \gamma \rho_v \rho_a/(1 - (r_{vi}/2r_{ai}))} \quad (A1)
\]

where \( R_{at-1} \) is the net radiation below the layer, and \( D_{i-1} \) is the vapor pressure deficit within the layer but outside the leaf boundary layer. This equation gives the water vapor flux density from an equivalent extended isothermal one-sided leaf with boundary layer resistances \( r_{hi} \) and \( r_{vi} \) to sensible heat and vapor transport, respectively, and a surface or canopy resistance \( r_{st} \) to vapor transport. The water vapor flux density on a ground area basis from a canopy layer of hypostomatous leaves with a projected leaf area index \( a_i \) and a fraction of the leaf area wet \( (W_i) \) can be written as

\[
E_i = W_i [s(R_{at} - R_{ai-1})/a_i + \rho_c \Delta D_{i-1}/(\rho_v/2)]
\]

\[
+ (1 - W_i) \frac{s \Delta D_{i-1}/\rho_v}{L(s + \gamma \rho_v \rho_a/(1 - \Delta H_i/2))} \quad (A2)
\]

The first bracketed term of (A2) is the evaporation rate from the average wet leaf on a projected leaf area basis in layer \( i \), the second bracketed term is the transpiration rate from the average dry hypostomatous leaf on a projected leaf area basis in layer \( i \), \( r_{st} \) is the leaf stomatal resistance of the side with stomata, and \( r_{hi} \) and \( r_{vi} \) are leaf boundary layer resistances on one side. In order that (A2) can be rewritten in the form of (A1) by making \( r_{st} \) a function of \( W_i \), we require \( r_{hi} = r_{st}/(2a_i) \) and

\[
1 = \frac{s}{\gamma(\rho_v/\rho_a)}(1 + (r_{st}/\rho_v))
\]

\[
= \frac{s}{\gamma(\rho_v/\rho_a)} + \frac{1 - W_i}{s + \gamma(\rho_v/\rho_a)} \quad (A3)
\]

Solving for \( r_{st} \) we have

\[
r_{st} = \left[ \frac{W_i}{s(\rho_v/\rho_a + r_{vi}/2a_i)} + \frac{1 - W_i}{s(\rho_v/\rho_a + r_{vi}/2a_i)} \right]^{-1} - \frac{s(\rho_v/\rho_a + r_{vi}/2a_i)}{s(\rho_v/\rho_a)} \quad (A4)
\]

where \( r_{vi} = r_{vi}/(2a_i) \) which reduces to (4) when \( r_{vi} \) and \( r_{hi} \) are assumed to be equal and written as \( r_{st} \).

Since (A2) can be written in the form of (A1), the canopy layer has an effective leaf temperature \( T_{ei} \) [Campbell, 1977]. Applying Ohm’s Law to the electrical analogue of the model for canopy layer \( i \) shown in Figure 8, the relationships between fluxes and resistances can be written as [Shuttleworth, 1979, p. 321]

\[
T_{ei} - T_{ei-1} = -H_i r_{st}/\rho_v \quad (A5)
\]

\[
T_{ei-1} - T_{ei-2} = -(H_i - H_{i-1}) r_{HI}/2a_i \quad (A6)
\]

\[
e_{ei} - e_{ei-1}(T_{ei}) = -L(\rho_v/\rho_a r_{st}/\rho_v) \quad (A7)
\]

\[
- L(E_i - E_{ei-1}) (r_{st} + (r_{vi}/2a_i))/\rho_v \quad (A7)
\]
where $H$ is the sensible heat flux density; $e$ is the vapor pressure; and $e^*(T_a)$ is the saturation vapor pressure at the effective leaf temperature. Using the Pennam transformation, we have

$$e_i = e^*(T_a) = D_i + s(T_i - T_{i-1}) + s(T_{i-1} - T_a)$$  \hspace{1cm} (A8)

where, since $T_a - T_i$ is not large, the same value of $s$ is used for both temperature differences. The energy balance equation for all layers $1$ to $i$ (neglecting energy storage) is

$$R_a - G = H_i + LE_i$$  \hspace{1cm} (A9)

where $LE_i$ is the latent heat flux density above layer $i$. Substituting (A5), (A6), and (A7) into (A8), using (A9) and dividing by $L$, we have

$$E_i = \frac{s(R_a - G) + pc_i(D_i + \delta_i)/r_{AH}}{L(s + r_{SAV}/r_{AH})(1 + (r_i/r_{AV}))}$$  \hspace{1cm} (A10)

where

$$\delta_i = [LE_{i-1} - [r_{vi}/(2a_i)]y_i] + [r_{wi}/(2a_i)]s_i - [s_{i-1} - [r_{wi}/(2a_i)]y_i]/pc_i$$  \hspace{1cm} (A11)

with $r_{AH} = r_{vi}/2a_i + r_{wi}$ and $r_{AV} = r_{vi}/2a_i + r_{vi}$. Equation (A10) is the same as (9) in the work by Shuttleworth [1979]. Subtracting $E_{i-1}$ from (A10) and assuming similarity (i.e., $r_{vi} = r_{wi}$ and $r_{wi} = r_{w}$) give (1).

The rate of evaporation of intercepted water from layer $i$ ($E_i$) is obtained by multiplying the fraction of leaf area (one side) that is completely wet (W) by (A1) with $r_{el} = 0$ which gives

$$E_i = \frac{W[i(s(R_a - R_{i-1}) + pc_i(D_i - y_{i-H})]}{L(s + r_{SAV}/r_{AH})}$$  \hspace{1cm} (A12)

Dividing (A12) by (A1), assuming similarity (i.e., $r_{HA} = r_{el} = r_{el}/2a_i$), making use of (4) and rearranging give (5).

Acknowledgments. This research was supported by a grant from the Natural Science and Engineering Research Council of Canada and a contract from the British Columbia Ministry of Forests. We appreciate the assistance of D. Beames, R. Adams, R. Emerson, and the staff of the University of British Columbia Research Farm at Oyster River. We are grateful to D. L. Spittlehouse and M. D. Novak for valuable discussions on the paper.

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