

FACTORS AFFECTING THE CANOPY RESISTANCE OF A DOUGLAS-FIR FOREST

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Abstract. The physiological nature of canopy resistance was studied by comparing the stomatal and canopy resistance of a 10-m high Douglas-fir forest. Stomatal resistance of the needles was measured using porometry, while the canopy resistance was calculated using energy balance/Bowen ratio measurements of evapotranspiration. A typical steady increase in the forest canopy resistance during daytime hours, even at high soil water potentials, was observed. A similar trend in the stomatal resistance indicated that increasing canopy resistance during the daytime was caused by gradually closing stomata. During a dry period when soil water potentials declined from 0 to -10.5 bars, the mean daytime value of canopy resistance increased in proportion to the mean daytime value of the stomatal resistance. Values of canopy resistance calculated from stomatal resistance and leaf area index measurements agreed well with those calculated from energy balance measurements. The dependences of stomatal resistance on light, vapour pressure deficit, twig and soil water potentials are summarized.

List of Symbols

A	available energy for evapotranspiration: $(R_n - G - M)(W m^{-2})$
E	evapotranspiration rate ($kg m^{-2} s^{-1}$)
G	soil heat flux ($W m^{-2}$)
H	sensible heat flux ($W m^{-2}$)
L	latent heat of vapourization of water ($J kg^{-1}$)
LAI	leaf area index or needle area (projected area basis)/unit area of ground surface (dimensionless)
LAI _{<i>j</i>}	LAI of <i>j</i> th canopy layer (dimensionless)
LE	latent heat flux ($W m^{-2}$)
M	rate of heat storage in canopy volume on an area basis ($W m^{-2}$)
R_n	net radiation flux ($W m^{-2}$)
c_p	specific heat of moist air ($J kg^{-1} K^{-1}$)
e_z	water vapour pressure at height <i>z</i> (mb)
e_z^*	saturation water vapour pressure at height <i>z</i> (mb)
r_c	canopy or surface resistance ($s cm^{-1}$)
r_{ci}	canopy resistance at the <i>i</i> th hour of the daytime ($s cm^{-1}$)
\bar{r}_c	mean daytime canopy resistance; defined by equation (6) ($s cm^{-1}$)
r_H	aerodynamic resistance to heat exchange between the forest and the height <i>z</i> ($s cm^{-1}$)
r_s	stomatal resistance on a projected leaf area basis ($s cm^{-1}$)
r_{sj}	stomatal resistance of the <i>j</i> th canopy layer ($s cm^{-1}$)
r_v	aerodynamic resistance to water vapour exchange between the forest and the height <i>z</i> ($s cm^{-1}$)

s	slope of the saturation water vapour pressure curve (mb K^{-1})
v.p.d.	vapour pressure deficit; $(e_z^* - e_z)$ (mb)
v.p.d. _{<i>i</i>}	v.p.d. at the <i>i</i> th hour of the daytime (mb)
v.p.d.	arithmetic mean of values of v.p.d. during daytime (mb)
ψ_s	soil water potential; includes only matric and osmotic terms (bar)
ψ_t	twig water potential; as measured by Scholander pressure chamber (bar)
β	Bowen ratio; H/LE (dimensionless)
γ	psychrometric constant (mb K^{-1})
θ	volumetric water content of soil (m^3 of water/ m^3 of soil)
ρ	density of moist air (kg m^{-3})

1. Introduction

Improved procedures of estimating evapotranspiration are required in hydrological studies of vegetated areas. Hydrologists are well aware that potential evaporation estimates can often greatly exceed actual values of evapotranspiration. Any realistic evapotranspiration model must include plant or soil parameters that provide an accurate description of the process when it is limited by the supply of water. One such parameter is the canopy or surface resistance which is contained in the Penman–Monteith model of transpiration (Monteith, 1965). In view of the complexity of many plant canopies, this is a greatly simplified model; however, it has been remarkably successful in its application to agricultural crops (Monteith *et al.*, 1965; Black *et al.*, 1970; Szeicz *et al.*, 1973). These workers have shown that for well-ventilated agricultural crop canopies, the canopy resistance is approximately equal to the stomatal resistance of the leaves acting in parallel. Recently, several forest micrometeorologists have calculated, using the Penman–Monteith model, hourly, daily and monthly values of canopy resistance of forests in various parts of the world (e.g., Szeicz and Long, 1969; Stewart and Thom, 1973; McNaughton and Black, 1973; Gash and Stewart, 1975). Little is known as to the physiological nature of the forest canopy resistance and whether it is possible to model it from an understanding of the behaviour of the stomata of the trees (Federer, 1975). The objectives of this paper are: (i), to show the relationship between canopy and stomatal resistance in a 21-yr old Douglas-fir forest; (ii), to describe the relationship between canopy resistance and environmental parameters; and (iii), to assess whether canopy resistance behaviour can be inferred from knowledge of stomatal response to environmental parameters.

2. Theory

Total evapotranspiration can be considered as mainly transpiration with small error for forests with no intercepted water present, since evaporation from the soil is small. The Penman–Monteith model of transpiration assumes that the canopy is isothermal and that the canopy resistance r_c is the resistance of all stomata of the leaves acting

in parallel. The equation expressing the model can be written as

$$E = \frac{sA + \rho c_p (e_z^* - e_z) / r_H}{[s + \gamma(1 + r_c / r_H)]L} \quad (1)$$

which assumes that the aerodynamic resistances, r_v and r_H , are equal. Thom (1972) gives the form of (1) with $r_v \neq r_H$ and Tanner and Fuchs (1968) give an alternative equation to (1) for the case of a non-isothermal canopy.

On re-arrangement of (1), the canopy resistance can be written as

$$r_c = \frac{\rho c_p (e_z^* - e_z)}{\gamma L E} + r_H \left[\frac{s}{\gamma} \left(\frac{A}{LE} - 1 \right) - 1 \right]. \quad (2)$$

Both Stewart and Thom (1973) and McNaughton and Black (1973) have shown that when r_H (and r_v) $\ll r_c$, as in a forest, the second term of (2) is much smaller than the first so that to a good approximation

$$E = \frac{\rho c_p}{\gamma L} (e_z^* - e_z) / r_c. \quad (3)$$

This relation indicates the importance of the vapour pressure deficit ($e_z^* - e_z$) in the transpiration process in the forest.

The canopy resistance is a function of stomatal resistance r_s , the leaf area index LAI and the diffusion resistance to water vapour through the canopy air volume. The assumption that the latter resistance is much smaller than r_s in forest canopies would imply that r_c can be calculated from

$$1/r_c = \sum_{j=1}^n (\text{LAI}_j / r_{sj}) \quad (4)$$

where r_{sj} and LAI_j are, respectively, the r_s and LAI of the j th canopy layer and n is the number of layers.

3. Experimental Procedure

3.1. EXPERIMENTAL SITE

The site was approximately 27 km northwest of Courtenay, B.C., on the eastern coast of Vancouver Island. The measurements were made in an unthinned stand of Douglas fir planted in 1953, located on the relatively extensive coastal plain between Courtenay and Campbell River. The wet, mild winters and dry, warm summers experienced by the area provide a wide range of soil moisture conditions. The topography is generally flat, although there are several ridges of approximately 20–30 m relief, and some low swampy areas which dry out during the summer. The site was located at an elevation of 150 m.

At the time of the research, the trees ranged in height from 7 to 10 m, and averaged 10.6 cm in diameter at breast height. There were approximately 1840 stems ha^{-1} and the basal area was 27.5 $\text{m}^2 \text{ha}^{-1}$. The soil, belonging to the Dashwood series,

was a well-drained gravelly sandy loam of 45–60 cm depth overlying a deep layer of compacted basal till. Measurements of root density indicated that the majority of the roots were in the upper 45 cm of the soil.

The area is considered an excellent one for micrometeorological research. Effects of local advection were felt to be absent with 8 km of forested land separating the site from the Strait of Georgia, and forest extending upwards of 32 km in either direction along the coast. Although the west-to-south sector included hilly terrain and deforested areas on the lower slopes of mountains within 3 to 4 km of the site, winds were virtually never from that direction. Prevailing winds were from the east to northeast.

3.2. MEASUREMENTS

Continuous half-hourly measurements of evapotranspiration were made from June 14 until August 15, 1974 using the Bowen ratio/energy balance technique. The Bowen ratio, β , was measured at the 10.5-m level using the psychrometric apparatus described in Black and McNaughton (1971). The net radiation flux, R_n , was measured at the top of the canopy with a Swissteco S-1 net radiometer, continuously ventilated with dried air from an aquarium-type pump. The soil heat flux, G , was measured at the 5-cm depth with two heat-flux plates, and corrected for storage in the upper 5 cm using an integrated temperature measured with a diode integrating thermometer (Tang *et al.*, 1974). Storage, M , of sensible and latent heat within the canopy was estimated from wet- and dry-bulb temperatures taken every 15 min at the 3-, 5-, and 7-m levels, and from estimates of the heat capacity of the canopy based on the work of Stewart and Thom (1973). The evapotranspiration rate, E , was then calculated using the equation:

$$E = (R_n - G - M) / [L(1 + \beta)] \quad (5)$$

where L is the latent heat of vapourization.

Wind speed was measured by a sensitive Casella anemometer located at a height of 10.5 m. The aerodynamic resistance was estimated using the logarithmic wind profile equation and assumed values of surface roughness and displacement height.

Supporting measurements were made continuously of incident solar radiation above the canopy, and at various levels through the canopy at selected times using a Kipp and Zonen solarimeter. Wind direction above the canopy was measured using a Climet wind vane. Precipitation was recorded each day with a 10.2-cm diameter rain gauge at the data-logging trailer.

Data signals were carried back to the trailer by 75 m of shielded cables where they were recorded with a Hewlett-Packard 2707A data logger. Net radiation, solar radiation and Bowen-ratio data signals were integrated using voltage integrators (Tang *et al.*, 1976). Bowen ratio data were further monitored on a strip-chart recorder.

Soil water potential between 0 and -1 bar was measured by a tensiometer-transducer system. Four tensiometers were used and were located at depths of 15, 30, 45

and 60 cm. Soil water potential less than -1 bar was measured using a Wescor HR-33T dew point microvoltmeter and PT51-10 hygrometers. Six hygrometers, two each at the 15- and 30-cm depths, and one each at the 45- and 60-cm depths, were used. Soil water potential measured by the tensiometer-transducer system was recorded at 15-min intervals, while soil water potentials measured by the hygrometers were recorded three times each day. In this study, only daily values of soil water potential are used.

Soil water content was measured both gravimetrically and by use of the neutron moisture meter. Neutron moisture measurements were made every seven days in six access tubes. Gravimetric sampling of the root zone was taken every one to two weeks, depending on the stage of the drying period.

The stomatal resistance, r_s , and twig water potential, ψ_t , at the 8-m height were measured on a routine basis three times a day (0700 to 0830, 1300 to 1430 and 1600 to 1730 PST) on the majority of days during the period June 12 to August 18. Measurements of r_s and ψ_t at the same height were made every two hours during the daytime on twelve days. On eight of the twelve days that ψ_t was measured, r_s was also measured at approximately the same time. A pressure chamber located in the data-logging trailer was used to make the ψ_t measurements (Scholander *et al.*, 1965). At least two twig samples were used to obtain each value of ψ_t and two readings were taken for each twig. Stomatal resistance measurements were made using a ventilated porometer designed by Turner *et al.* (1969). Modifications of the porometer electronics and the sensing head, and our calibration procedure are described in Black *et al.* (1974). A sample of four needles was brought down from the tree, attached to a modelling clay plug and inserted into the porometer. At least two samples of four needles each were used to obtain a value of r_s .

On August 6, r_s and light quanta flux (0.4 to 0.7 μm) were measured every three hours at the 8-, 6- and 4-m heights, while on August 1 and 2 these measurements were made at the 8- and 6-m heights. Light quanta flux was measured with a Lambda model LI-185 light meter with the quantum sensor held by hand near the point at which the needles were removed from the tree.

4. Results and Discussion

4.1. COURSE OF SOIL WATER POTENTIAL DURING THE MEASUREMENT PERIOD

Figure 1 shows the average soil water potential, ψ_s , for the period June 17 to August 19, 1974 for the root zone (0 to 45 cm depth). Daily values of precipitation are shown for reference. The average soil water content for the root zone over the same period ranged approximately from 0.23 to 0.08 on a volumetric basis which included stones. The daily (24-hr) value of the ratio of latent heat flux to the net radiation flux (LE/R_n) ranged from 0.58 to 0.27 over the period of measurement. The dependence of LE/R_n on ψ_s for eighteen fine ($R_n > 14.0 \text{ MJ m}^{-2} \text{ day}^{-1}$) days is shown in Figure 2.

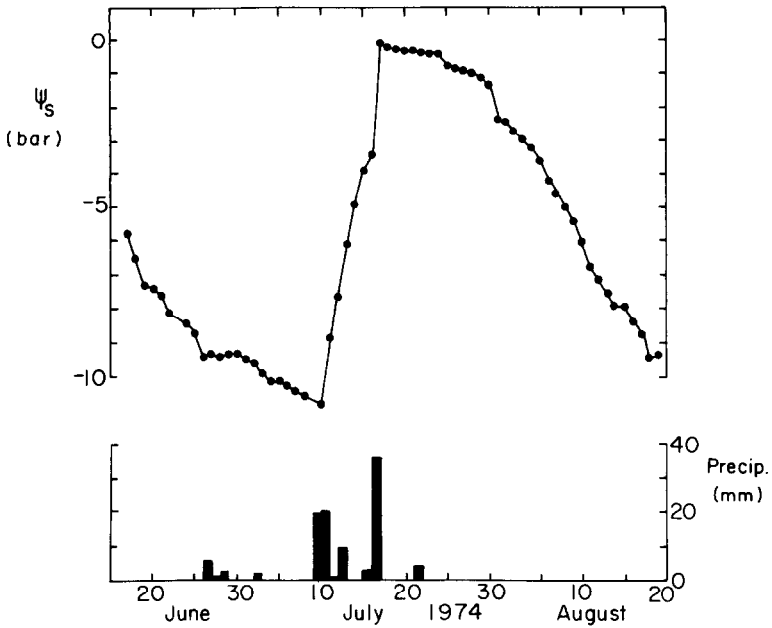


Fig. 1. Soil water potential, ψ_s , during the period, June 17–August 19, 1974. Each data point is the average value of the water potentials at the 15-, 30- and 45-cm depths.

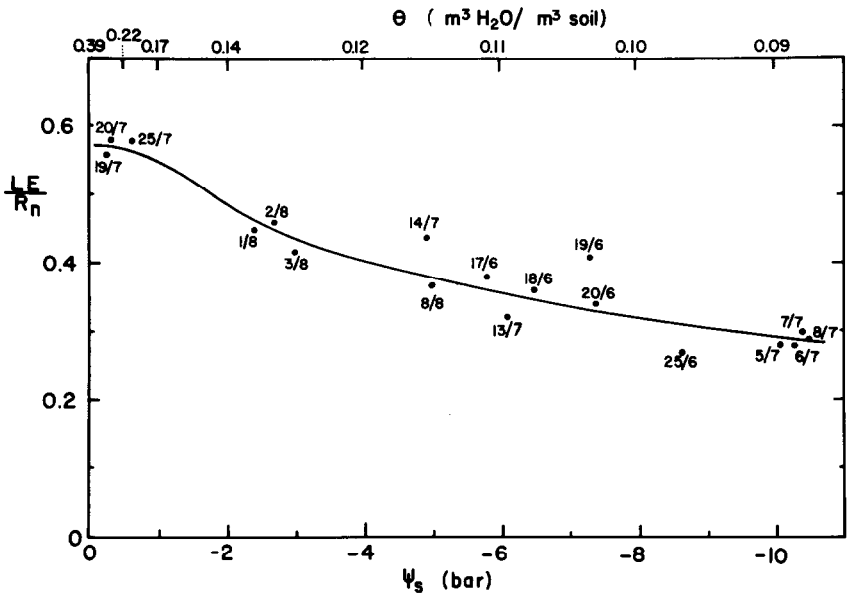


Fig. 2. The relationship between the 24-hr value of the ratio, LE/R_n and the soil water potential, ψ_s , for 18 fine ($R_n > 14.0 \text{ MJ m}^{-2} \text{ day}^{-1}$) days in 1974. The number adjacent to each data point is the date. Values of the average root zone soil water content, θ corresponding to ψ_s are also shown.

4.2. DAYTIME COURSE OF NET RADIATION AND LATENT HEAT FLUX FOR TWO SELECTED DAYS

The days selected for the comparison of stomatal and canopy resistances were July 25 and June 18. The former day had an average soil water potential of -0.6 bar, while the latter had a potential of -6.5 bar. Consequently there was a considerable difference in the availability of soil water to the trees on these days. The daytime course of R_n and LE for both days is shown in Figure 3. The latent heat flux on July 25 did not display the mid-afternoon peak observed by McNaughton and Black (1973) in a Douglas-fir forest where ψ_s was always greater than -0.5 bar. This suggests some restriction to transpiration during the afternoon when the vapour pressure deficit (v.p.d.) was at its daily maximum. The reason may well be that in the extremely coarse soil, the hydraulic conductivity is low near the roots. The 24-hr value of LE/R_n of 0.58 on July 25 (Figure 2) was the highest observed during the study.

On June 18, R_n was much higher than on July 25. A reduction in transpiration was apparent at 1030 PST by which time LE had reached its daily maximum. The latent heat flux decreased during the late morning and early afternoon to a minimum of 80 W m^{-2} at 1430 PST when the v.p.d. and stomatal resistance both reached maximum daily values (see Figure 6). Resistance to transpiration is quite apparent in this case with the 24-hr value of LE/R_n being only 0.36.

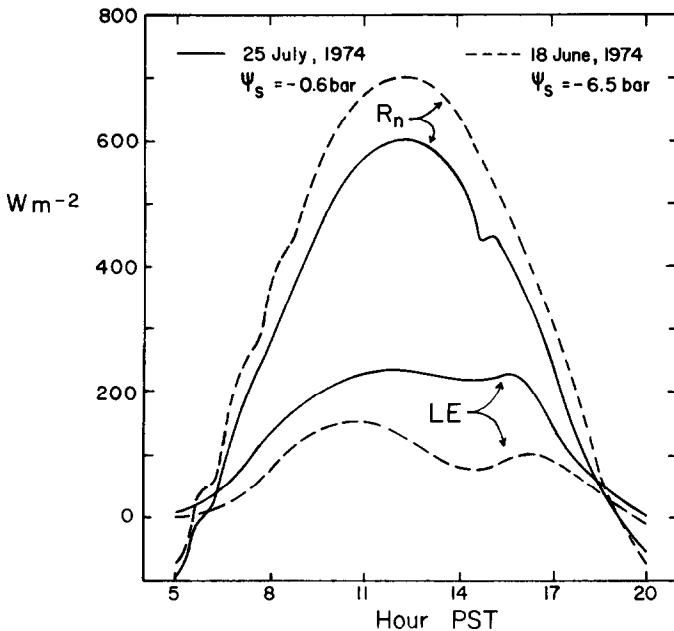


Fig. 3. Daytime course of net radiation, R_n , and latent heat flux, LE , for June 18 and July 25, 1974, showing the effects of decreased soil water potential, ψ_s .

4.3. COMPARISON OF DAYTIME COURSES OF STOMATAL AND CANOPY RESISTANCE

From the measurements of r_s made on August 6 at the 4-, 6- and 8-m heights, it was found that r_s increased slightly with decreasing height in the canopy. The value of r_s at the 4-m height was approximately 20% higher than that at the 8-m height. Since the stomatal resistance measured at the 8-m height represented the resistance of the largest portion of the canopy, it was used in subsequent comparisons with canopy resistance, r_c .

Figure 4 compares r_c with r_s at the 8-m height for July 25 and June 18. Canopy resistance was calculated from (2) but differed very little from that calculated from (3) and the difference became negligible as r_c increased. The low values of canopy resistance in the morning and its steady increase during the daytime on July 25 were also observed by McNaughton and Black (1973). Similar daytime courses of canopy resistance have been reported by Stewart and Thom (1973) and Gash and Stewart (1975) for a pine forest with high values of soil water potential. The pattern of the daytime course of stomatal resistance on July 25 is very similar to that of canopy resistance. On June 18, when soil water potential was low, the stomatal resistance rose to a maximum of approximately 60 s cm^{-1} at about 1500 PST, then declined markedly before stomatal closure. The canopy resistance shows a similar pattern but displays some variation which is a consequence of scatter in the energy balance data. Figure 5 shows a good correlation between canopy resistance and stomatal resistance at the 8-m height for ten of the twelve days on which stomatal resistance was intensively measured. Stomatal resistance measurements on the other two days were not used because of energy balance instrumentation maintenance.

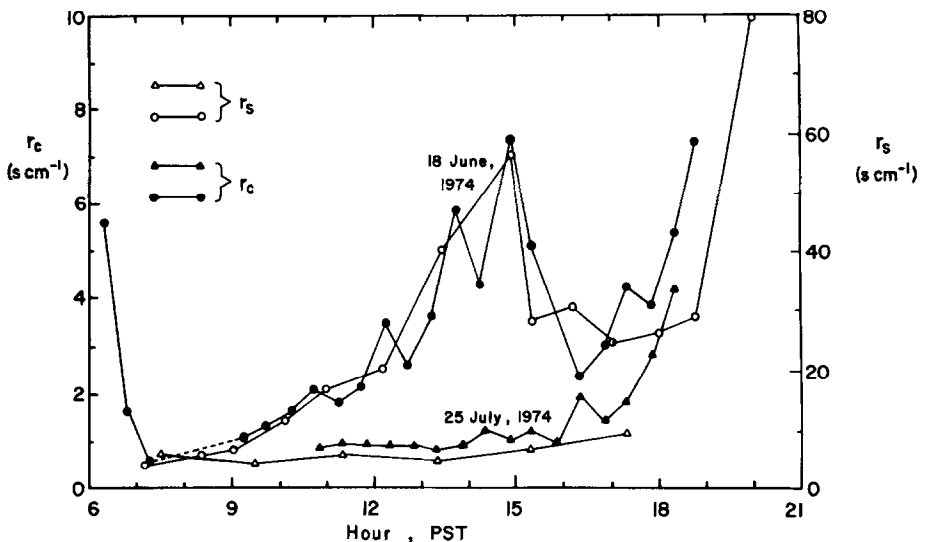


Fig. 4. Daytime course of canopy resistance, r_c , and stomatal resistance, r_s , (projected leaf area basis) at the 8-m height for the days in Figure 3.

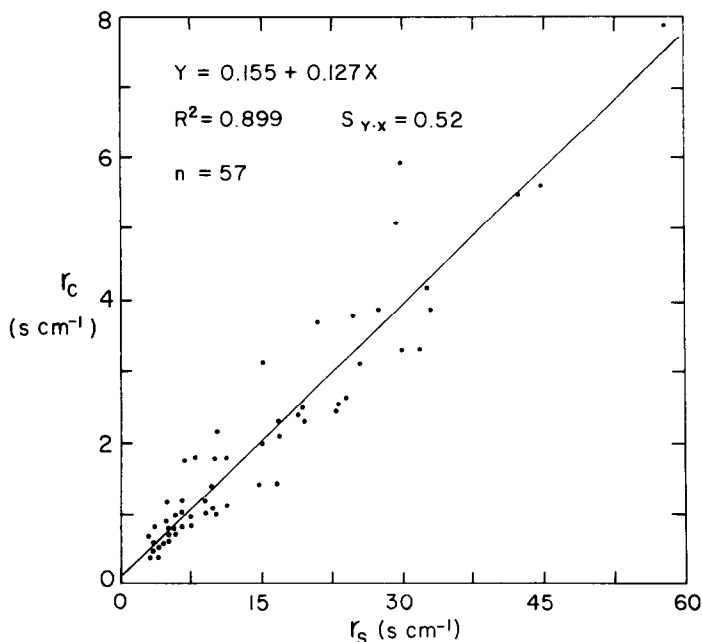


Fig. 5. The relationship between canopy resistance, r_c , and stomatal resistance, r_s , at the 8-m height for 10 days.

Leaf area index, LAI, measurements were made on four trees at a location within the same forest, but $1\frac{1}{2}$ km from the study site. Trees at this location were the same age, height and diameter at breast height as those at the study site. Results of these measurements indicated that the average value of LAI at the study site was between 7.5 and 8.0 (projected area basis). Assuming the stomatal resistance shown in Figures 4 and 5 applied to the whole canopy, then from (4), r_c should be between one seventh and one eighth of the stomatal resistance. This is the approximate relationship between r_c and r_s in Figures 4 and 5. The close similarity of patterns and the reasonable relationship between values of the two resistances indicates that the forest canopy resistance is largely of physiological origin, especially in the case of the water-short forest.

4.4. RELATIONSHIP OF STOMATAL RESISTANCE TO PLANT AND ENVIRONMENTAL PARAMETERS

Modelling of the canopy resistance requires knowledge of how plant and environmental parameters affect the stomatal resistance of each tree species. The response of stomata to light, internal water deficits of the tree, v.p.d. and temperature are particularly important (e.g. Jarvis, 1975; Schulze *et al.*, 1974). Stomatal resistance began to increase rapidly when solar radiation decreased to approximately 150 W m^{-2} ($350 \mu\text{E m}^{-2} \text{ s}^{-1}$ for the $0.4\text{--}0.7 \mu\text{m}$ wave band). The relationship between stomatal resistance and twig water potential was poorly defined. Although stomatal closure was observed at a twig water potential of -18 bar, the stomatal resistance varied from 3 to 50 s cm^{-1} at -20 bar during the daytime.

As can be seen from (3), the v.p.d. can be considered a water demand parameter in forests. The effect of the v.p.d. was particularly evident as can be seen in Figure 6 for June 18 and 19, both sunny days. The soil water potential on June 18 was -6.5 bar and decreased slightly to -7.2 bar on June 19. On June 18, the decrease in stomatal resistance between 1500 and 1900 PST appears to be related to the decrease in v.p.d. starting at 1400 PST. On the following day, the high and almost constant value of the v.p.d. throughout the late afternoon seems to maintain the stomatal resistance at a high value during this time.

Rather than to consider only plant and atmospheric parameters affecting stomatal resistance, the use of soil and atmospheric parameters may have some practical advantages. Since both the soil water content and conductivity decrease with decreasing soil water potential, the latter parameter will be used as a water supply parameter. Figure 7 shows stomatal resistance plotted against soil water potential and indicates that the relationship depends strongly on atmospheric demand for water. The data

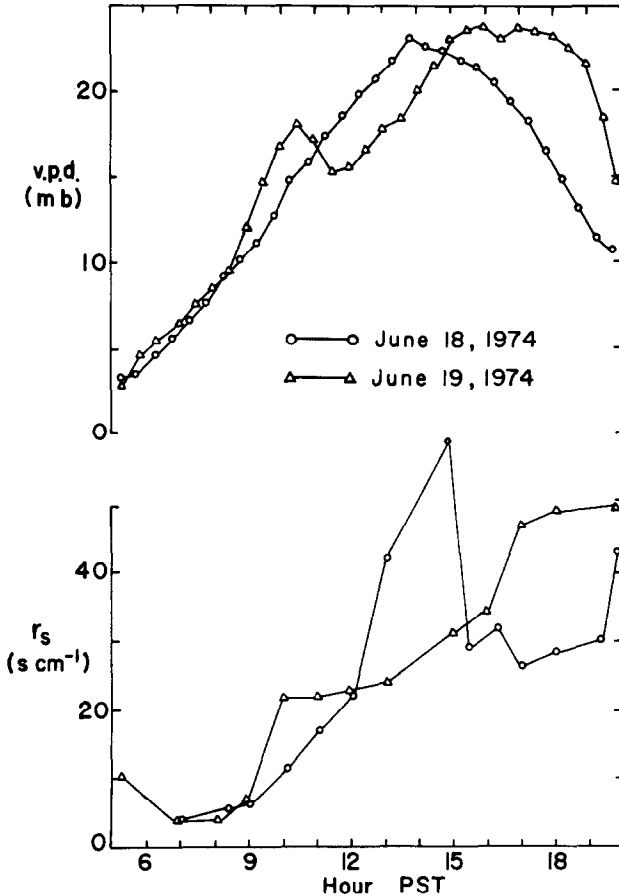


Fig. 6. Daytime courses of stomatal resistance, r_s , at the 8-m height and vapour pressure deficit, v.p.d., on two days with similar soil water potentials.

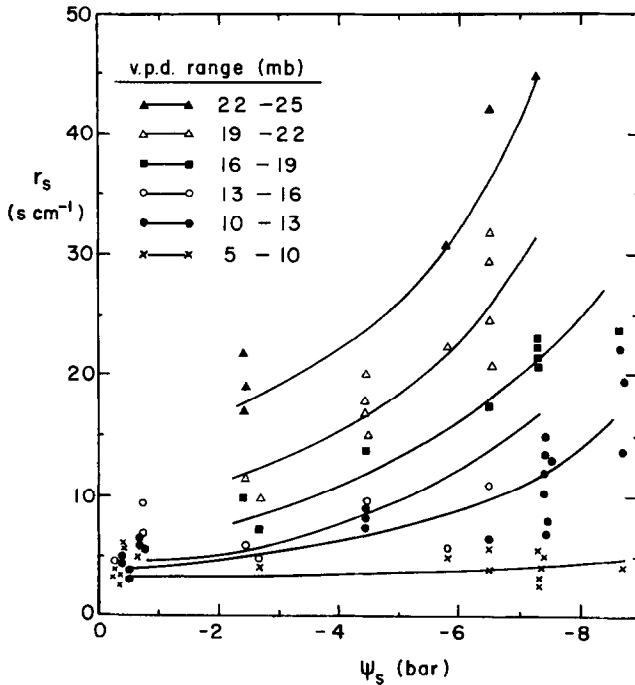


Fig. 7. The relationship between stomatal resistance, r_s , at the 8-m height and soil water potential, ψ_s . The data have been separated into six ranges of vapour pressure deficit, v.p.d., and were daytime measurements made on 12 days.

have been separated into six v.p.d. ranges and a line has been drawn by eye through each range. At a given potential the stomatal resistance increases with increasing v.p.d., as suggested in the previous paragraph. Szeicz *et al.* (1973) analyzed the relationship between stomatal conductance and soil water potential for sorghum. Brady *et al.* (1975), working on soybeans, plotted stomatal resistance against soil water potential. Much of the scatter in the data of both of these groups of workers may be due to variation in the v.p.d.

4.5. RELATIONSHIPS OF CANOPY RESISTANCE TO SOIL WATER POTENTIAL AND VAPOUR PRESSURE DEFICIT

Since the canopy resistance is closely related to the stomatal resistance, it should be possible to relate the canopy resistance to the same environmental parameters that influence the stomatal resistance. In view of the relationship between stomatal resistance and canopy resistance shown in Figures 4 and 5, canopy resistance would be related to soil water potential and v.p.d. in a manner similar to that for stomatal resistance in Figure 7. The value of the canopy resistance of the forest in this study for given values of soil water potential and v.p.d., can be obtained by dividing the value of the stomatal resistance on the ordinate of Figure 7 by about 7.5 (the ratio of the stomatal resistance at the 8-m height to the canopy resistance taken from Figure 4).

For the hydrologist interested in estimates of evapotranspiration over periods of days or weeks, a practical question is whether daytime mean values of canopy resistance can be related to daytime mean values of environmental parameters. Szeicz *et al.* (1973) related daytime canopy resistance of sorghum to the soil water potential of the root zone. They found that the resistance began to increase with decreasing potential when the potential was less than about -7 bar. Szeicz and Long (1969) found that when plotting mean monthly canopy resistance of a grass-clover crop against soil water potential, the resistance began to increase at a potential of -3.5 bar. In an alfalfa crop, van Bavel (1967) found no significant change in canopy resistance until the soil water potential decreased to -4 bar. In each of these cases there was considerable scatter in the plots of resistance against potential.

In Figure 8, values of the daytime mean canopy resistance for the forest in the present study are plotted against the daily mean soil water potential. The daytime mean canopy resistance, \bar{r}_c , was obtained by weighting the hourly values by the v.p.d. as follows:

$$\bar{r}_c = \overline{\text{v.p.d.}} / \sum_{i=1}^n (\text{v.p.d.}_i / r_{ci}) \tag{6}$$

where $\overline{\text{v.p.d.}}$ is the arithmetic average of the daytime v.p.d., and v.p.d._{*i*} r_{ci} are the hourly values of the v.p.d. and r_c , respectively. Much of the scatter in Figure 8 is removed by separating the data into v.p.d. ranges as suggested by the stomatal response shown in Figure 7. The weighted averaging of r_c results in a set of straight

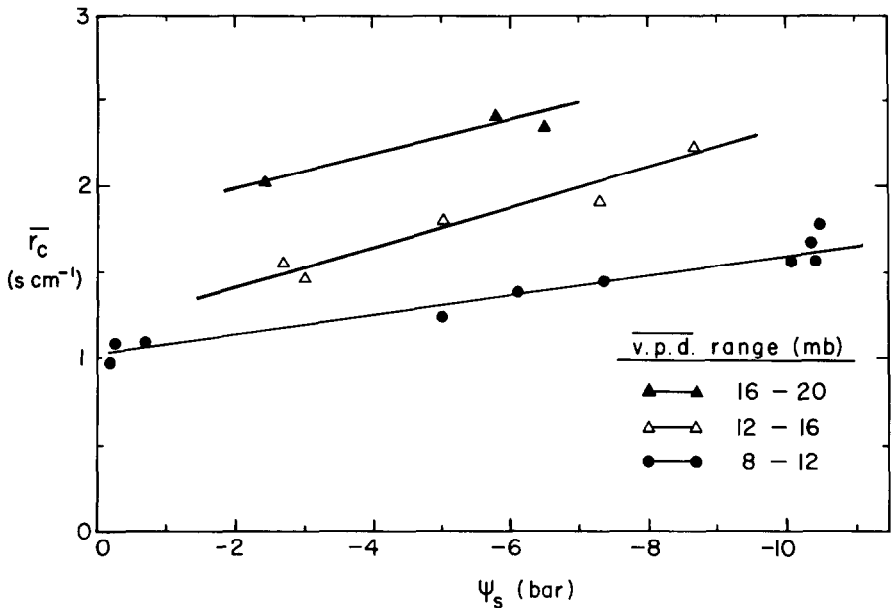


Fig. 8. The relationship between the mean daytime canopy resistance, \bar{r}_c , and soil water potential, ψ_s . The data have been separated into three ranges of mean daytime vapour pressure deficit, $\overline{\text{v.p.d.}}$, and were obtained over a period of 18 days.

lines rather than the curved lines in Figure 7. Canopy resistance appears to increase significantly at a soil water potential greater than -2.5 bar, reflecting the coarse soil and the shallow root zone. The separation of data into v.p.d. ranges indicates that if (1) or (3) is to be used to estimate daytime forest evapotranspiration using mean daytime values of the required parameters, then it is necessary to consider the dependence of canopy resistance on both soil water potential and v.p.d. It points out the influence of both water supply and demand on the canopy resistance. As we have seen earlier, this is mainly due to the action of the stomata in regulating water loss. Our results suggest that a good deal can be inferred about the canopy resistance from a knowledge of stomatal resistance characteristics of vegetation.

5. Conclusions

It has been shown that the canopy resistance of a 21-yr old Douglas-fir forest is largely of physiological origin. Both hourly and daytime values of canopy resistance depend on vapour pressure deficit as well as on soil water potential of the root zone. Daytime mean values of canopy resistance should be calculated by weighting hourly values by the vapour pressure deficit. The results of this study suggest that from a knowledge of the response of stomata to environmental parameters, useful relationships of canopy resistance to environmental parameters can be obtained.

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