EVAPOTRANSPIRATION AND SURFACE CONDUCTANCE FOR A
HIGH ELEVATION, GRASS COVERED FOREST CLEARCUT.

By

Ralph S. Adams

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Department of Soil Science
The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

Date:

30th April, 1990

Abstract

Evapotranspiration from a forest clearcut was measured over two growing seasons as part of a larger study of the microclimate of forest clearcuts and microclimate modification by site preparation. Pinegrass is the dominant species on clearcuts in the dry southern interior and is the major competitor with coniferous seedlings. This paper examines the water use of a pinegrass dominated clearcut and the response of surface conductance to environmental variables.

Evapotranspiration was derived from eddy correlation measurements of sensible heat flux and measurements of net radiation and soil heat flux. 419 hours of daytime energy balance data from the summers of 1987 and 1988 were analyzed. A rearranged form of the Penman-Monteith equation was used to calculate hourly mean surface conductances for the clearcut. Leaf area measurements were used to calculate stomatal conductance from surface conductances.

Stomatal conductance was modelled using boundary-line and non-linear optimization techniques. The most successful model ($R^2 = 0.71$) was obtained using non-linear optimization with stomatal conductance as a non-linear function of saturation deficit at the leaf surface (D_0) and solar irradiance. D_0 was calculated from measured evapotranspiration and surface conductance. Response of stomata to saturation deficit would be expected to be better correlated to D_0 than D measured at a reference height above the canopy. Stomatal conductance was also modelled as a function of D (measured at 1.3 m) and solar irradiance. The resulting model ($R^2 = 0.50$) was poor compared to that based on D_0 .

Saturation deficit and temperature were found to be highly correlated both at 1.3 m

above the canopy and at the leaf surface. Use of air temperature in the conductance model caused R^2 to decrease. No relationship between stomatal conductance and volumetric soil water content was found.

Hourly evapotranspiration rates calculated using modelled surface conductances agreed well with measured rates. ($R^2 = 0.89$).

Evapotranspiration was also modelled using the Priestley-Taylor approach. The mean hourly λ for all daylight data was found to be 0.81. This simple model was found to give comparable results to the stomatal conductance based model ($R^2 = 0.85$).

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Chapter 1

Introduction

In the dry southern interior of British Columbia, clearcutting of native stands of lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menzeizii* var. *glauca*) results in large areas dominated by grass and shrub species. Native pinegrass (*Calamagrostis rubescens*) invades the clearcuts soon after cutting and is a major competitor with coniferous seedlings planted into these sites. In 1985, the Forest Resource Development Agreement (FRDA) between the federal and provincial governments was initiated to reduce the amount of insufficiently regenerated land in British Columbia. In addition to replanting, research was conducted into all aspects of forest regeneration.

One of the projects was an intensive biometeorological study of clearcut microclimate, seedling water relations, and the microclimatic impact of site preparation treatments (Black *et al.* 1989). Since soil water deficits are one of the major factors limiting seedling growth on these sites, micrometeorological measurements of evapotranspiration were made to determine water use by the pinegrass clearcut.

Models of evapotranspiration are required to assess the effects of removing competing vegetation, to determine optimum seedling planting dates and to investigate plantation failures. Evapotranspiration models are also required in hydrological studies of forested watersheds containing increasing areas of clearcut land. Furthermore, current global circulation models require accurate estimates of evapotranspiration from different vegetation types (Dickinson and Sellers 1988). The Penman-Monteith (PM) equation (Monteith 1981) has been used in all of these situations. In addition to weather variables, the PM

equation also requires estimates of the surface conductance of each vegetated surface and the response of surface conductance to environmental variables.

The objectives of this thesis are (i) to determine the response of the surface conductance of a high elevation grass covered forest clearcut to environmental variables, (ii) to compare several techniques for determining the parameters used in modelling this response and (iii) to compare the effectiveness of the PM equation and the simpler Priestley and Taylor (1972) equation for estimating evapotranspiration.

Chapter 2

Theoretical Considerations

2.1 The Penman-Monteith Equation

The Penman-Monteith equation, which describes the isothermal, big leaf model of evapotranspiration from an extensive vegetated surface, is given by

$$\lambda E = \frac{s(R_n - G) + \rho c_p D_a g_a}{s + \gamma(1 + g_a/g_s)} \quad (2.1)$$

where $(R_n - G)$ is the available energy flux density (net irradiance – soil heat flux density (W m^{-2})), s is the slope of the saturation specific humidity curve at air temperature ($\text{kg kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), ρ is the density of air at air temperature (kg m^{-3}), c_p is the specific heat of air ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), λ is the latent heat of vaporisation at air temperature (J kg^{-1}), E is the flux density of water vapour from the surface ($\text{kg m}^{-2} \text{ s}^{-1}$), γ is the psychrometric constant (c_p/λ) ($^\circ\text{C}^{-1}$), D_a is saturation specific humidity deficit (kg kg^{-1}), g_a is the aerodynamic conductance between the effective canopy surface and the reference height at which air temperature and D_a are measured (m s^{-1}), and g_s is the surface conductance (m s^{-1}).

Assumptions in equation 2.1 are that (i) all leaf stomatal conductances can be combined in parallel to give the surface conductance, i.e.

$$g_s = \sum_{i=1}^n L_i g_{s_i} \quad (2.2)$$

where L_i is the leaf area index of element i and g_{s_i} is the stomatal conductance of element i and (ii) all leaf boundary-layer conductances and the eddy diffusive resistance above the

canopy can be combined to give a single aerodynamic resistance (Thom 1972). Although equation 2.1 is a simplification (Monteith 1981, Raupach and Finnegan 1988), in practice it has been found to successfully represent the surface conductance of real canopies (Black et al. 1970, Tan and Black 1976).

2.2 Stomatal Conductance

Stomatal conductance is known to respond to changes in quantum ($0.4\text{--}0.7\ \mu\text{m}$) irradiance (Q), leaf temperature (T_0), leaf surface saturation deficit (D_0), leaf water potential (Ψ_l), soil water potential (Ψ_s), and ambient CO_2 concentration (C). The relationship between g_s and an environmental variable, when others are held constant at non-limiting levels, is similar in many plant species and families (Jones 1983). It has not been possible to produce a mechanistic model of stomatal conductance. A phenomenological model was proposed by Jarvis (1976) to determine g_s as a function of a number of environmental variables. He proposed that g_s responds to each environmental variable independently and the value of g_s resulting from any combination of variables is given by

$$g_s = g_{s_{max}} f(Q) g(D_0) h(T_0) i(\Psi_l) j(C) \quad (2.3)$$

where $g_{s_{max}}$ is the maximum stomatal conductance which would occur if none of the environmental variables were limiting. The individual functions, with values between 0 and 1, are determined when all the other variables are not limiting. Equation 2.3 is referred to as the Jarvis or multiplicative model of stomatal conductance.

Jarvis suggested that, for application to porometer data taken under field conditions, functions determined in controlled environment chambers be used and the parameters be empirically fitted to the field data. Two methods can be used to determine the values of the individual parameters. Webb (1972) and Jarvis (1976) observed that the upper edge of a scatter plot of g_s against an environmental variable would indicate the response

to the variable when no other variables are limiting. By fitting a function, the form of which was determined in controlled environment studies, to the upper boundary of the data the values of the individual parameters can be determined. Unfortunately, as the upper points contain errors, judgement must be used to determine the most probable location of the boundary line. Also, it is not possible to describe the resulting function statistically. Boundary line analysis (BLA) has been successfully used by Livingston and Black (1987) to determine the parameters in a multiplicative model describing the stomatal conductance of conifer seedlings. They used solar irradiance (S), saturation deficit and temperature of the air, and soil water potential. They also found that time since sunrise had a significant effect on stomatal conductance.

Jarvis (1976) used non-linear least squares optimization to determine values for the parameters in the multiplicative model applied to shoots of Sitka spruce and Douglas-fir. This technique has also been applied to porometer measurements of stomatal conductance of a bracken understory (Roberts and Pitman 1984).

2.3 Surface Conductance

As surface conductance depends on the stomatal conductance of the vegetation, it would be expected that similar techniques could be used to model the response of surface conductance to environmental variables. The technique of stratification has been used by Stewart and de Bruin (1985), Callender and Woodhead (1981) and Black and Kelliher (1989). In this technique two environmental variables are assumed to control surface conductance. One variable is stratified into ranges. A family of curves is then developed to determine surface conductance as a function of the second variable, each curve corresponding to one of the ranges of the first variable. This technique is difficult to implement if surface conductance is to be related to more than two environmental variables. The

range of values assumed by one of the variables is discontinuous.

Stewart (1988) extended the Jarvis multiplicative model to the canopy of a pine forest. Stewart's equation was

$$g_s = g_{s_{max}} f(D) g(S) h(T_a) i(\delta\theta) \quad (2.4)$$

where S is the solar irradiance, D is the saturation specific humidity deficit at the reference height, T_a is the air temperature at the reference height, and $\delta\theta$ is the soil water storage deficit in the upper 1 m of soil. As the variation in C is small during outdoor experiments, it was neglected. The forms of the functions used were similar to those of Jarvis (1976). The parameters for each function were determined by non-linear least squares (NLLS) optimization. This approach has been used by Gash *et al.* (1989) for a stand of maritime pine and by Stewart and Gay (1989) for prairie grassland.

Price and Black (1989) also used the multiplicative model to estimate surface conductance of a Douglas-fir stand. The parameters were determined using boundary line analysis. They found that surface conductance was better modelled by substituting a limiting factor model for the multiplicative model. In their model, g_s was estimated from

$$g_s = g_{s_{max}} F \quad (2.5)$$

where F is the minimum of $f(D)$, $g(S)$, $h(T_a)$, $i(\delta\theta)$, and $j(t)$, where t is time since sunrise.

Monteith (1990) points out that stomata respond to saturation specific humidity deficit at the leaf surface (D_0) rather than that at a reference height above the canopy (D). D_0 as defined by the big leaf model is given by

$$D_0 = \frac{E}{\rho g_s} \quad (2.6)$$

From equation 2.1, it can be shown that when E is equal to the equilibrium evaporation rate, $E_{eq} = (s/(s + \gamma))(R_n - G)$, $D = D_0$. When $E < E_{eq}$, $D_0 > D$. When the surface

is rough and g_a is high, the two deficits will also be similar due to the large degree of coupling between the canopy and surface layer. Similarly, stomata must respond to the temperature of the leaf rather than to that at a reference height. The temperature of the effective canopy surface (T_0) is given by

$$T_0 = T_a + \frac{H}{\rho c_p g_a} \quad (2.7)$$

where H is the sensible heat flux density.

2.4 Evapotranspiration Models

Evapotranspiration can be estimated using equation 2.1, climate station data, and a model of surface conductance (Price and Black 1989, Dolman 1988). Evapotranspiration is usually estimated more accurately than surface conductance is modelled (Stewart 1988, Gash *et al.* 1989, Stewart and Gay 1989). This is because E in equation 2.1 depends only in part on g_s . The sensitivity of E to g_s for forests is expected to be greater than for agricultural crops because g_a is greater than for agricultural crops (Raupach and Finnegan 1988).

Priestley and Taylor (1972) proposed a model of regional evapotranspiration for vegetated surfaces with no shortage of soil water in the form

$$\lambda E = \alpha \frac{s}{s + \gamma} (R_n - G) \quad (2.8)$$

where α is an empirical constant. They found that a value of $\alpha = 1.26$ fit data from several sources. McNaughton and Spriggs (1989) showed that for surfaces with values of $g_s > 17\text{--}20\text{mm s}^{-1}$, equation 2.8 with this value of α gives estimates of evapotranspiration, in the absence of advection, that agree with equation 2.1. This model has been applied to vegetation which was not well supplied with water, resulting in values of α less than 1.26.

Chapter 3

Experimental Procedures

3.1 Site Description

The site is at an altitude of 1220 m and is located at 50° 40'N, 120° 54'W on the Thompson plateau in the southern interior of British Columbia, Canada. The Thompson plateau is a large area approximately 900 × 400 km formed by lava flows from fissures and shield volcanoes during the Tertiary period. The landscape consists of rolling terrain with 300 to 900 m deep river valleys cut into the plateau. The soil on the site is an Orthic Grey Luvisol derived from a morainal blanket composed of mixed volcanic materials. The upper 30 cm has a loam texture with a high stone content (Mitchell *et al.* 1981). A layer with high bulk density (1700–2200 kg m⁻³) is found below 40 cm.

The closest station at which long term weather records are available is 15 km to the south west at a similar altitude and with similar topography. The mean annual rainfall is 390 mm, and the mean rainfall in the growing season (May–August) is 164 mm. In the two years of this study, the growing season rainfall measured at the experimental site was 163 mm in 1987 and 275 mm in 1988. Frequent frosts occur throughout the growing season. In 1987, there were 37 nights with air temperatures (measured at 15 cm) below 0 °C. These frosts were frequently below –5 °C and caused significant damage to planted conifer seedlings.

The natural vegetation consists of coniferous forest composed of lodgepole pine and interior Douglas-fir with an understory dominated by pinegrass. The 10 ha experimental

site was clearcut logged in 1982 and scarified with a crawler tractor brush blade in 1984 leaving a large number of stumps and coarse woody fragments. The predominant vegetation in the clearcut during the experiment was pinegrass, prickley rose (*Rosa acicularis*), dwarf blueberry (*Vaccinium cespitosum*) and arctic lupine (*Lupinus arcticus*). Visually pinegrass, which grows to a height of 15–30 cm, appears to dominate the site due to the large biomass of standing dead material that remains from year to year.

3.2 Measurements

3.2.1 Climate Station Measurements

An automated climate station using a Campbell Scientific 21X datalogger has been used since May 1986 to collect hourly mean microclimate data. The sensors are read at 10 s intervals and means calculated at the end of each hour. Solar irradiance was measured with a Licor silicon cell pyranometer. This unit was calibrated in the field annually against a Moll-Gorczynski pyranometer, manufactured by Kipp and Zonen. The calibration of the second instrument was traceable to a national standard. Air temperature and relative humidity (RH) were measured with a Fenwall UUT-51J1 thermistor and a Phys Chem sulphonated polystyrene sensor respectively, housed in a Stevenson screen at a height of 1.3 m. The sensors were regularly checked with an aspirated Assmann psychrometer. For a 6 week period in each year an automated aspirated psychrometer (Spittlehouse and Black 1981) was used to measure wet and dry bulb temperatures at 1.3 m. Due to the power requirements of this instrument, aspiration was applied only for the 5 min preceding a spot measurement every 30 min. Excellent agreement was found between the hourly mean values from the thermistor and RH sensor and the mean of the three 30 min spot readings taken each hour with the aspirated psychrometer. The saturation deficit values used in the analysis were taken from the thermistor and RH sensor. Wind speed

was measured at a height of 1.3 m with a Met-One cup anemometer with a stall speed of 0.47 m s^{-1} . Wind speed during the day tends to be high (hourly mean 2.73 m s^{-1}) and examination of the data revealed no mean wind speeds that were suspect due to stalling. Wind direction was monitored with a Met-One windvane mounted at 1.3 m. Air temperature at a height of 15 cm was measured using a Fenwall UUT-51J1 thermistor potted in epoxy and mounted in a radiation shield consisting of two horizontal square aluminum plates 20 cm wide. The upper surface was covered with aluminized mylar and all other surfaces were allowed to oxidise. Tests with fine-wire thermocouples showed that the radiation error was less than 0.1°C . Rainfall and soil temperature were also measured at the climate station.

3.2.2 Energy Balance Measurements

An area was set aside for energy balance measurements to prevent destruction of vegetation. The site chosen was flat with changes in topography of no more than 0.5 m in height. However, no stumps or large slash were removed. It was estimated that approximately 5% of the area was covered by stumps or coarse woody fragments. The fetch extended approximately 100 m downwind to the forest edge. Due to the location of site preparation treatments and a small depression, only data collected with the wind in the sector from 90° to 200° was used in analysis. In 1988, poplar saplings began to grow in this area and were manually removed.

Net irradiance was measured with a Swissteco S1 net radiometer mounted at a height of 1 m over vegetation considered to be characteristic of the area downwind. The radiometer was inflated by a flow of dry nitrogen gas from a compressed gas cylinder. A shortwave calibration by shading outdoors was performed before the radiometer was taken into the field. The domes were frequently checked for condensation or rain droplets and any data taken when the domes were wet were discarded. In August 1988, another

S1 net radiometer was used in an experiment to determine the spatial variation of net radiation at the site. It was run for two days within 30 cm of the fixed radiometer for calibration. It was then moved to various positions in the clearcut to determine the variation in net irradiance caused by slight changes in vegetation and the presence of slash. It was found that R_n varied by less than 5% even near large pieces of slash and so no attempt was made to correct values measured with the fixed radiometer.

Soil heat flux was measured with a pair of Middleton heat flux plates buried in the area below the net radiometer. The plates were inserted at the interface between the organic and mineral horizons at a depth of 3 cm. Correction for heat storage in the organic layer was done using a pair of integrating thermometers made by winding 30 gauge Nickel resistance wire on a 5 mm diameter glass rod and coating with epoxy.

Sensible heat flux was measured using the eddy correlation method with three Campbell Scientific one-dimensional sonic anemometers and fine-wire (0.013 mm diameter) thermocouples. The instruments were read at a frequency of 10 Hz and the mean covariance of vertical wind velocity and air temperature was recorded every 30 min using a Campbell Scientific 21X datalogger. The three instruments were mounted at a height of 1 m on masts 10 m apart, arranged as an equilateral triangle. At intervals during the growing season, the three instruments were mounted at a height of 1 m around a single tower. Each sensor being separated from its nearest neighbour by at least 80 cm. It was found that all anemometers agreed to within 10% of the mean value for the three. Due to the variability of the site and the minimum separation required to prevent cross-talk, this was considered good agreement. When mounted on the three towers, the instruments agreed to within $\pm 25\%$ of the mean value. The mean value was used in the energy balance analysis. Another test was conducted in which the three instruments were mounted on one tower at three heights: 0.5, 1, and 1.5 m. There was no significant variation in heat flux observed, which indicated that fetch was adequate for the 1 m height used.

A 3-day run was made with a reversing Bowen-ratio apparatus using aspirated psychrometers with silicon diode temperature sensors (Spittlehouse and Black 1981). The separation of the sensors was 1 m with the lower sensor at a height of 0.5 m.

3.2.3 Soil Moisture and Leaf Area

Volumetric soil water content was determined at weekly intervals through the growing season. Gravimetric sampling was used in the upper 10 cm and a calibrated neutron probe (Fleming 1990) at the 19, 30, 45, 60, and 90 cm depths. Three shallow (60 cm) and three deep access tubes were installed. If necessary, the value of θ was interpolated to determine the value for a particular day. The volumetric water content in the upper 5 cm was used to determine the volumetric heat capacity of the organic layer required in correcting soil heat flux measurements. The mean value of θ from 0 to 30 cm was used in the modelling of surface conductance.

Leaf area index was measured at 2–4 week intervals during the experiment. A square meter of vegetation was selected which did not contain large pieces of slash or atypical species composition. All vegetation was removed at the soil surface and stored in a refrigerator. The samples were later sorted into grass and herbaceous components. The senesced grass was removed from the sample. Leaf areas were then measured using a Licor leaf area meter. Due to the large spatial variability in vegetated cover and the difficulty in separating the living from senesced grass, measurements from three years were combined and a quadratic fitted to the data to give an estimate of total L as a function of Julian date (J). This was found to be

$$L = -4.66 + 0.0556J - 0.00014J^2 \quad (3.9)$$

Although the clearcut appeared to be dominated by pinegrass, the other species contributed up to 45% of the leaf area. This was due to the large amount of standing dead

grass and because a small amount of broadleaved vegetation significantly affected the value of L . The total leaf area index never exceeded 1 and the growing season mean was 0.56. The maximum leaf area index occurred in mid July. This is similar to the results reported by (Nicholson 1989, and Stout & Brooke 1985) for pinegrass in the central interior of B.C.

3.2.4 Data Analysis

After removing eddy correlation data collected when fetch was inadequate or the surface was wet with dew or rain, 419 hours of data remained. The 30 min mean values were averaged to give hourly mean values, this was necessary in order to combine hourly data from the climate station. Covariance measurements were converted to sensible heat fluxes assuming a constant air pressure of 87.5 kPa. The latent heat flux (λE) was then calculated using the energy balance equation

$$\lambda E = R_n - G - H \quad (3.10)$$

The energy stored in the canopy and used in photosynthesis was assumed to be negligible. After correcting for variations in the psychrometric constant due to elevation and the changes in air density due to fluxes of heat (Webb *et al.* 1980), it was found that the Bowen ratio apparatus overestimated mean 30 min values of the Bowen ratio compared to the Bowen ratio calculated from R_n , G and the eddy correlation measurement of H . This resulted in λE determined from the Bowen ratio/energy balance method being up to 30% less than that from the eddy correlation/energy balance method. A similar phenomenon was observed by Leuning *et al.* (1982) over a rice stubble surface. The errors in the Bowen ratio/energy balance method were likely due to (i) the lower sensor of the Bowen ratio apparatus being within the wake zone of the surface elements and (ii) marked differences in the locations of sources of sensible and latent heat in the sparse pinegrass canopy, which

tend to invalidate the similarity assumption used in the Bowen ratio/energy balance method (Thurtell 1987, Raupach 1989). A comparison was made between estimates of evapotranspiration based on the eddy-correlation/energy balance technique, and weekly measurements of soil water content. Daytime values of α were calculated for the days on which eddy-correlation data were available. These values were then extrapolated to days when no eddy-correlation data were available. Measured daytime mean air temperature and net radiation were used with equation 2.8 to estimate evapotranspiration over the growing season. The estimates based on the eddy-correlation/energy balance technique agreed well with the soil water balance indicating that the Bowen ratio apparatus was in error.

Aerodynamic conductance for neutral conditions was calculated using (Verma 1989)

$$\frac{1}{g_a} = \frac{\ln((z-d)/z_0^m) \ln((z-d)/z_0^h)}{k^2 u} \quad (3.11)$$

where d is the zero plane displacement height, z_0^m and z_0^h are the roughness lengths for momentum and heat transfer respectively, k is von Karman's constant and u is the windspeed at the reference height z . d was assumed to be $2h/3$, where h is the height of the vegetation, while the roughness lengths were calculated using $z_0^m = h/10$ and $z_0^h = z_0^m/10$ (Verma 1989). No correction for stability was made.

The surface conductance g_s was then calculated using a rearranged form of equation 2.1. Mean stomatal conductance was calculated using

$$g_s = \frac{g_a}{L} \quad (3.12)$$

D_0 and T_0 were calculated from equations 2.6 and 2.7 respectively. Data was analysed and investigated for each day to determine if all values appeared reasonable. On two days, extremely high values of g_s in the morning indicated that the surface was wet, although it appeared dry. These data were removed. Data were also removed if the value

of $(R_n - G)$ was less than 25 W m^{-2} because, under these conditions, estimates of λE were erratic. All hourly data were then combined into three data sets: 1987, 1988 and both years combined. A total of 419 hours of data was used in the modelling.

Modelling Mean Stomatal Conductance

Boundary line analysis.

The maximum value of g_s observed in the two years of data was 42 mm s^{-1} , this was used as the maximum in both years. The functions used in the BLA were selected from controlled environment studies if possible.

The function used for the response of g_s to D_0 was

$$\begin{aligned} f(D_0) &= 1 - K_1 D_0 & 0 < D_0 \leq K_2 \\ &= 1 - K_1 K_2 - K_3 D_0 & D_0 > K_2 \end{aligned}$$

This is similar to the function used by Stewart (1988) except that the lower arm was horizontal in that case. The function is a linear approximation of the exponential decay function given by Jarvis (1976) and Jones (1983). Jones showed that an exponential decay function is produced by a negative feedback model of stomatal response to saturation deficit, while a linear decrease is produced by a feedforward response. The choice of two linear segments was made in this case to avoid rounding errors, which caused the software to abort when many exponential functions were used in the NLLS optimization.

The function used for the response of g_s to solar irradiance was

$$g(S) = 1 - e^{K_4 S}$$

This is the form given by Jones (1983).

The function used for the response of g_s to temperature was

$$h(T_0) = \frac{(T_0 - T_{min})(T_{max} - T_0)^{K_5}}{(K_6 - T_{min})(T_{max} - K_6)^{K_5}}$$

$$K_5 = (T_{max} - K_6)/(K_6 - T_{min})$$

where T_{min} was taken as 0°C and T_{max} was taken as 42°C . This is the function presented by Jarvis (1976). K_6 is the temperature at which the function reaches its maximum. In this study T_{min} and T_{max} were considered to be constants. The response of g_s to the soil water regime was described by a function relating g_s to the volumetric soil water content (θ) in the upper 30 cm

$$i(\theta) = \frac{(\theta - K_7)(\theta_{max} - \theta_{min})}{\theta_{max}((\theta - K_7) + \theta_{min})}$$

At very low θ , g_s approaches 0. It increases rapidly with increasing θ until it reaches a level where increasing θ has little effect.

Price and Black (1989) and Livingston and Black (1987) found that there was a response by g_s to time since sunrise. There is a relationship between time since sunrise and D_0 , as saturation deficit usually increases during the daytime; however, there is evidence (Zang and Davies 1988) that g_s responds to abscisic acid transported from the roots to the leaf epidermis during the day. It is possible that this effect is independent of the daytime trend in saturation deficit. The function used to model the response of g_s to time since sunrise (hours) was

$$\begin{aligned} j(t) &= 1 & 0 < t \leq K_8 \\ &= 1 - K_9(t - K_8) & t > K_8 \end{aligned}$$

Delucia (1987) found that photosynthesis and stomatal conductance of conifer seedlings was decreased after being subjected to short periods of low temperature. As the experimental site is subject to frequent summer frosts, a response of g_s to the minimum air temperature the previous night was investigated. The minimum air temperature at a height of 15 cm was determined for the night before each day of eddy correlation measurements. All hourly mean conductance data were paired with the minimum temperature

for the previous night. No boundary line relationship could be determined and it was concluded that the vegetation in the clearcut did not show a response in conductance to exposure to freezing temperatures.

The starting values for the parameters were chosen by inspection and the functions were plotted onto the scatterplots using a commercial plotting routine (Wilkinson 1989). The parameters were refined until it was judged that the BLA curve had been achieved. The parameters were then tested in the multiplicative model. This was repeated for each year individually and then with both years combined.

Non linear least squares optimization

The maximum value of g_s and the same functions described above were used except the function used to describe the response of g_s to S was

$$g(S) = \frac{(1000 + K_4)S}{1000(K_4 + S)}$$

This is the function used by Stewart (1988), and approximates the exponential function described above. It was chosen to avoid rounding errors during optimization. The optimization was performed using SYSTAT, a commercial statistical package containing a general non linear modelling unit and an integrated graphics capability (Wilkinson 1989).

These functions were used in the multiplicative model of mean stomatal conductance in the form

$$g_s = g_{s_{max}} f(D_0) g(S) h(T_0) i(t) j(\theta) \quad (3.13)$$

where the maximum mean stomatal conductance $g_{s_{max}}$ was 42 mm s^{-1} for all years and models.

3.2.5 Testing of Models

Models of g_s and λE were tested using the same data set used to determine the values of the parameters. The success of the models was determined using linear regression with

intercepts. The measured and modelled values were the independent and dependent variables respectively. Wilkinson (1989) and Kvalseth (1985) point out that the algorithms used to determine the coefficient of determination (R^2) are not equivalent when intercepts are not calculated. Many statistical programmes use different algorithms, which makes the comparison of R^2 from different workers impossible if intercepts are not used.

Chapter 4

Results and Discussion

4.1 Diurnal Energy Balance

Figure 4.1a shows the diurnal energy balance for July 1, 1987. The maximum hourly mean solar irradiance was 880 W m^{-2} . At this point in the growing season, leaf area index was approaching maximum (0.7) and no mineral soil surface was visible. Volumetric soil water content on this day was estimated to be 0.08 in the upper 30 cm of soil. This was the lowest value of θ for this layer observed in both years. The saturation deficit was high and followed the characteristic trend through the day as shown in Figure 4.1b. Although saturation deficit was high and soil moisture content was low, the latent heat flux was high. The Bowen ratio reached a maximum for the day of only 0.8 by late morning. This suggests that the vegetation of the clearcut was adequately supplied with water. This is probably mainly due to the deep rooting characteristics of pinegrass (Fleming, 1990). Volumetric soil water content in the 19 to 60 cm zone was 0.24 on this day. There was little variation in θ at the 1 m depth during both of the growing seasons.

The response of H and λE to changes in the available energy flux shown in Figure 4.1a display characteristics of both aerodynamically rough surfaces such as forests and aerodynamically smooth surfaces such as grass or short crops. Above a rough surface, λE tends to respond to changes in D rather than to available energy flux. This is shown in Figure 4.1a by the tendency for λE to remain high as the available energy flux drops in the afternoon. Above a smooth surface, λE tends to follow the available energy flux.

Figure 4.1: Diurnal energy balance and hourly mean environmental variables for July 1, 1987. A, the hourly mean values of energy balance components. B, The diurnal trend in saturation deficit. D was measured at 1.3 m and D_0 was calculated with equation 2.6. C, Diurnal trend of g_s and g_a , g_a calculated with equation 3.11, g_s calculated with a rearranged form of equation 2.1 and g_a . D, diurnal trend in α calculated with equation 2.8, and Ω calculated with equation 4.14.

This behaviour is shown in Figure 4.1a by the decrease in λE and R_n at noon as a cloud moved past. Figures 4.1a and b show that this was not accompanied by a decrease in D . McNaughton and Jarvis (1983) defined the coupling coefficient (Ω) to describe the coupling between λE and the saturation deficit of the mixed layer of the atmosphere as

$$\Omega = \left(1 + \frac{g_a}{g_s} \left(\frac{s}{s + \gamma} \right) \right)^{-1} \quad (4.14)$$

Rough surfaces such as forests are well coupled to the mixed layer and have values of Ω less than 0.5. Smooth surfaces are not well coupled to the mixed layer, show a marked response to available energy flux and have values of Ω greater than 0.5. Figure 4.1 d shows the diurnal trend in hourly mean Ω . Hourly Ω varied between 0.65 and 0.35, and the mean value for the period 07:00–18:00 PST was 0.52. Hourly values of Ω varied from 0.2 to 0.7 during the growing season; however, the daytime mean values only varied between 0.3 and 0.6. Characteristically Ω was higher in the morning and decreased through the day. This reflects the diurnal trend in g_s and g_a shown in Figure 4.1 c. Surface conductance tends to decrease in the afternoon in response to increasing saturation deficit. Wind speed often increases in the afternoon resulting in g_a increasing.

The surface conductances shown in Figure 4.1 c are similar to those reported for other grass surfaces. Table 4.1 lists daily mean values of g_s from several studies selected for days when soil water was not considered to be limiting evapotranspiration. The value from Stewart and Gay (1989) was the daytime mean of nine days of data, all other values were calculated from data for a single day. For species with similar stomatal characteristics, g_s would be directly related to L . This would indicate that the pinegrass clearcut has a high surface conductance relative to the low leaf area index. Stewart and Gay (1989) and Parton *et al.* (1981) did not observe the characteristic decrease in g_s in the afternoon as was observed in this and the other reported studies; however, as they do not show the diurnal trend in D this may be due to unusual conditions. The mean hourly g_s over the

Table 4.1: Daytime mean surface conductances and leaf area indices for grassland without soil water limitation.

Vegetation	g_s (mm s ⁻¹)	L (m ² m ⁻²)
Shortgrass steppe ^a	5 ^f	0.5
<i>Agropyron-Koeleria</i> ^b	9.1	1.45
Tussock grass ^c	5.7	—
Tallgrass prairie ^d	10.1	—
Pinegrass clearcut ^e	6.7	0.75

^aParton *et al.* (1981).^bRipley and Redmann (1976).^cCampbell (1989).^dStewart and Gay (1989).^ePresent study.^fThis study did not separate g_s and g_a , but as wind speeds were high g_a was small.

419 hours of this experiment was 6.14 mm s^{-1} with a standard deviation of 3.53 mm s^{-1} . The maximum and minimum values were 24.9 mm s^{-1} and 1.02 mm s^{-1} , respectively.

4.2 Modelling Surface Conductance

As indicated earlier, here L is considered to be known, so that modelling surface conductance depends on the success in modelling stomatal conductance. Figure 4.2 shows the relationship between g_s calculated using equation 3.12 and the saturation specific humidity deficit at the leaf surface calculated using equation 2.6, stratified by solar irradiance. A clear response to D_0 and S is indicated. Idso (1990) suggests that many of the reported responses of g_s to D_0 are due to changes in leaf environment following enclosure in porometer chambers. These data for pinegrass were determined from energy balance measurements and are free of enclosure effects, but show a marked response to saturation deficit. Similar results have been obtained in other studies, (Black and Kelliher 1990, Stewart 1988, Gash *et al.* 1989, Stewart and Gay 1989). McNaughton and Jarvis (1983) point out that as most grasses evolved in arid conditions, such a response would be advantageous and not unexpected.

4.2.1 The Technique of Boundary Line Analysis

The values of the parameters for the functions described above determined using the BLA technique are listed in Table 4.2. These parameters were used with equation 3.13 to estimate g_s with the three data sets used in the determination of the parameters. The results of the models are listed in Table 4.3. The models were tested by successively adding functions to the multiplicative model given by equation 3.13 to determine the response of g_s . Tables 4.2 and 4.3 show that there is little difference between the two years in both the values of the parameters and value of R^2 for the various models. The

Figure 4.2: Mean canopy stomatal conductance plotted against saturation deficit, stratified by solar irradiance. Hourly mean data from 1987 and 1988, $\bullet = S > 200 \text{ W m}^{-2}$, $\circ = S \leq 200 \text{ W m}^{-2}$.

Table 4.2: Parameters for multiplicative model of g_S determined by BLA.

Parameter	Data set used in analysis		
	1987	1988	Combined
K_1	0.069	0.052	0.052
K_2	11	14	14
K_3	0.006	0.006	0.008
K_4	0.004	0.006	0.004
K_6	15	20	21
K_7	0.075	0.075	0.075
K_8	0	4	4
K_9	0.052	0.08	0.08

Table 4.3: Results of testing models of g_S with parameters determined by BLA.

Variables used	R^2	Intercept (mm s^{-1})	Slope
<i>1987 data set</i>			
D_0, S	0.39	10.04	1.07
D_0, S, T_0	0.22	5.01	1.07
D_0, S, T_0, t	0.26	1.57	0.87
D_0, S, T_0, t, θ	0.28	1.08	0.84
<i>1988 data set</i>			
D_0, S	0.41	9.64	0.81
D_0, S, T_0	0.32	7.44	0.82
D_0, S, T_0, t	0.27	3.71	0.72
D_0, S, T_0, t, θ	0.28	3.21	0.69
<i>Combined data set</i>			
D_0, S	0.41	11.32	0.84
D_0, S, T_0	0.27	9.80	0.86
D_0, S, T_0, t	0.26	4.41	0.83
D_0, S, T_0, t, θ	0.23	3.70	0.79

most successful models with all three data sets were those which included only functions of D_0 and S . Inclusion of any other functions produced a significant decrease in R^2 . This indicates that the vegetation mainly responded to changes in D_0 and S during the two years of this experiment. The lack of response to θ is not surprising as θ did not change significantly at depths below 30 cm and pinegrass is known to have roots extending well below 30 cm. The lack of a response to T_0 is due to the strong correlation between D_0 and T_0 . Livingston and Black (1987), Stewart (1988), and Gash *et al.* (1988) all found that stomatal or canopy conductance responded to air temperature (T was used, not T_0).

The limiting factor approach of Price and Black (1989) was also tested but the value of R^2 was found to be only 0.03. Figure 4.3a and b show the boundary line functions derived from the three data sets plotted onto the combined data set. There is a more distinct boundary to the scatter plot of g_s plotted against D_0 than to that plotted against S . This indicates, as shown in Figure 4.2, that S limits g_s less frequently than D_0 .

The above results indicate that the best model for mean stomatal conductance was of the form $g_s = g_{s_{max}} f(D_0) g(S)$. This model, with parameters determined using boundary line analysis, explained 40 % of the variance in g_s .

4.2.2 The technique of NLLS Optimization

The values of the parameters determined using the technique of NLLS optimization are listed in Table 4.4. Parameters $K_6 \dots K_9$ could not be determined using NLLS optimization for any of the data sets. As indicated above, there was a strong correlation between D_0 and T_0 . The NLLS optimization showed that there was no response in g_s to the environmental variables T_0 , t , and θ . If these variables were used, the optimization model did not converge or gave unreasonable values for all parameters. The SYSTAT software used in this analysis also indicated if correlations existed between variables in the model being tested; however, it did not indicate which variables were correlated. Casement

Figure 4.3: A and B, Functions with parameters determined by BLA for the response of g_s to D_0 and S respectively. C and D, Functions with parameters determined by NLLS optimization for the response of g_s to D_0 and S respectively. Dotted lines = 1987, dashed lines = 1988, and solid lines = combined data sets.

Table 4.4: Parameters for multiplicative model of g_s determined by NLLS optimization.

Parameter	Data set used in analysis		
	1987	1988	Combined
<i>Modelled using D_0 and S.</i>			
K_1	^a 0.110 (0.0019)	0.0810 (0.0035)	0.084 (0.0026)
K_2	6.56 (0.077)	7.73 (.35)	8.15 (0.27)
K_3	0.0079 (8.0E-4)	0.016 (1.9E-3)	0.011 (0.00099)
K_4	421 (44)	730 (156)	758 (97.4)
<i>Modelled using D and S.</i>			
K_1			0.16 (0.0041)
K_2			4.44 (0.100)
K_3			0.011 (0.0013)
K_4			268 (45.4)
^a value (standard error)			

plots of the data sets showed that D_0 , T_0 , and t were correlated. NLLS optimization was also used to determine the parameters for a multiplicative model substituting the saturation deficit measured at the reference height (D) for the saturation deficit at the leaf surface (D_0). The model was optimized using the same functions as above and the combined data set was used. The values of the parameters are listed in Table 4.4.

The models were tested and the results are listed in Table 4.5. These results indicate that, as with the results of the BLA analysis, there is little variation in the R^2 between years. The model using the variables D_0 and S explained 71% of the variance in g_s when the two years were used in the analysis. This is significantly higher than that explained by the model when the parameters were determined using BLA. The value is similar to that found by Stewart and Gay (1989) working over a short grass prairie. Their model used the variables D and S , and the R^2 was 0.73. As they did not compute the intercept, a direct comparison is impossible. Using definition 7 of Kvålseth (1985) for R^2 with an intercept of 0, the R^2 in this model increases to 0.94. The higher R^2 for the model using D_0 suggests that mean stomatal conductance should not be related to D except in instances when D is similar to D_0 (Monteith 1990).

The forms of the functions are plotted on the combined data set in Figure 4.3c and 4.3d. Models produced by both techniques tended to underestimate g_s at high values of g_s . The model using the parameters determined by NLLS optimization tended to underestimate more than that using parameters determined by BLA (Figure 4.4). This can be seen by comparing the slopes of the regression lines given in Tables 4.3 and 4.5. This effect is due to the form of the multiplicative model. Any points which lie above the functions shown in Figure 4.3 must be underestimated by the model. The functions used in the relationship between g_s and D_0 tend to fall below the edge of the scatterplot at low values of D_0 .

Table 4.5: Results of testing models of g_S with parameters determined by NLLS optimization.

Variables used	R^2	Intercept (mm s^{-1})	Slope
<i>1987 data set</i>			
D_0, S	0.65	3.9	0.68
<i>1988 data set</i>			
D_0, S	0.73	3.74	0.611
<i>Combined data set</i>			
D_0, S	0.71	3.22	0.63
<i>Combined data set</i>			
D, S	0.50	4.38	0.50

Figure 4.4: Regression analysis of models of g_s with parameters determined using NLLS optimization. A, Model of g_s based on D_0 and S . B, Model of g_s based on D and S .

4.3 Modelling Evapotranspiration

Evapotranspiration models using the PM equation and the Priestley-Taylor (PT) equation were compared. The combined data set was used in all cases. The first model used a model of g_s based on D_0, S given in Table 4.4 and 4.5. It uses values of D_0 calculated from measurements of λE to estimate g_s . Clearly, this model cannot be used to estimate evapotranspiration from routine climate station data in which only D was available. The second model used the same model for g_s as above, but iteratively calculated D_0 and λE . D was used as the initial estimate of D_0 . The third model used the model of g_s based on D and S . Finally, the mean hourly α defined by the PT equation, equation 2.8 and Table 4.6 was determined to be 0.89 with a standard deviation of 0.29. λE was then estimated using this value of α and equation 2.8. Values of s and γ were determined from the mean hourly T measured at the reference height.

The resulting regression analysis of these models is shown in Figure 4.5 and Table 4.6. The most successful model was that using the PM equation and the first model of g_s based on D_0 and S with an R^2 of 0.92. However, when this model was run iteratively, the R^2 fell to 0.81. This is less than the model using the PM equation and the model of g_s based on D and S . These two results indicate that although the two models of g_s explained only 71 and 50 % of the variance respectively (Table 4.6) in g_s , when used with the PM equation to estimate λE , a higher proportion of the variance in λE is explained. This reflects the sensitivity of equation 2.1 to changes in g_s in a partially coupled system (Raupach and Finnegan 1988). Even in a 20 m tall forest Stewart (1988) and Gash *et al.* (1989) found substantially better agreement between modelled and measured λE than between modelled and measured g_s . This indicates that in an apparently highly coupled system there is still a significant dependence of λE on available energy flux ($R_n - G$).

The model using the PT equation and a hourly mean value of α explained 85% of

Figure 4.5: Regression analysis of models of λE . A, PM equation with model of g_s based on D_0 (calculated from measured values of λE) and S . B, PM equation with model of g_s based on D_0 (Iterated). C, PM equation with model of g_s based on D and S . D, PT equation with $\alpha = 0.89$. Solid line is the 1:1 line, dotted line is regression equation given in Table 4.6.

Table 4.6: Results of testing models of λE using different models of g_S , using the combined data set.

R^2	Intercept (W m^{-2})	Slope
<i>PM equation with $g_S = f(D_0, S)$</i>		
0.919	22.55	0.877
<i>PM equation with $g_S = f(D_0, S)$ iterated.</i>		
0.81	43.46	0.85
<i>PM equation with $g_S = f(D, S)$.</i>		
0.88	21.67	0.89
<i>PT equation with $\alpha = 0.89$.</i>		
0.85	8.2	1.02

the variance in λE . This is higher than the iterative model using the PM equation and very similar to the two other PM based models, and it does not tend to underestimate at high evapotranspiration rates. For estimates of evapotranspiration using climate station data, the Priestley-Taylor approach produces very similar results to the more complex PM equation combined with a model of surface conductance. McNaughton and Spriggs (1989), using a mixed-layer model with the PM equation, show that values of α of 0.9 would be observed for a surface with values of g_s in the range 4 to 10 mm s^{-1} . Figure 4.2 shows that most of the observed values of g_s for this site fell between 3 and 10 mm s^{-1} . The mean value of g_s was 6.18 mm s^{-1} with a standard deviation of 3.52 mm s^{-1} . Even though the vegetation appeared to be adequately supplied with water, the low L of the surface causes g_s and α to be lower than expected for a well watered grass.

Although the PM equation describes the physical processes of evapotranspiration and can be used to determine the response of a surface to environmental variables, λE must be measured with great accuracy in order to determine the g_s response functions.

Chapter 5

Conclusions

Although the area in which this study took place is considered to be subject to drought, evapotranspiration rates were generally 0.9 of the equilibrium evaporation rate. The maximum daily evapotranspiration was as much as 4.1 mm. Surface conductance responded to changes in saturation deficit and solar irradiance, but no response could be found to soil water content in the upper 30 cm. The mean hourly value of Ω over the two years of the study was found to be 0.45, a value intermediate between those typical of forests and short grass. Calculated values of surface conductance were similar to those found by other workers for unmanaged grasslands where soil water was not limiting. The generally low values of surface conductance at this site are attributable to the low leaf area index (maximum of 0.8).

The NNLS technique was superior to the BLA technique for determining the parameters in the Jarvis multiplicative model of surface conductance. The limiting factor approach was unsuccessful. The model produced using NLLS optimization explained a greater proportion of the variance in surface conductance than that produced with the BLA technique. NLLS optimization has several other advantages. It does not require subjective judgement in setting the position of the boundary line curves. Most statistical software used for NLLS optimization will automatically detect interactions between variables, and will provide standard errors for each parameter. It is significantly faster to carry out because the repeated plotting used in BLA to refine the estimates of the parameters is not required.

Due to the large variation in leaf area index through the season, it was necessary to separate mean canopy stomatal conductance and L . Models of the response of mean canopy stomatal conductance to environmental variables explained more of the variance than models of the response of surface conductance, (i.e. without L removed). The best model for g_s required only D_0 and S as inputs. Soil water content, air temperature, and minimum air temperature the previous night, did not improve the model. Soil water content did not effect g_s because the soil water content below 30 cm did not vary significantly during the growing season (pinegrass roots extend below 70 cm). Air temperature was highly correlated with saturation deficit. The addition of temperature to the multiplicative model decreased the explained variance of g_s due to interaction between D_0 and T_0 . The lack of improvement in the estimation of evapotranspiration when using a model based on D_0 rather than D is due to the errors in calculating g_s from energy balance measurements and the Penman-Monteith equation, and to the fact that a large proportion of the observed evapotranspiration rates were near E_{eq} .

The mean hourly value of the Priestley-Taylor α was found to be 0.89 with a standard deviation of 0.29. This is similar to values found for coniferous forests and is consistent with the observed values of surface conductance of the clearcut. The estimates of hourly evapotranspiration using this value in the Priestley-Taylor equation were only slightly less successful than estimates of hourly evapotranspiration using the Penman-Monteith equation and the multiplicative model of surface conductance.

Bibliography

- [1] Black, T. A., and Kelliher, F. M., 1989. Processes controlling understory evapotranspiration. *Phil. Trans. R. Soc. Lond. Ser B*, 324: 207–231.
- [2] Black, T. A., Tanner, C. B., and Gardner, W. R., 1970. Evapotranspiration from a snap bean crop. *Agron. J.*, 62: 66–69.
- [3] Black, T. A., Novak, M. D., Fleming, R. L., Adams, R. S., and Eldridge, N., 1989. Site preparation procedures to minimize seedling water and temperature stress in backlog areas in the Southern Interior. Annual report to the Southern Interior FRDA technical advisory committee. B.C. Ministry of Forests, Kamloops, B.C., 160 pp.
- [4] Callander, B. A., and Woodhead, T., 1981. Canopy conductance of estate tea in Kenya. *Agric. Meteorol.*, 23: 151–167.
- [5] Campbell, D. I., 1989. Energy balance and transpiration from tussock grassland in New Zealand. *Boundary-Layer Meteorol.*, 46: 133–152.
- [6] Delucia, E. H., 1986. The effect of freezing nights on photosynthesis, stomatal conductance, and internal CO₂ concentration in seedlings of Engelmann spruce (*Picea engelmannii* Parry). *Plant, Cell and Environment*, 10: 333–338.
- [7] Dickinson, R. E., and Henderson-Sellers, A., 1988. Modelling tropical deforestation: a study of GCM land surface parametrizations. *Q. J. Roy. Meteorol. Soc.*, 114: 439–462.
- [8] Fleming, R. L., 1990. Effects of site preparation treatments on the soil water regime and water relations of planted conifer seedlings in a high elevation clearcut. Ph.D. thesis, University of British Columbia, Vancouver, B.C., In preparation.
- [9] Gash, J.H.C., Shuttleworth W. J., and Llyod C. R., 1989. Micrometeorological measurements in Les Landes forest during HAPEX-MOBILHY. *Agric. For. Meteorol.*, 46: 131–147.
- [10] Idso, S. B., 1990. Stomatal response to humidity as inferred by porometry and infrared thermometry. *Agric. For. Meteorol.*, 1990: 169–172.
- [11] Jarvis, P. G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. R. Soc. Lond. Ser. B*, 273: 593–610.

- [12] Jones, H. G., 1983. *Plants and Microclimate*. Cambridge University Press. Cambridge. 323 pp.
- [13] Kvalseth, T. O., 1985. Cautionary note about R^2 . *The American Statistician*, 39: 278–285.
- [14] Leuning, R., Denmead, O. T., Lang, A. R. G., and Ohtaki, E. H., 1982. Effects of heat and water vapour transport on eddy covariance measurement of CO_2 fluxes. *Boundary-Layer Meteorol.*, 23: 209–222.
- [15] Livingston, N. J. and Black, T. A., 1987. Stomatal characteristics and transpiration of three species of conifer seedlings planted on a high elevation south-facing clear-cut. *Can. J. For. Res.*, 17: 1273–1282.
- [16] McNaughton, K. G. and Jarvis, P. G., 1982. Predicting the effects of vegetation changes on transpiration and evaporation. In: Kozlowski, J. (ed.), *Water Deficits and Plant Growth*. Vol. VII, Academic Press, New York, 1–47.
- [17] McNaughton, K. G., and Spriggs, T. W., 1989. An evaluation of the Priestley and Taylor equation and the complementary relationship using results from a mixed-layer model of the convective boundary layer. In: Black, T. A., Spittlehouse, D. L., Novak, M. D., and Price, D. T. (ed.), *Estimation of Areal Evapotranspiration*, 89–104. Publ. No. 177, International Association of Hydrological Sciences, Wallingford.
- [18] Mitchell, W. R., Green, R. E., Lloyd, D., Russell, F., Erickson, W., and Walkem, D., 1981. *Identification and Interpretation of Ecosystems of the Western Kamloops Forest Region*. vol. 1, B. C. Ministry of Forests, Victoria, B.C.
- [19] Monteith, J. L., 1981. Evaporation and surface temperature. *Q. J. Roy. Meteorol. Soc.*, 107: 1–27.
- [20] Monteith, J. L., 1990. Porometry and baseline analysis: the case for compatibility. *Agric. For. Meteorol.*, 49: 155–167.
- [21] Nicholson, A. C., 1989. Water relations, survival and growth of Douglas-fir seedlings at a pine grass dominated site in the Interior Douglas-fir zone of South-central British Columbia. Unpublished M.Sc. thesis, Oregon State Univ, Corvallis, OR., 114 pp.
- [22] Parton, W.J., Lauenroth, W.K., and Smith, F. M., 1981. Water loss from a short-grass steppe. *Agric. Meteorol.*, 24: 97–109.
- [23] Price, D. T. and Black, T. A., 1989. Estimation of forest transpiration and CO_2 uptake using the Penman-Monteith equation and a physiological photosynthesis model.

- In: Black, T. A., Spittlehouse, D. L., Novak, M. D., and Price, D. T. (ed.), *Estimation of Areal Evapotranspiration*, 213–227. Publ. No. 177, International Association of Hydrological Sciences, Wallingford.
- [24] Priestley, C. H. B., and Taylor, R. J., 1972. On the assessment of the surface heat flux and evaporation using large scale parameters. *Mon. Weather Rev.*, 100: 81–92.
- [25] Raupach, M. R., 1989. Stand overstory processes. *Phil. Trans. R. Soc. Lond. Ser. B*, 324: 175–190.
- [26] Raupach, M. R. and Finnegan J. J., 1988. 'Single-layer models of evaporation from plant canopies are incorrect but useful, whereas multilayer models are correct but useless' discuss. *Aust. J. Plant. Physiol.*, 15: 705–716.
- [27] Ripley, E. A. and Redmann, R. E., 1976. Grassland. In: Monteith, J. L. (ed.), *Vegetation and the Atmosphere*. Vol. III, Case studies. 351–398. Academic Press, London.
- [28] Roberts, J. and Pitman R. H., 1984. Factors affecting stomatal conductance of bracken below a forest canopy. *J. App. Ecology*, 21: 643–655.
- [29] Spittlehouse, D. L. and Black, T. A., 1981. A comparison of reversing psychrometric Bowen ratio measurement systems. *Atmosphere-Ocean*, 19: 372–379.
- [30] Stewart, J. B., 1983. A discussion of the relationships between the principal forms of the combination equation for estimating crop evaporation. *Agric. For. Meteorol.*, 30:111–127.
- [31] Stewart, J. B., 1988. Modelling surface conductance of pine forest. *Agric. For. Meteorol.*, 43: 19–35.
- [32] Stewart, J. B., and de Bruin, H. A. R. 1985. Preliminary study of dependence of surface conductance of Thetford forest on environmental conditions. In: B. A. Hutchinson and B. B. Hicks (ed.), *Forest Atmosphere Interactions*. Reidel: 91–104.
- [33] Stewart, J. B. and Gay L. W., 1989. Preliminary modelling of transpiration from the FIFE site in Kansas. *Agric. For. Meteorol.*, 48:305–315.
- [34] Stout, D. C. and Brooke, B., 1985. Growth and development of pinegrass in Interior British Columbia. *Journal of Range Management*, 38: 312–316.
- [35] Tan, C. S., and Black T. A., 1976. Factors affecting the canopy resistance of a Douglas-fir forest. *Boundary Layer Meteorol.*, 10: 475–489.

- [36] Thom, A. S., 1972. Momentum, mass and heat exchange of vegetation. *Qart. J. Roy. Meteorol. Soc.*, 98: 124–134.
- [37] Thurtell, G. W., 1989. Comments on using K-theory within and above the plant canopy to model diffusion processes. In: Black, T. A., Spittlehouse, D. L., Novak, M. D., and Price, D. T. (ed.), *Estimation of Areal Evapotranspiration*, 81–85. Publ. No. 177, International Association of Hydrological Sciences, Wallingford.
- [38] Verma, S. B., 1989. Aerodynamic resistances to tranfers of heat, mass and momentum. In: Black, T. A., Spittlehouse, D. L., Novak, M. D., and Price, D. T. (ed.), *Estimation of Areal Evapotranspiration*, 13–20. Publ. No. 177, International Association of Hydrological Sciences, Wallingford.
- [39] Webb, R.A., 1972. Use of the boundary line in the analysis of biological data. *J. Hort. Sci.*, 47: 309–319.
- [40] Webb, E. K., Pearman, G. I., and Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. *Q. J. Roy. Meteorol. Soc.*, 106: 85–100.
- [41] Wilkinson, L., 1989. *SYSTAT: The system for statistics*. SYSTAT Inc., Evanston, Il., 822 pp.