EVAPOTRANSPIRATION FROM A DRY DOUGLAS FIR FOREST

by

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ABSTRACT

Evapotranspiration measurements using the Bowen ratio/energy balance technique were made over a dry Douglas fir forest. Soil water matric potential over the period of measurement varied from 0 to -10.5 bars. With the premise that the equilibrium evaporation rate associated with adequate water supply essentially expresses evapotranspiration as a fraction of daily net radiation, the ratio of latent heat flux to net radiation for 24-hour periods is examined as a function of soil water matric potential. This ratio is reduced to approximately half its maximum value as the matric potential approaches -10 bars for the experimental site. The reduction is not as great as that implied by changes in soil water storage, indicating that evapotranspiration of water not originating in the root zone is carried on during periods of considerable water stress. While some water may be flowing upward from below the root zone, it is felt that over half of the daily evapotranspired water is released from storage in tree stems during the most severe period.

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LIST OF SYMBOLS

D	Drainage
E	Evapotranspiration
G	Soil heat flux density
L	Latent heat of vapourization
LE	Latent heat flux density
LE_{eq}	Equilibrium latent heat flux density
M	Storage of sensible and latent heat within the canopy
R_n	Net radiant energy flux density
v.p.d.	Vapour pressure deficit
ΔT	Dry-bulb temperature difference over height
ΔT_w	Wet-bulb temperature difference over height
$\Delta\theta$	Change in soil water storage
β	Bowen ratio
θ	Volumetric soil water content
ψ_m	Soil water matric potential

INTRODUCTION

Evapotranspiration is an important term in both the water balance and the energy balance of a forest. However, the complexity of the surface features and physical geometry, as well as the sheer size of a forest canopy, makes the application of theoretical expressions for evapotranspiration a difficult task for the forest hydrometeorologist. Nonetheless, researchers have been actively seeking a means of making useful estimates of evapotranspiration taking into account the basic meteorological and hydrological parameters of available energy and available water in a practical way.

If potential evapotranspiration were taken to be the evapotranspiration when fetch and soil water are adequate, then this parameter is of necessity a meteorological one. It has been shown that this is approximately equal to the "equilibrium" rate (McNaughton, 1974) for a west-coast forest environment. When used as an estimate of evapotranspiration under suitable conditions, the equilibrium model is physically justified and extremely simple to apply, since it represents essentially a slightly temperature-dependent fraction of the daily net radiation.

The simplicity of the equilibrium model is due in part to the fact that it applies only to a well-watered system, and it avoids the question of an evapotranspiration rate with soil moisture and physiological parameters taken into account. A theoretical modification of the equilibrium model applying to all conditions of soil moisture and plant water stress would render it unwieldy from a practical point of view. However, the fraction of daily net radiation represented in the equilibrium rate provides a useful vehicle for a straightforward study of the reduction in evapotranspiration under conditions of water stress.

Some earlier studies of the reduction of evaporation associated with water stress in agricultural plants were reported by Denmead and Shaw (1962) and Gardner and Ehlig (1963). Further studies on crops carried out in field plots were made by a number of other workers (van Bavel, 1967; Denmead and McIlroy, 1970; Davies and Allen, 1973; Ritchie, 1973). Only a few have looked at the problem related to forest vegetation, and these have been primarily on seedlings in the laboratory (Zatikovsky and Ferrel, 1968; Lopushinsky and Klock, 1974), owing to the difficulty in making *in situ* measurements of evapotranspiration of a forest stand.

The fact that such a study of a forest stand must ultimately be made in the field, together with the confidence gained in the technique and apparatus used in the Bowen ratio approach (Black and McNaughton, 1971), provides the basis for the objectives of this study. These objectives can be summarized as follows:

1. To determine whether the evapotranspiration rate at the experimental site when water is not limiting is equal to the equilibrium rate, thereby providing a further check on the results previously obtained in a west-coast Douglas fir stand (McNaughton and Black, 1973).
2. To measure evapotranspiration from a dry Douglas fir stand, and observe the effect of decreasing soil moisture on the fraction of daily net radiation used in evaporating water.

Diurnal trends in the energy balance provide some insight into the processes controlling evapotranspiration, and therefore will be touched upon. Nevertheless, the emphasis of this study will be upon daily changes in the evapotranspiration component of the water balance, and its relation to daily changes in soil water status and net radiation.

EXPERIMENTAL PROCEDURE

A. *Experimental Site*

Selection of a site for this study was contingent upon the necessity for an area which could be considered simple from a micrometeorological point of view, and yet one which represents a natural environment from which practical conclusions could be drawn. Considerable effort was then put into finding an existing forest stand which met the following criteria:

1. The site must experience water stress during the summer.
2. The site must be free of advective effects, requiring an extensive forested area of reasonably uniform vegetation, flat topography, and good fetch.
3. The stand should be primarily Douglas fir.
4. The site should be accessible by road.

The site chosen was on Crown Zellerbach Company property approximately 17 miles northwest of Courtenay, B.C., on the eastern coast of Vancouver Island. The site met most of the requirements for the study from both a micrometeorological and an operational point of view. 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 provided the range of soil moisture needed for the study. The topography is generally flat, although there are several ridges of approximately 20-30 m relief, and some depressional areas of a swampy nature 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 approximately 15 cm in diameter. There were approximately 1730 stems ha^{-1}, and the basal area was 27.5 $m^2 ha^{-1}$, with a competitive stress index of 340. 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 bulk of the roots were in the upper 45 cm of the soil.

Operationally, the site provided good access with main logging roads leading to within 2 miles of the study area from the Island Highway. Smaller roads led right to the site, alongside which were placed the two trailers and the generator. The 12.2 m high instrumentation tower was placed 30 m from the trailers.

It is felt that the area is an excellent one for a micrometeorological study. Advective effects were felt not to be present, with five miles of forested land separating the site from the Straight of Georgia, and forest extending upwards of 20 miles in either direction along the coast. Although the west-to-southeast sector included irregular terrain and deforested areas on the slopes of mountains rising into the Forbidden Plateau area within 2 miles of the site, winds were virtually never from that direction. Prevailing winds were from the north to northeast.

B. Experimental Methods

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 8.5 m level using the psychrometric apparatus described in Black and McNaughton (1971). Optimum placement of the sensor over the canopy was sought after some experimentation with various heights and positions relative to the top of the tower. The sensor remained in the same location from June 17 until August 1. On August 1, a second Bowen ratio apparatus identical to the first was placed above the first one, and the positions of the two machines were periodically switched in order to check on the operation of each, and to test for any sensor placement problems. Placement of the sensors is discussed briefly in the next section.

Net radiation 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. Soil heat flux G was measured at the 5 cm level 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 of sensible and latent heat within the canopy M was estimated from wet and dry bulb temperatures taken every 15 minutes 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). Evapotranspiration E was then calculated using the equation

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

where L is the latent heat of vapourization.

Supporting climatological measurements were made of incident solar radiation R_s at the top of the tower, and at various levels through the canopy at selected times. Wind speed and direction were monitored using a Cassela sensitive anemometer and Climet wind vane mounted at the top of the tower. Precipitation was recorded each day with a 10.2 cm (4") diameter rain gauge at the trailer.

Data signals were carried back to the data logging trailer by 75 m shielded cables where they were recorded with a Hewlett-Packard 2707 A data logger, and R_n, R_s, and Bowen ratio data signals were integrated using voltage integrators (Black *et al.*, 1974). Bowen ratio data was further monitored on a Honeywell strip-chart recorder. The system was powered by a 6.5 kW Kohler diesel generator.

Soil water content was measured both gravimetrically and by use of the neutron moisture meter. Neutron moisture measurements were made every 2 to 3 days in six access tubes. The basal till limited the depth of the tubes to 45-60 cm. Gravimetric sampling of the root zone was taken every 5 to 16 days, depending on the state of the drying period.

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 Campbell Scientific HR-33T dew point microvoltmeter and PT-10 hygrometers. Six hygrometers, two each at the 15 and 30 cm depth, and one each at the 45 and 60 cm depth, were used. Soil water potential by the tensiometer-transducer system was recorded at 15 minute intervals, while soil water potentials by the hygrometers was measured three times each day. In this study, only daily values of soil water potential are used in the analysis.

Soil water retention curves were determined in the laboratory by (i) hanging column method from saturation to a water potential of -0.12 bar and (ii) pressure plate extraction from -0.33 bar to -15 bars. In addition, texture, bulk density, and root distribution measurements were made.

Stomatal resistance r_s at the 10 m height was measured on a routine basis three times a day on the majority of days during the period June 14 to August 18 and measurements were made every two hours during the daytime on 16 selected days. The measurement was made using the ventilated porometer described in Black *et al.* (1974). At least two samples of four needles each were used to obtain a value of r_s.

RESULTS AND DISCUSSION

A. *Soil water content and matric potential*

The average water retention curve for the 0-60 cm depths is shown in Figure 1. The curve represents the average of laboratory analyses for four depths, with the bars indicating the range of deviations. Field measurements of soil water content and matric potential confirm this curve. The available water capacity is approximately 0.14 cm^3 cm^{-3} for the matric potential range -1/3 to -15 bar. The results of the mechanical analysis of soil particles with a diameter less than 2 mm was 63.5% sand, 21.9% silt, and 14.6% clay by weight. The volume fraction of stones (particles greater than 2 mm) was 20%.

Figure 2 shows the average soil water matric potential ψ_m for the period June 17 to August 19, 1974 for the root zone (0-45 cm). Daily values of precipitation in mm are included for reference. It can be seen that the summer can be divided into three periods: (i) a drying period in the late spring, which was already in progress when the equipment was set up in June, (ii) a wetting period in mid-July, when the bulk of the summer's precipitation occurred (precipitation for July, 1974 was abnormally high),

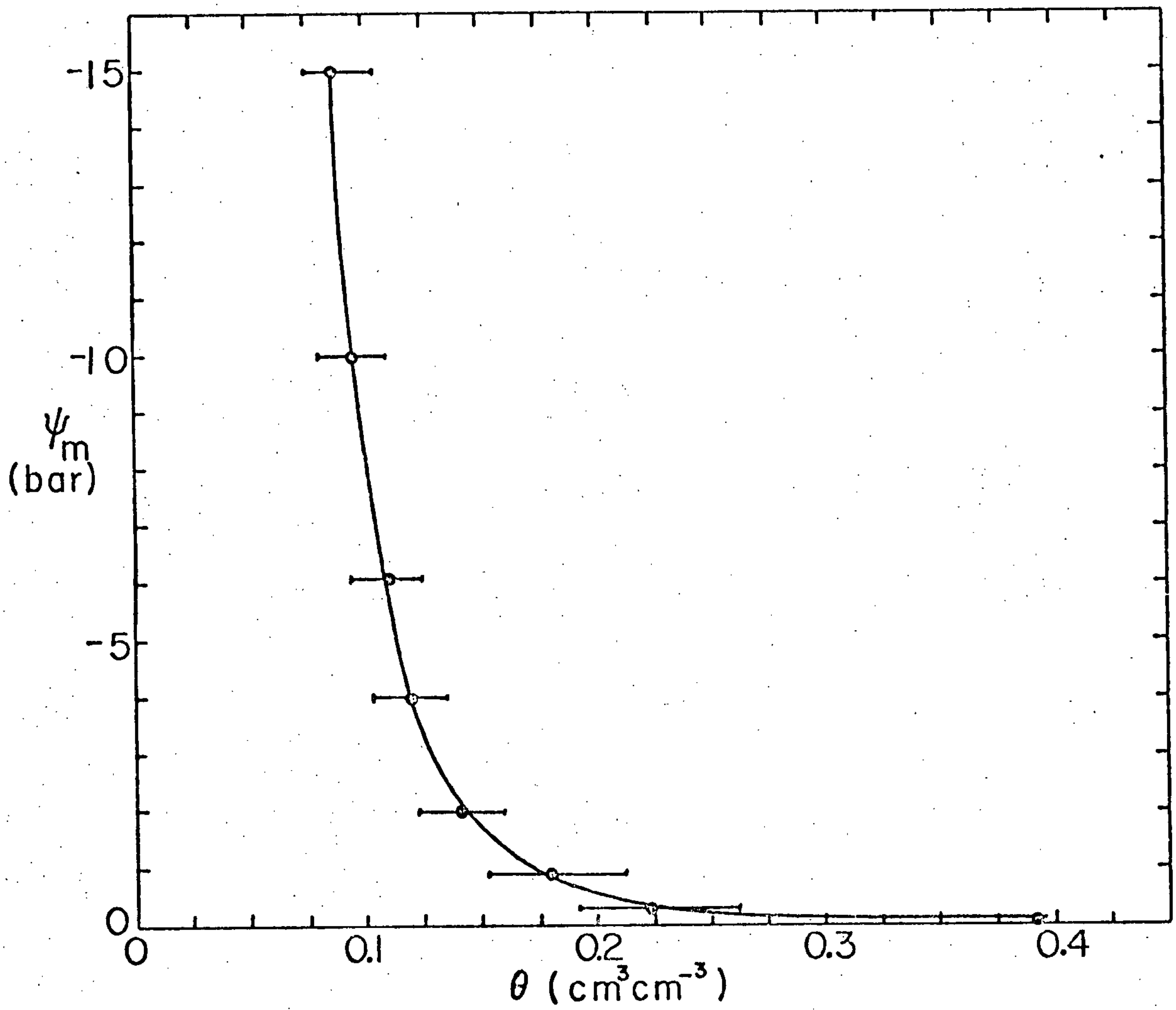

Figure 1. Water retention curve for Dashwood series gravelly sandy loam. Each point is the average water content θ of the 15, 30, 45 and 60 cm depth samples at a single value of soil water matric potential ψ_m. Bars indicate range of water contents.

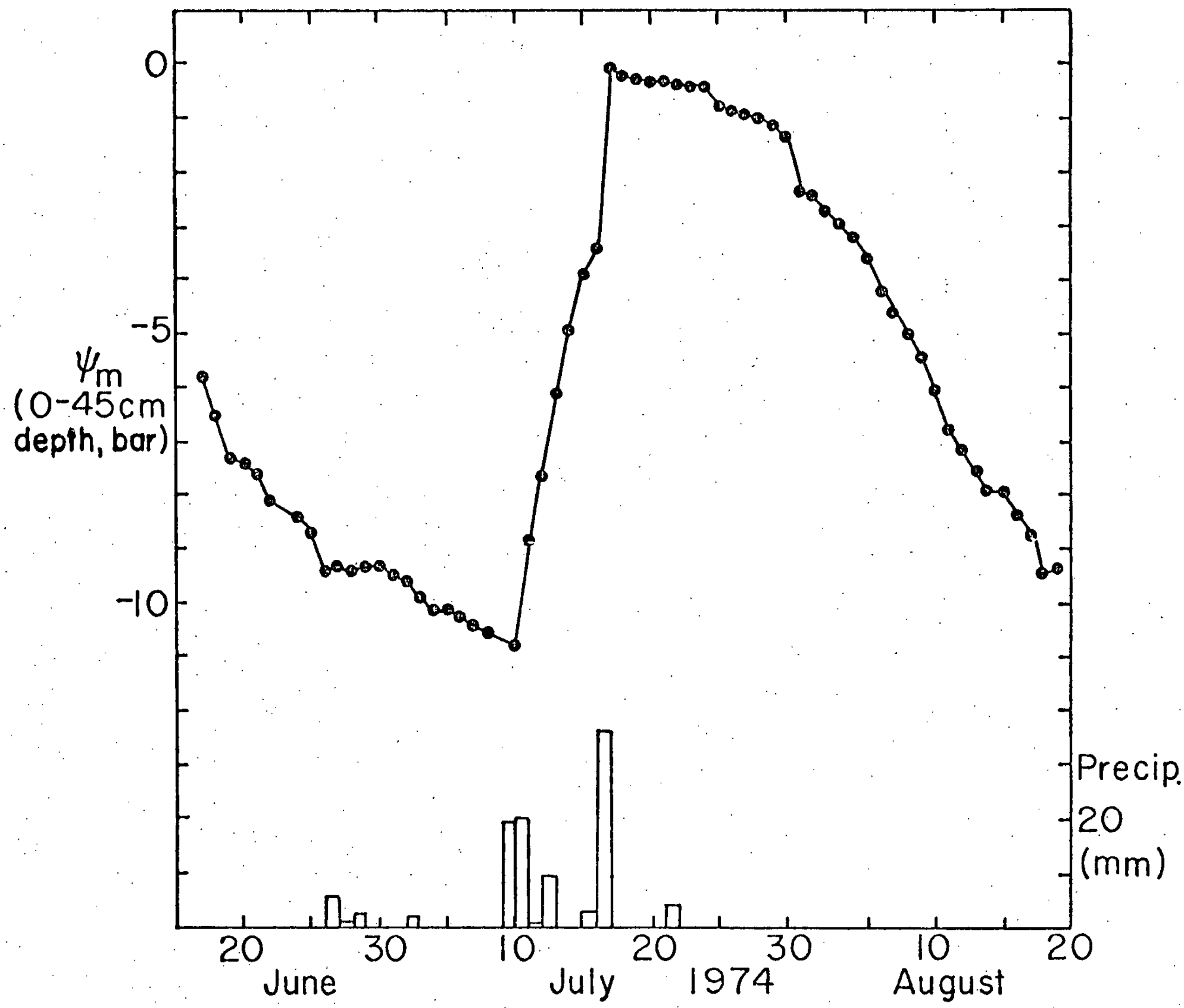

Figure 2. Soil water matric potential ψ_m for June 17-August 19, 1974. Each point is the average value of the matric potentials at the 15, 30 and 45 cm depths.

restoring the soil to zero matric potential, and (iii) a second drying period with no precipitation occurring throughout until the end of the period. This weather afforded two separate periods at the dry end of the range of water contents in the soil.

Average soil water content, shown in Figure 3, ranged from 9-23 percent on a volumetric basis which includes stones. The 0 to 60 cm layer was used in this average because it is felt that water content changes down to 60 cm may be significant in the forest water balance. This matter will be discussed in more detail later. Precipitation is again included in the figure for reference.

B. Daytime course of net radiation and latent heat flux

Detailed computation of half-hourly energy balances was restricted primarily to fine days when resolution was good in diurnal fluctuations of energy fluxes. It was found that the small gradients of wet and dry bulb temperatures over the dry forest produced more scatter in the evapotranspiration measurement than had been expected. The size of these gradients is evident when Figure 4, showing ΔT_W and ΔT through the course of the day on June 18, is compared with the gradients shown in Figure 6 in Black and McNaughton (1971).

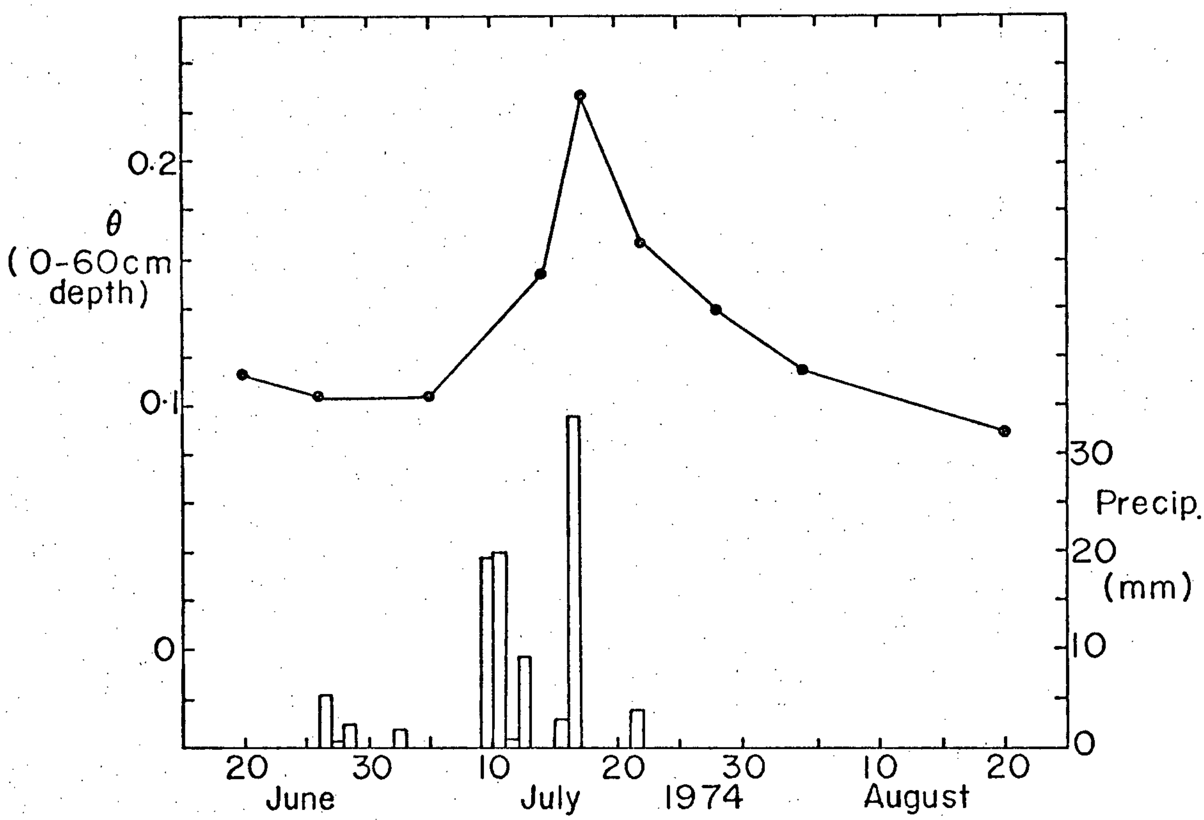

Figure 3. Average volumetric water content for June 20-August 20 of the 0-60 cm depth of soil from gravimetric sampling.

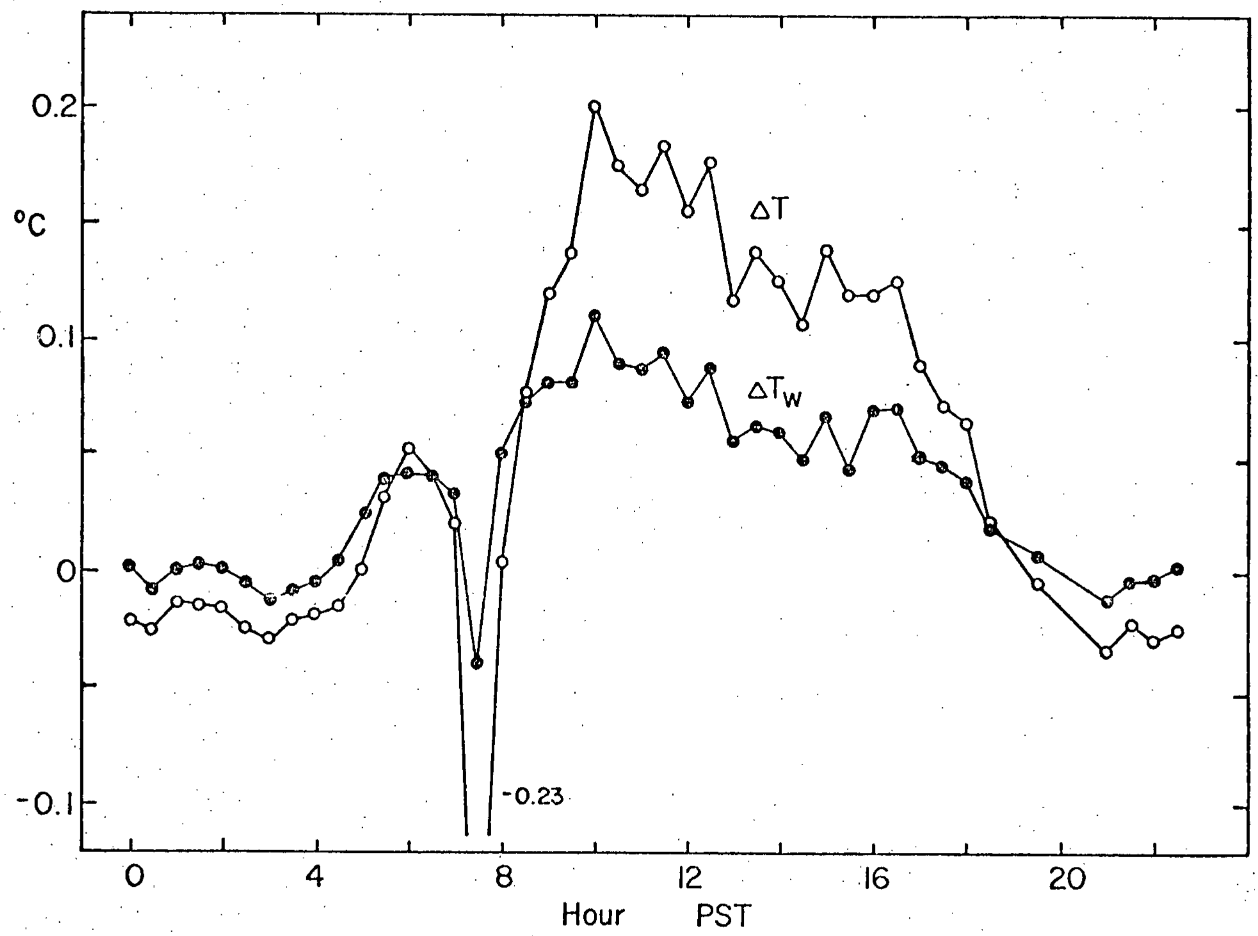

Figure 4. Diurnal trend in wet- and dry-bulb temperature differences ΔT_W and ΔT respectively over 1 m height above the canopy for June 18, 1974. Note the reversing of the gradients around 0800 PST.

Negative values of ΔT, causing overestimates of LE frequently exceeding R_n, were consistently seen in the period from sunrise until approximately 1000 PST. It was felt that the problem was caused by the sensor being placed too low and consequently measuring gradients within the canopy rather than over it at certain times. A settling of the maximum temperature of the profile into the canopy after 1000 PST could explain morning inversions and successful afternoon Bowen ratio measurements. Also, since the terrain sloped gently to the northeast, the apparent height of the sensor was greater when winds were from the northeast, which was the predominant wind direction in the afternoon.

Since advective effects were considered absent, it was felt that the true value of LE should be somewhat lower than R_n during this time period. Results from the forest at Haney (McNaughton and Black, 1973) would suggest that a value closer to one-half of R_n would be a better estimate. Independent estimates of LE using the Monteith equation and observed values of stomatal resistance to calculate surface resistance show good agreement with energy balance measurements in the afternoon, but tend to support the one-half R_n relationship in the morning. Figure 5 compares stomatal resistance r_s with surface resistance r_c calculated from

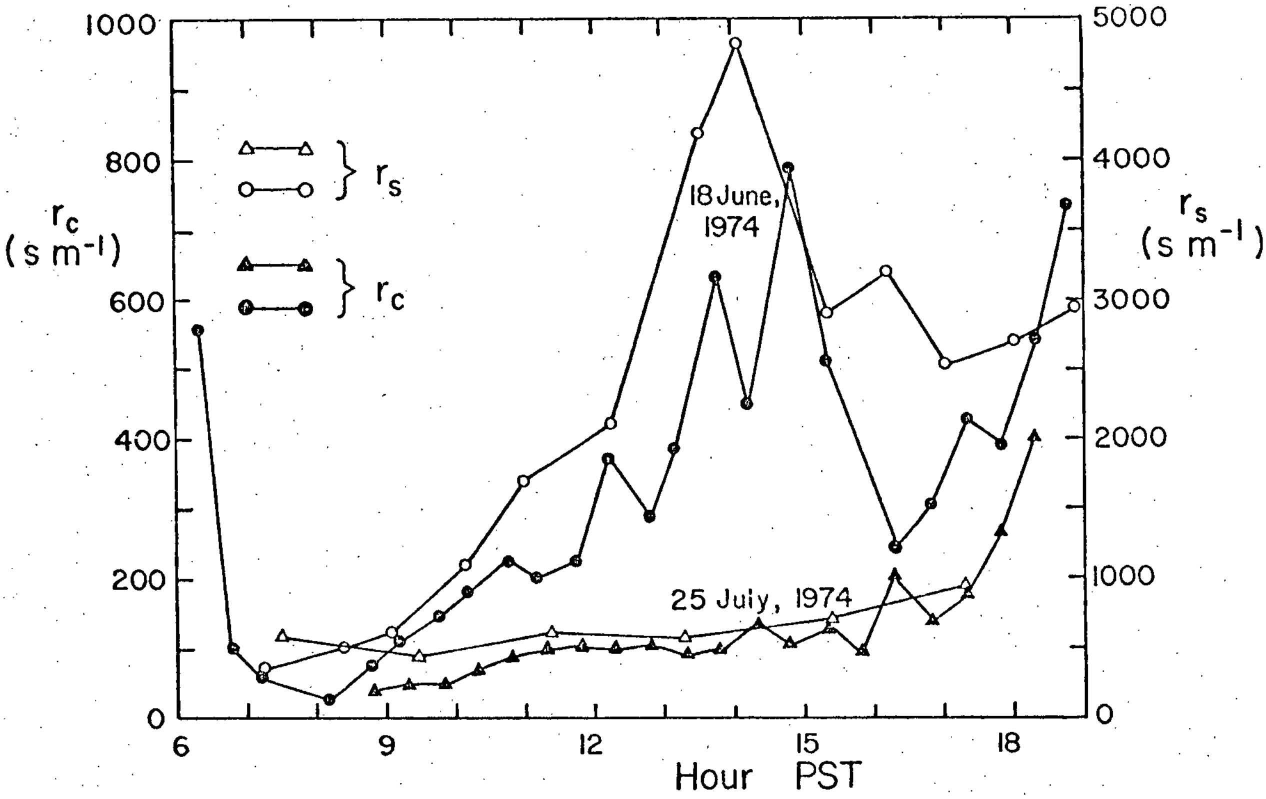

Figure 5. Daytime course of surface resistance r_c (from energy balance measurements) and stomatal resistance r_s (projected leaf area basis) for June 18 and July 25, 1974. The disagreement of the two values is large on a percentage basis in the morning.

the energy balance estimates of LE and the Monteith equation. Note that in the morning r_s and r_c often differ by over a factor of two, whereas in the afternoon they show good agreement on a percentage basis.

At times when the second Bowen ratio apparatus was placed above the first one, its measurements also suggest that the one-half R_n relationship is a good estimate. The success of the second machine in this position tends to support the conclusion that with such small gradients, placement of the sensors can be critical: too low a sensor may be subject to inversion effects in the morning, and too high a sensor may not be able to sufficiently resolve the smaller gradients. It may well be that the most viable alternative to variable placement of the sensor with height over the day is an increased separation of the sensors for dry forest measurements.

Figure 6 shows the diurnal course of R_n and LE for (a) June 18, 1974, and (b) July 25, 1974. The solid dots show the energy balance values of LE, while the circles represent LE estimates from stomatal resistance measurements. Daily totals of evapotranspiration were obtained from the solid line, drawn by eye. Note the apparent overestimation of measured LE over what is felt to be the better approximation in the daylight period before 1000 hrs. This

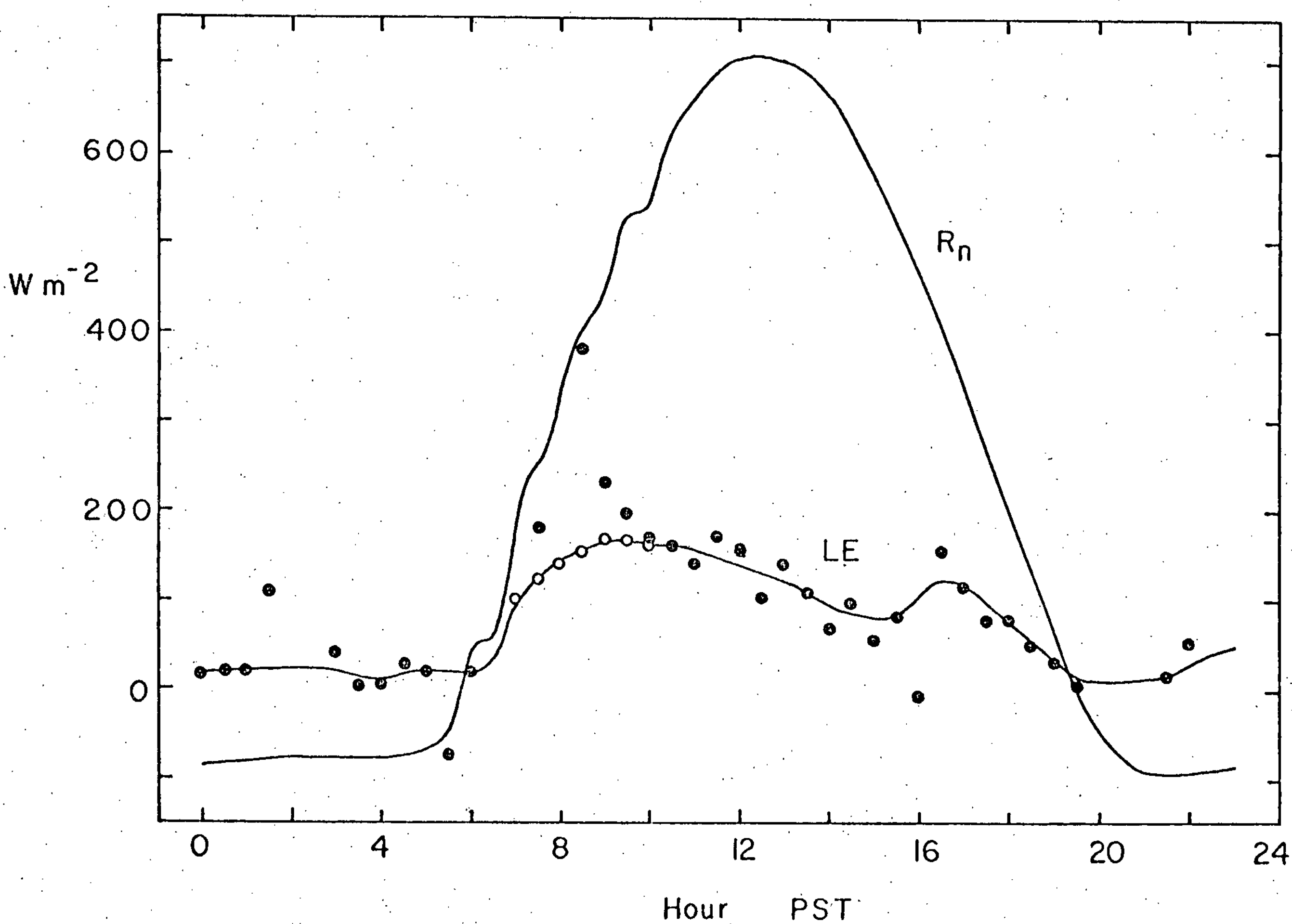

Figure 6a. Diurnal trend in R_n and LE for June 18, 1974. Solid dots are energy balance measurements of LE, while circles show LE estimated from stomatal resistance measurements. The solid line for LE was drawn by eye.

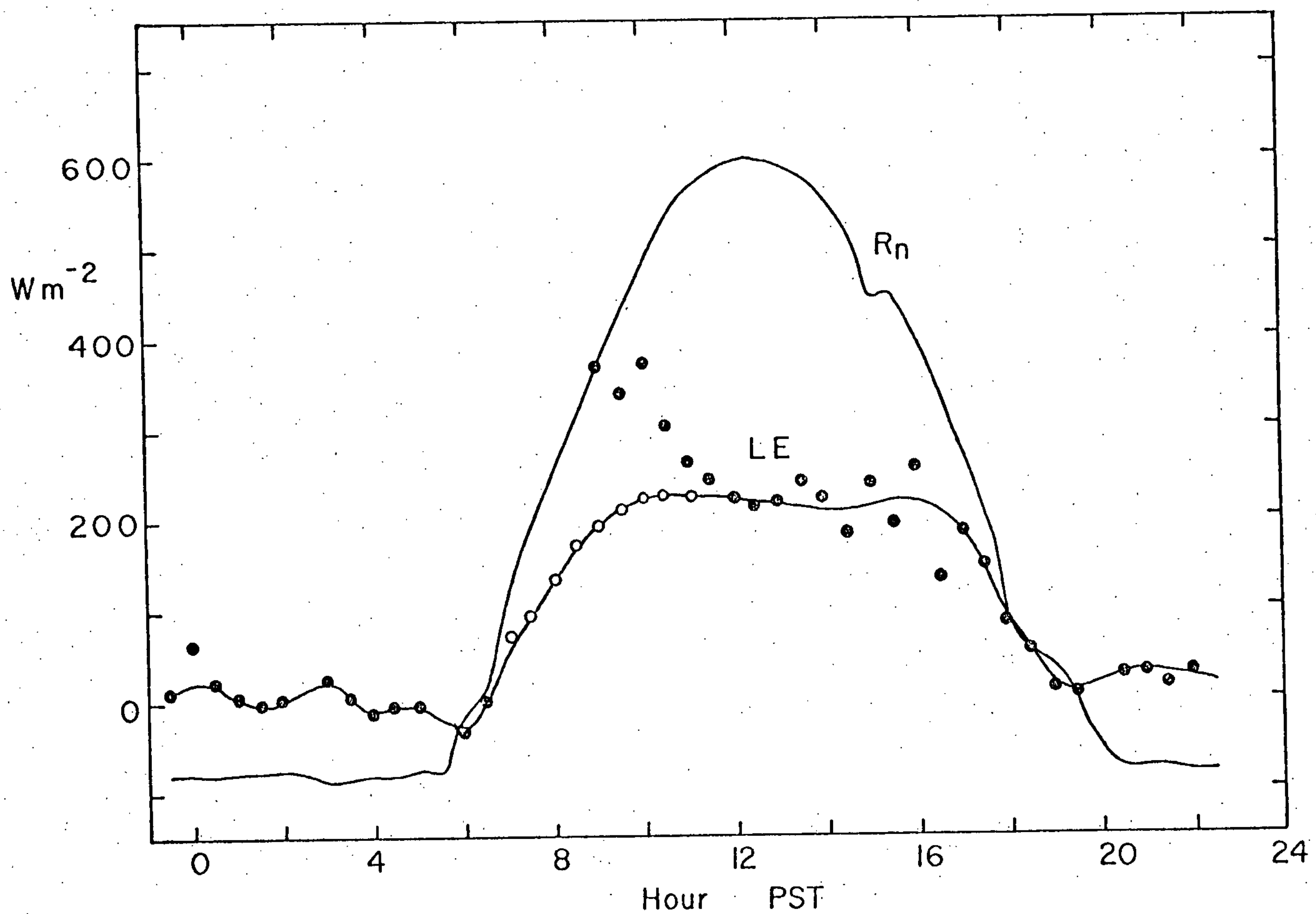

Figure 6b. Diurnal trend in R_n and LE for July 25, 1974. Solid dots are energy balance measurements of LE, while circles show LE estimated from stomatal resistance measurements. The solid line for LE was drawn by eye.

overestimation usually amounted to approximately ten percent of the daily total evapotranspiration.

Figures 6 (a) and (b) are combined in Figure 7 to contrast their curves of LE and R_n. July 25 was a fine day sufficiently long after the rainy period that there was no free water on the trees, yet a day when soil water could be considered adequate at a matric potential of -0.7 bar. The latent heat flux on July 25 does not display the mid-afternoon peak observed at Haney by McNaughton and Black (1973). In fact, although it was present, it was not pronounced in the latent heat flux plot for July 19 (shown in Figure 8), the first clear day after the wetting period. This suggests more restriction to transpiration than was present at Haney in the period of peak afternoon vapour pressure deficit. The 24-hour values of LE/R_n of 0.54 and 0.58 for July 19 and 25 respectively are slightly lower than the respective values of 0.61 and 0.63 predicted by the equilibrium evaporation rate. The restriction may well be a function of the low hydraulic conductivity associated with a very coarse soil.

June 18, a day when the matric potential was -6.5 bars following several weeks of generally clear weather, presents a much different picture. Note, first, that R_n

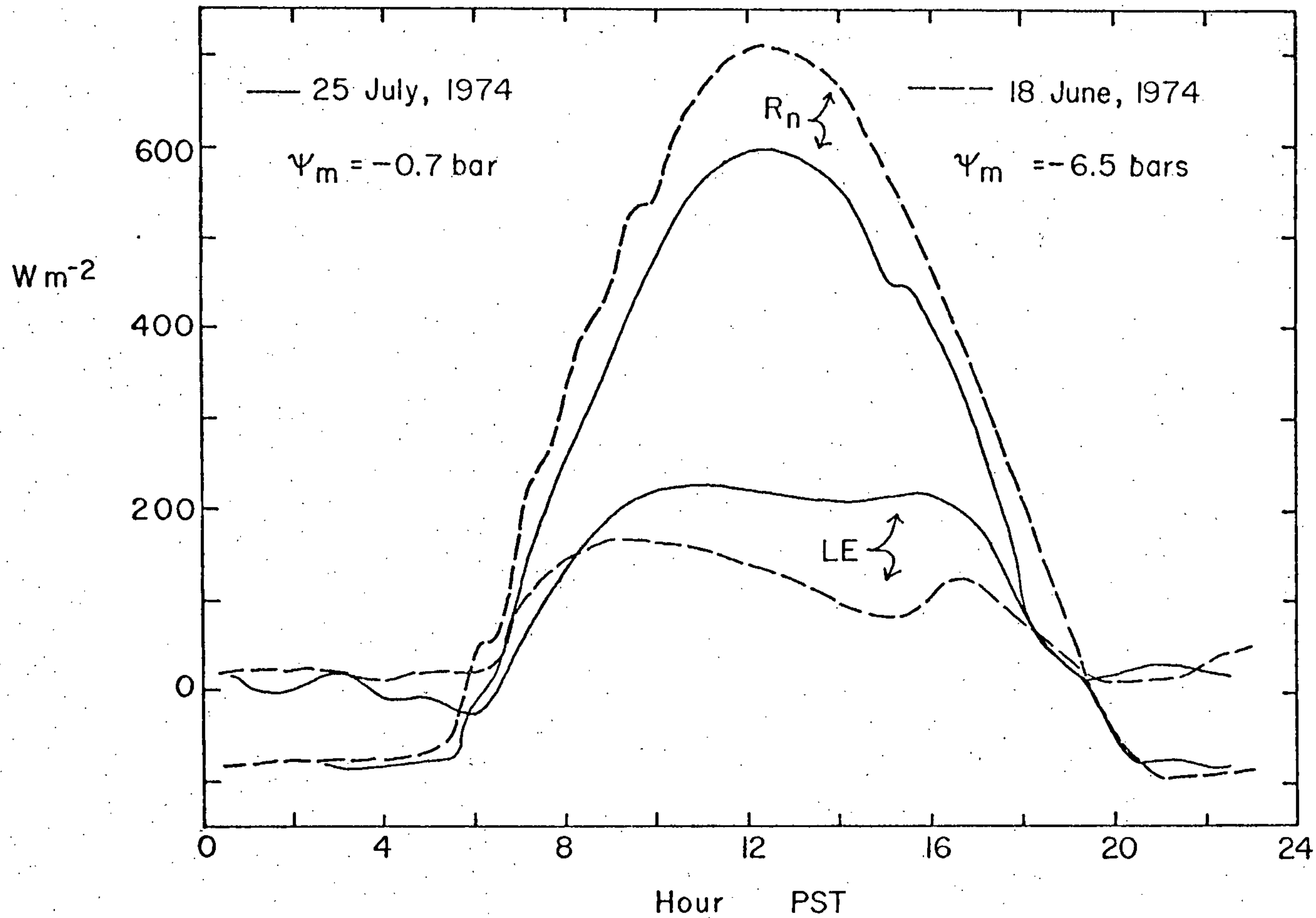

Figure 7. Figures 6a and 6b together to illustrate the effects of decreased soil water matric potential ψ_m on LE. Note that R_n is higher on June 18.

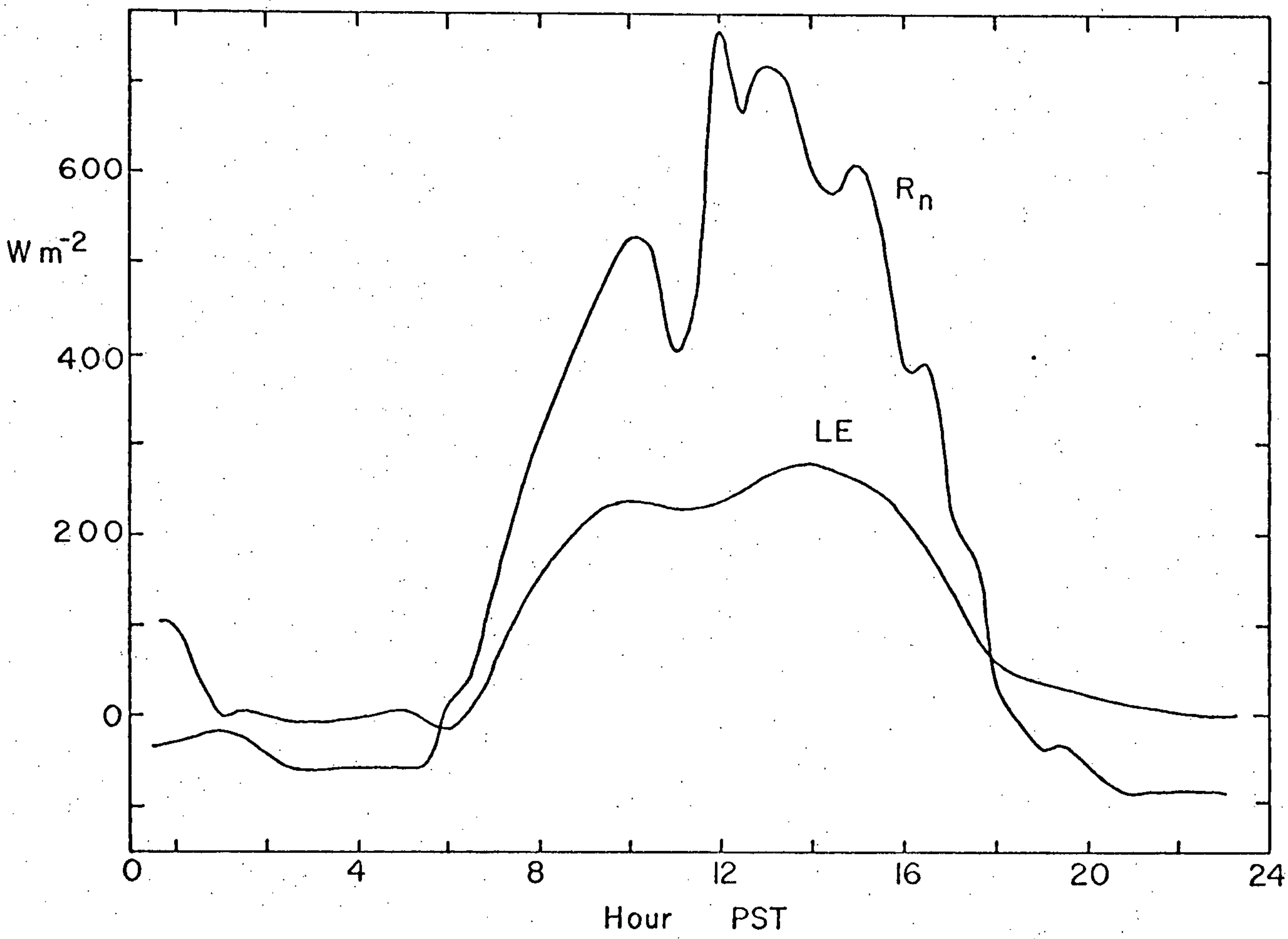

Figure 8. R_n and LE on July 19, the first clear day after the rainy period in mid-July. The mid-afternoon peak in LE is present, but not pronounced.

is higher on June 18, being only 3 days from the summer solstice. The cutback in LE was apparent as early as 1000 PST, at which time the evapotranspiration rate reached its daily maximum. The latent heat flux decreased during the late morning and early afternoon to a minimum of 80 Wm^{-2} at 1430 PST when the v.p.d. and stomatal resistance both reached maximum daily values (Black *et al.*, 1975). Resistance to transpiration is obvious in this case with the 24-hour value of LE/R_n being only 0.38.

July 8, whose diurnal courses of LE and R_n are shown in Figure 9, can be considered the most severe observed day of the summer, with an average ψ_m of -10.5 bars, R_n of 6.75 mm equivalent, and LE/R_n of only 0.26. Gradients in the wet and dry bulb temperatures were so small that the observed vapour pressure gradient was negligible at 1600 PST.

C. The relationship between LE/R_n and ψ_m

As mentioned in the introduction, the equilibrium evaporation rate predicts an approximately constant value of the ratio LE/R_n for adequate soil water. Since the evapotranspiration rate depends on evaporative demand as well as water supply, we will examine the effect of decreasing soil water matric potential on LE/R_n.

Figure 10 shows the 24-hour value of the ratio LE/R_n as a function of ψ_m for ten selected fine days including

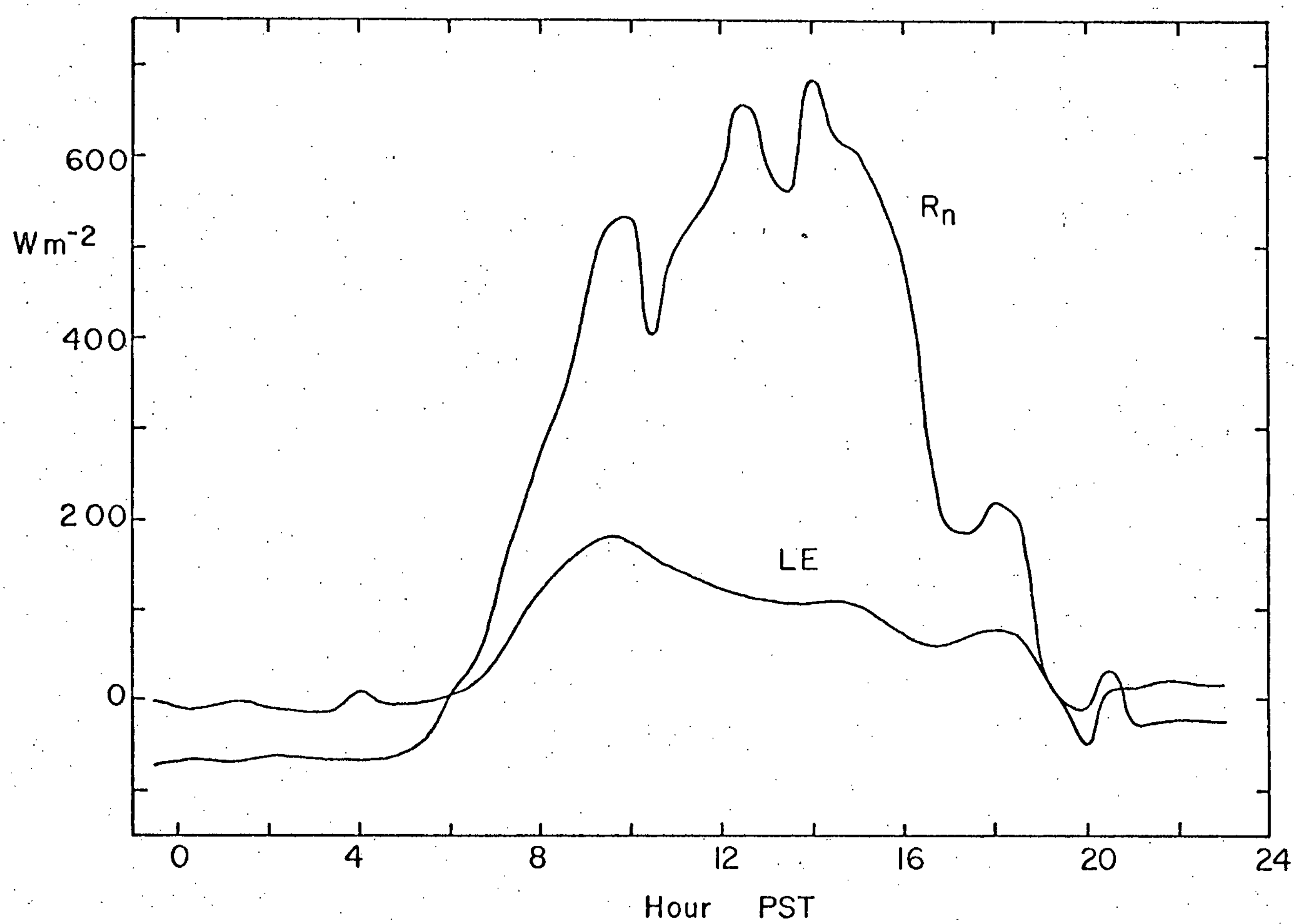

Figure 9. R_n and LE on July 8, the last day of the first drying period, and the most severe observed day from the aspect of water stress. LE/R_n was only 0.26.

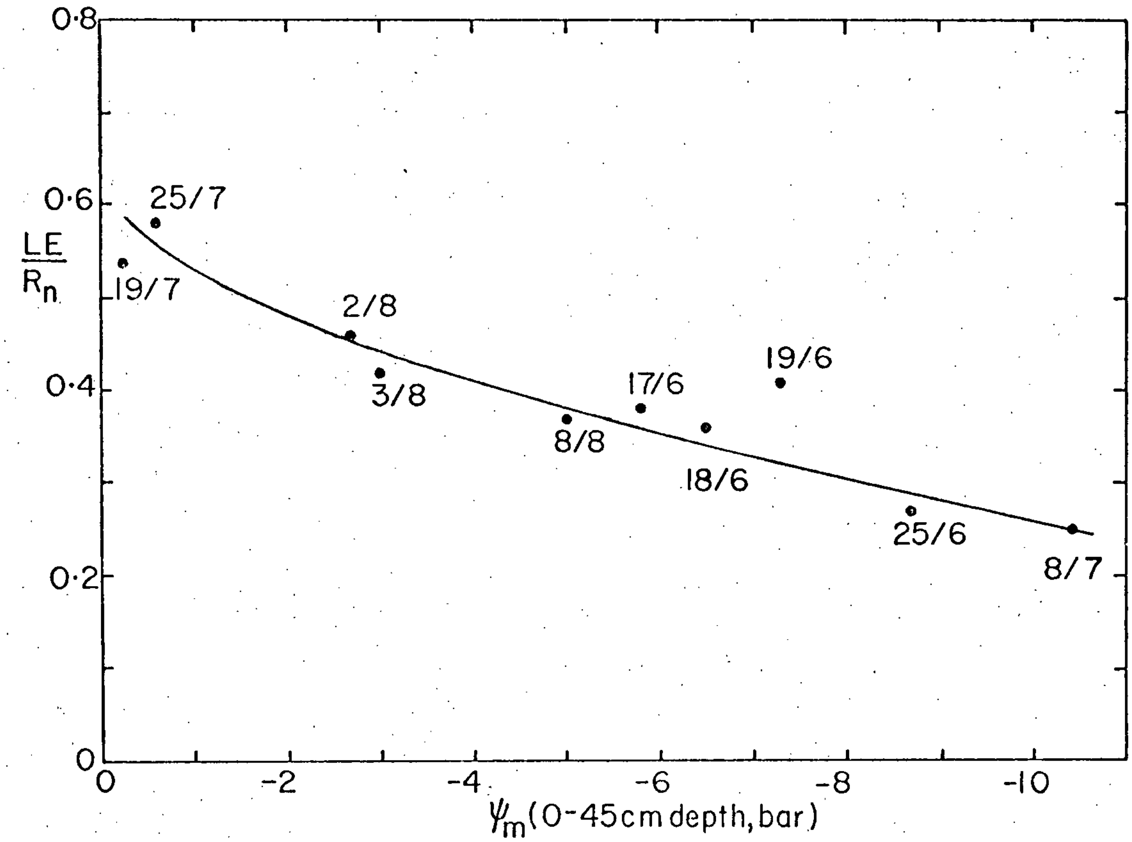

Figure 10. LE/R_n as a function of soil water matric potential ψ_m for ten selected fine days. The number adjacent to each point is the date.

the four days previously discussed. ψ_m represents the average value for the root zone, as in Figure 2. A curve of best fit was drawn by eye. The curve indicates that LE/R_n decreased continuously to approximately half its maximum value as ψ_m approached -10 bars. It is possible that less scatter would be obtained by taking into account such factors as stomatal resistance, v.p.d., and the magnitude of R_n, but the complexities involved in doing this defeat the purpose of the simple approach used here. The high value of LE/R_n for June 19 (0.41) may be due to the somewhat higher v.p.d. on that day, but further speculation would not be justified without a great deal more data.

Workers in agriculture have often used variations on the Penman potential evaporation equation rather than R_n to normalize LE to evaporative demand. The difficulties in calculating and interpreting the Penman potential evaporation rate have been discussed by McNaughton and Black (1973). Figure 11 shows the ratio LE/LE_{eq} as a function of ψ_m, where LE_{eq} is the equilibrium evaporation rate determined from daily air temperatures and net radiation. The similarity between this graph and Figure 10 essentially underlines the degree to which the equilibrium rate can be expressed as a constant fraction of R_n. Because

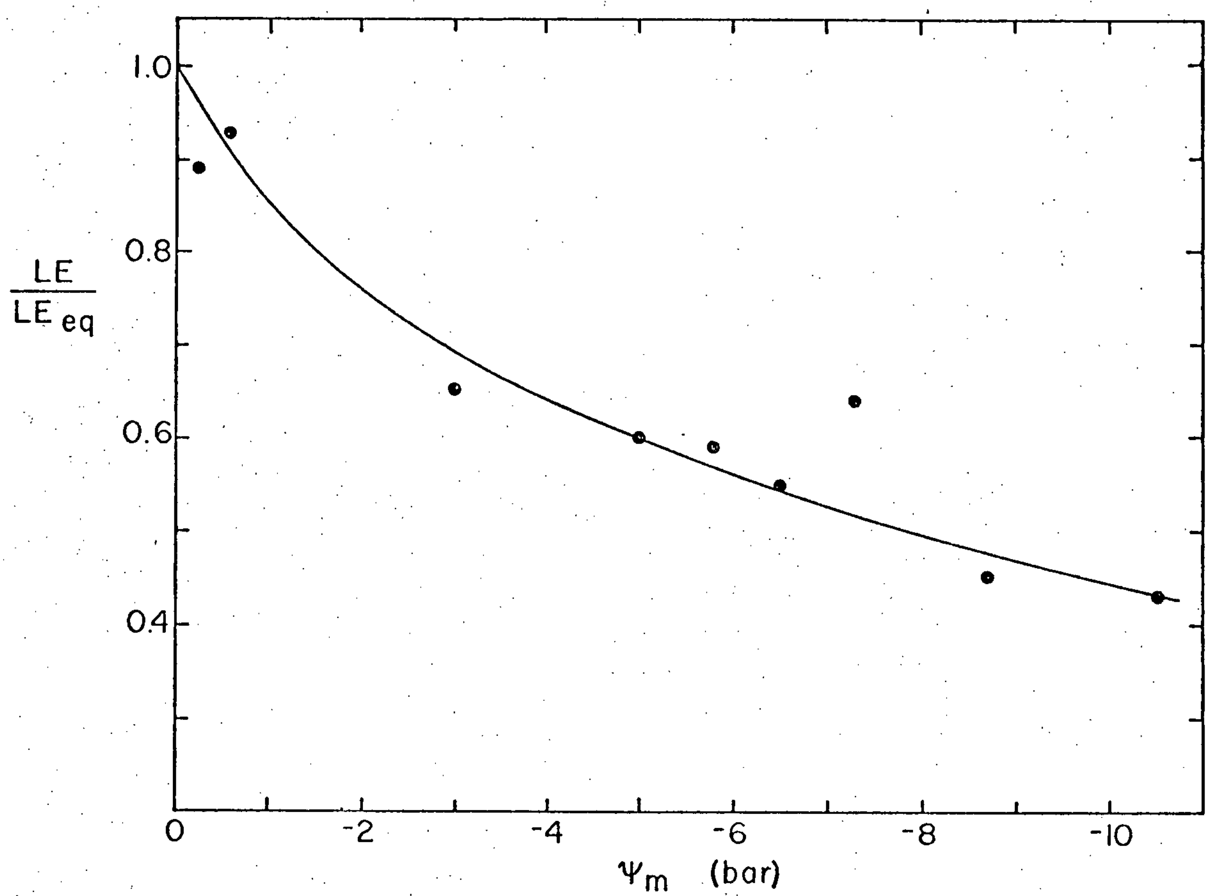

Figure 11. LE/LE_{eq} as a function of ψ_m where LE_{eq} represents the daily equilibrium evaporation rate. Differences in this curve and Figure 10 are due only to differences in daily mean temperatures.

of the frequently strong dependence of water content on high values of ψ_m for most agricultural soils, curves such as that in Figure 11 are often shown with ψ_m on a logarithmic scale to expand the high ψ_m range. Such a curve, taken from Figure 11, is shown in Figure 12 along with various other curves taken from van Bavel (1967) for comparison. It should be noted that determination of maximum rates of LE is not the same for all authors. Also in the coarse soil of this study, hydraulic conductivity tends to drop off faster with decreasing matric potential than in most agricultural soils.

While the energy-based parameter ψ_m is used extensively by environmental physicists, hydrologists and agriculturalists often find it more convenient to use volumetric water content θ as a measurement of soil water. It should be possible, then, to draw a relationship between LE/R_n and θ by use of Figure 10 and a water retention curve for the soil under study. Such a relationship, derived from Figures 1 and 10, is shown in Figure 13. The use of such a curve would allow the use of a daily gravimetric or neutron meter measurement of θ along with daily R_n data to estimate daily values of evapotranspiration.

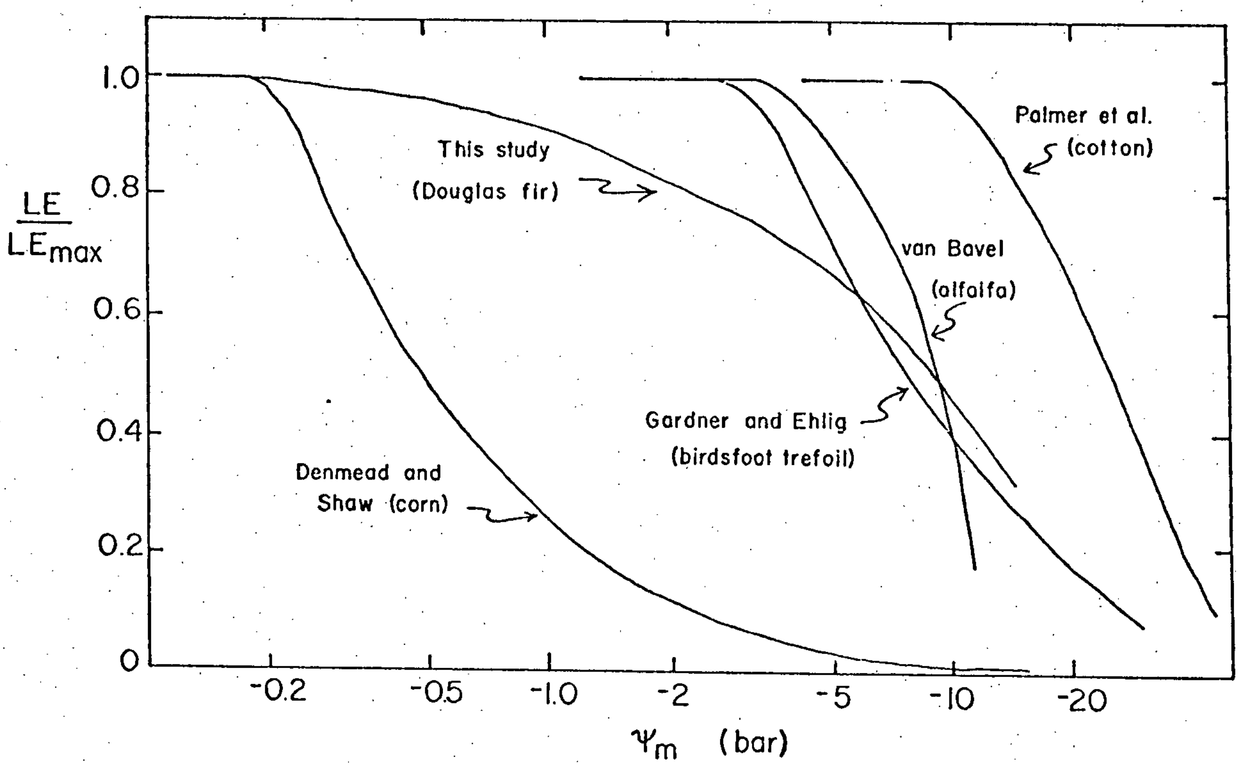

Figure 12. LE/LE_{max} as a function of ψ_m (logarithmic scale) for various authors (taken from van Bavel, 1967). Note that the maximum evapotranspiration rate LE_{max} is determined differently for different authors, and in this study is taken as the equilibrium rate.

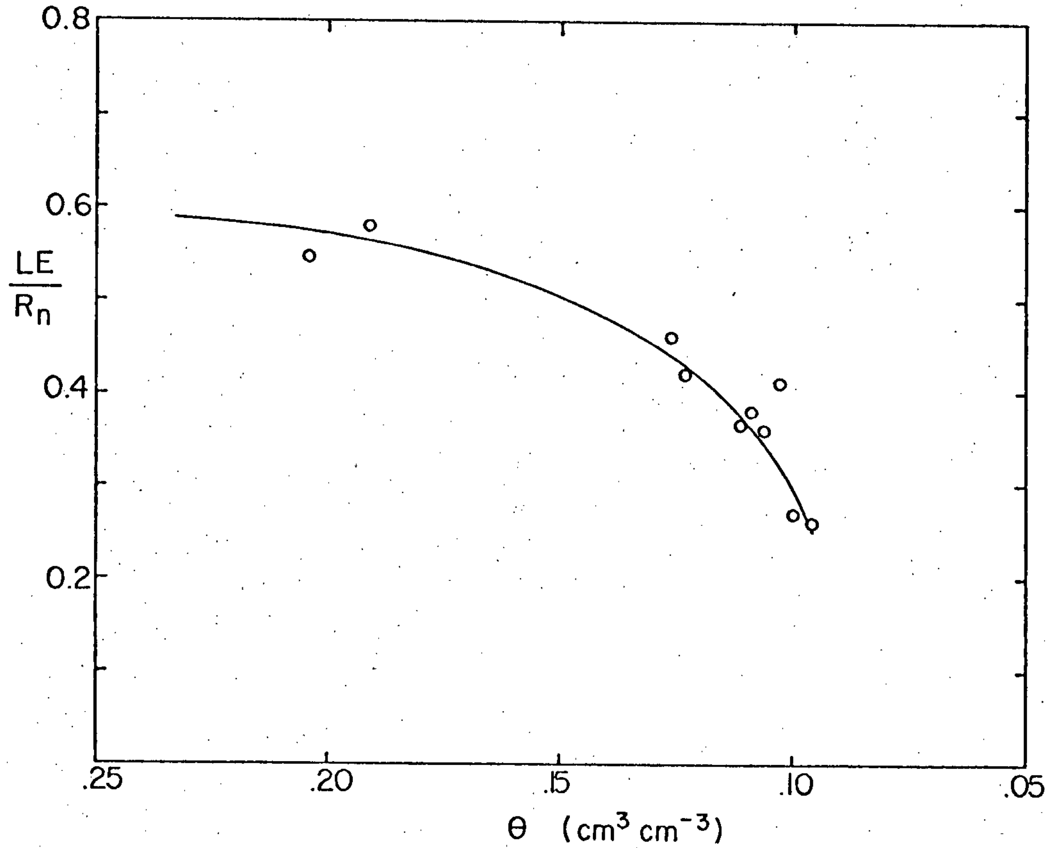

Figure 13. LE/R_n as a function of volumetric water content. This and Figure 10 are related through the water retention curve for the soil, and allow evapotranspiration estimates from water content measurements to be made.

D. Evapotranspiration estimates using R_n and ψ_m data

A relationship such as that in Figure 10 can be used to estimate evapotranspiration using measured values of daily R_n and ψ_m. This approach requires only one more measurement, that of ψ_m, than the equilibrium approach, and yet it applies to a wide range of soil moisture. Figure 14 shows the seasonal trend in evapotranspiration in mm estimated from ψ_m from Figure 2 and daily values of R_n (expressed in mm), using the relationship between LE/R_n and ψ_m drawn in Figure 10. Values of evapotranspiration for days used to obtain Figure 10 were used in Figure 14 for those days, and are shown as triangles to distinguish them from values of LE derived from the relationship between LE/R_n and ψ_m. While it may be argued that Figure 10 should apply only to fine days of high R_n, it can be seen in Figure 14 that evapotranspiration on days when R_n is low is only a small fraction of the summer total, and small errors in estimating evapotranspiration on days of low demand are not critical for long term predictive estimates. Values of R_n and LE shown in Figure 14 are given in tabulated form in Appendix I.

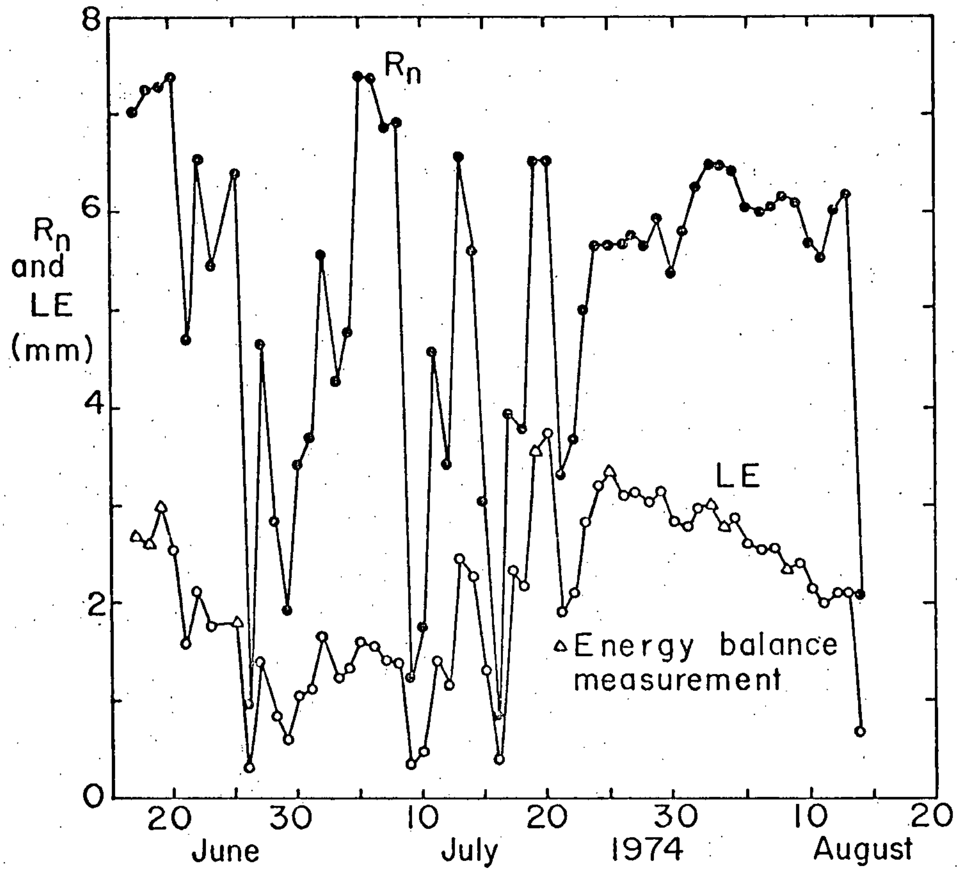

Figure 14. Daily total of R_n and LE for June 17-August 14, 1974. Points used to obtain Figure 10 are shown as triangles. R_n and LE are shown as mm water equivalent.

E. Water balance of the forest

While the changes in soil water content shown in Figure 3 could be used to check on the estimated values of evapotranspiration, the significance of such a comparison is doubtful since no independent measurements of drainage were made. On the other hand, a water balance could be obtained using evapotranspiration and soil water content values, with drainage as the residual using the water balance equation

$$P = E + \Delta\theta + D$$

where P is the precipitation, $\Delta\theta$ is the change in water content in the 0-60 cm layer of soil, and D is the drainage. Surface runoff was not observed at the site. Average daily values of $\Delta\theta$ were obtained from the curve in Figure 3 for the eight period between data points. Daily values of P and E for the corresponding periods were averaged from Figures 3 and 14 respectively, and average daily values of drainage were then calculated. The water balance components thus obtained are presented in Figure 15, and given in tabular form in Appendix II.

Note that drainage appears as an input as well as an output to the root zone. While the negative drainage

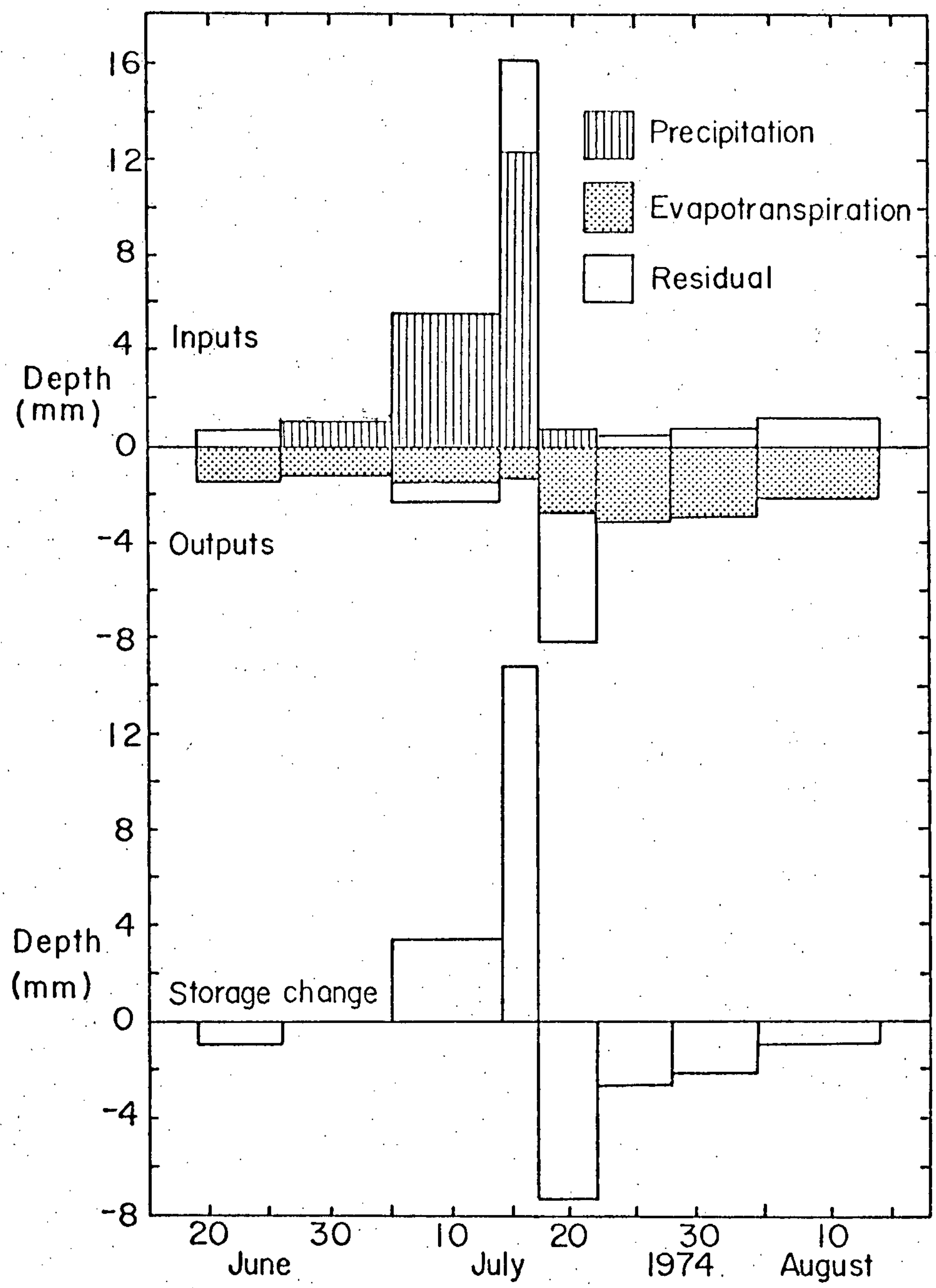

Figure 15. Water balance of the 0-60 cm depth of soil for June 17-August 14, 1974. Values are daily averages in mm of water. The residual term is discussed in the text.

calculated for the period July 14-17 could easily be caused by small errors in measurements of precipitation and soil water storage for this short period, there is an obvious trend in the residual of the water balance for drier periods that indicates that evapotranspiration continued at progressively higher rates than would be predicted from soil moisture depletion. Since there is little evidence to indicate that roots extended below the 45 cm level, there is an apparent source of water which is not taken into account in a conventional water balance of the root zone.

There is some evidence that this source is, in part, upward movement of water into the 0-45 cm layer. For this reason the water content at the 60 cm level was included in calculating $\Delta\theta$. Inspection of the profile of soil matric potential (Figure 16) indicates that indeed gradients existed during the drier periods that would tend to induce flow upwards from below the 60 cm level. Application of Darcy's law to these gradients and the magnitude of the negative drainage values gives values of unsaturated hydraulic conductivities that are reasonable for a coarse soil. However, this conductivity should become progressively lower as the apparent negative drainage increases. It is also difficult to

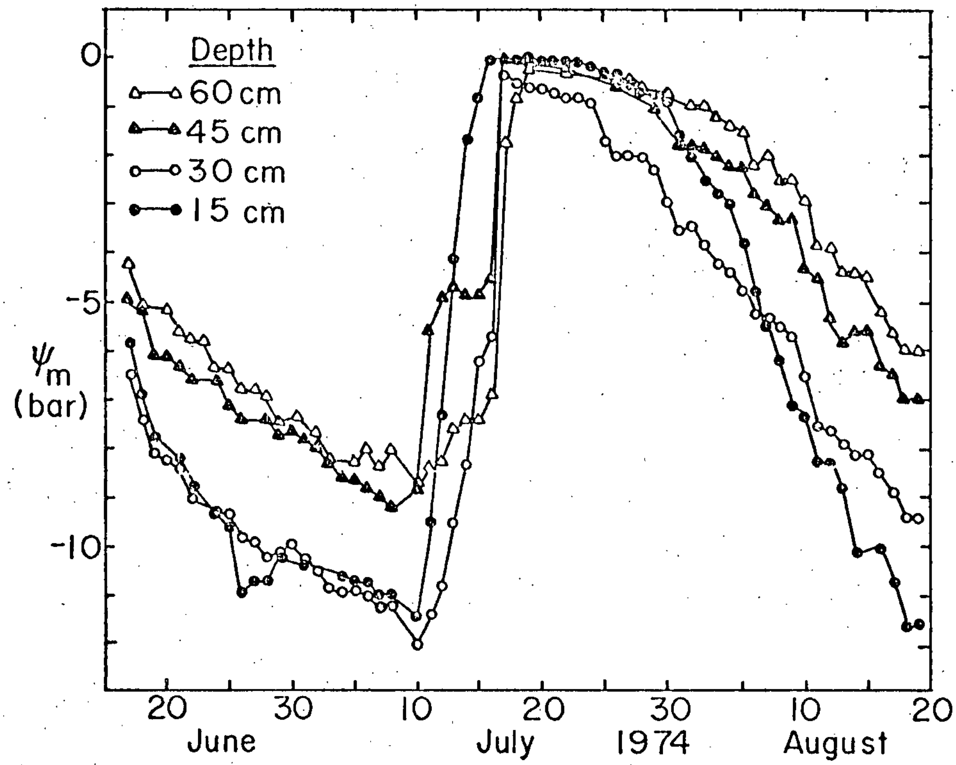

Figure 16. Soil water matric potential at four depths for June 17-August 19, 1974, indicating direction of gradients in the vertical axis.

believe that over half of the water transpired during the dry period in mid-August, as indicated by the water balance, originated from the nearly impermeable layer of basal till below 60 cm.

It has been recently suggested that the amount of water capable of being stored in the wood of conifers can be important in the transport of water through the trees (Running *et al.*, 1975). Significant amounts of water may be released by the wood when supply at the roots becomes inadequate, in order to meet evaporative demand. This is in accord with some recent experimental findings for Douglas fir (Lassoie, 1973) and White Oak (Hinckley and Bruckerhoff, 1975). The fact that water potentials in the twigs and roots of the trees under study decrease throughout the drying cycle (Black *et al.*, 1975) indicates that the trees are losing water which has not explicitly been taken into account in the water balance. Although measurements of tree water content were not made, it is reasonable to speculate that progressively more of the "negative drainage" term in the water balance is due to changes in tree water storage than in soil water storage. This amounts to over half the daily average evapotranspiration in the last period. It is expected that the negative drainage term would begin to decrease under more extreme drying conditions, causing a more marked decrease in transpiration.

The water balance analysis serves to illustrate the usefulness of micrometeorological measurements in understanding the water regime of a forest, and indeed it has provided some insight into the process of water transport through trees in a water-stressed forest. It is quite conceivable that with a better understanding of the relationship between soil moisture and the proportion of transpired water released from storage in the wood, a reasonably accurate water balance could be predicted from estimates of daily net radiation and precipitation alone. Beginning with a known condition of soil moisture in the early part of the season, evapotranspiration for each day can be used, along with an estimate of the proportion of the day's transpired water taken from tree stem storage, to calculate a value of ψ_m for the next day. This will in turn be used to determine LE/R_n for the next day. In this way good hydrological predictions could be made from the straightforward measurements of precipitation and net radiation.

CONCLUSIONS

Evapotranspiration from a water stressed Douglas fir forest has been measured throughout the range of soil matric potentials from 0 to -10.5 bars, and daily values of LE/R_n have been calculated for selected days. These values have been used to express a relationship between evapotranspiration, net radiation, and soil matric potential to be used to predict evapotranspiration from radiation and soil water data. The following conclusions can be drawn:

1. Evapotranspiration at the experimental site is nearly equal to the equilibrium rate when soil water is felt not to be limiting. Calculated daily values of LE/R_n were slightly lower than those associated with equilibrium rates even for fine days following rain, and it is seen from the diurnal trend in LE that there appears to be a restriction to transpiration in the afternoon period. This reduction may be the result of low hydraulic conductivity near the roots preventing the mid-afternoon peak in LE observed at Haney. While it appears that the equilibrium rate would be a good estimate of evapotranspiration when the soil is completely saturated, these results

suggest that it may slightly overestimate the true value even at matric potentials as high as -0.5 bar if the soil displays poor water retention characteristics.

2. The ratio LE/R_n decreases to approximately half its maximum value as ψ_m decreases to -10 bars at this site. The relationship between LE/R_n provides a simple approach to estimating evapotranspiration from a water stressed forest using only daily values of R_n and ψ_m. The dependence of LE/R_n on R_n itself is felt to be of lesser importance when estimating evapotranspiration over the long term. The relationship of LE/R_n to such factors as species, soil type, physiology and macro-climate has yet to be determined.

3. The decrease in LE/R_n for the experimental site appears to be immediate following a drop in ψ_m from saturation. Evapotranspiration appears to be more sensitive to a given change in matric potential at the wet end of the range than at the dry end. While the soil is at high ψ_m, changes in soil water storage account for the daily

average evapotranspiration rates reasonably well. However, at low ψ_m evapotranspiration continues at a rate higher than that reflected in the soil water storage change, indicating a source of water that is released only when soil water is not adequate. While some upward flow of water from below the root zone is in evidence from matric potential gradients, it is believed that release of water stored within the tree stems will primarily account for the continuing evapotranspiration under fairly extreme drying conditions.

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APPENDIX I

Date 1974	R_n (mm)	LE (mm)	LE/R_n	ψ_m (bars)
June 17	7.03	2.69	.38	-5.8
18	7.27	2.62	.36	-6.5
19	7.29	2.99	.41	-7.3
20	7.41	2.45	.33	-7.4
21	4.69	1.50	.32	-7.6
22	6.57	2.04	.31	-8.1
23	5.44	1.69	.31	-8.3
24	***	***	***	-8.4
25	6.49	1.78	.27	-8.7
26	0.97	0.27	.28	-9.4
27	4.66	1.33	.28	-9.3
28	2.84	0.80	.28	-9.4
29	1.92	0.55	.28	-9.3
30	3.43	0.98	.28	-9.3
July 1	3.73	1.05	.28	-9.5
2	5.58	1.56	.28	-9.6
3	4.28	1.16	.27	-9.9
4	4.73	1.28	.27	-10.1
5	7.40	2.00	.27	-10.1
6	7.38	1.96	.26	-10.3
7	6.87	1.79	.26	-10.4
8	6.75	1.74	.26	-10.5
9	1.23	0.32	.26	-10.6
10	1.76	0.45	.25	-10.8
11	4.60	1.38	.30	-8.8
12	3.40	1.09	.32	-7.6
13	6.61	2.38	.26	-6.1
14	5.62	2.19	.39	-4.9
15	3.03	1.27	.42	-3.9
16	0.84	0.36	.43	-3.4
17	3.97	2.38	.60	-0.1
18	3.72	2.22	.59	-0.2
19	6.54	3.55	.54	-0.2
20	6.55	3.83	.58	-0.3
21	3.32	1.94	.58	-0.3
22	3.69	2.14	.58	-0.3
23	4.99	2.89	.58	-0.4
24	5.65	3.14	.55	-0.4
25	5.66	3.31	.58	-0.7

Date 1974	R_n (mm)	LE (mm)	LE/R_n	ψ_m (bars)
July 26	5.69	3.07	.54	-0.9
27	5.77	3.12	.54	-0.9
28	5.67	3.00	.53	-1.0
29	5.96	3.16	.53	-1.1
30	5.39	2.80	.52	-1.3
31	5.82	2.73	.47	-2.3
Aug. 1	6.29	2.92	.46	-2.4
2	6.51	2.98	.46	-2.7
3	6.49	2.75	.42	-3.0
4	6.44	2.84	.44	-3.2
5	5.99	2.55	.42	-3.6
6	6.00	2.46	.41	-4.2
7	6.27	2.51	.40	-4.6
8	6.26	2.31	.37	-5.0
9	6.11	2.29	.37	-5.4
10	5.68	2.04	.36	-6.1
11	5.52	1.88	.34	-6.7
12	6.03	1.99	.33	-7.1
13	6.23	2.03	.32	-7.5
14	2.08	0.66	.31	-7.9

APPENDIX II

Water Balance Data
Daily averages given in mm

Period	P	E	Δθ	Residual
June 20- June 26	0.00	1.50	-0.90	-0.60
June 26- July 5	1.19	1.19	0.00	0.00
July 5- July 14	5.50	1.48	3.27	0.75
July 14- July 17	12.33	1.34	14.80	-3.81
July 17- July 22	0.80	2.74	-7.32	5.38
July 22- July 28	0.00	3.09	-2.60	-0.49
July 28- Aug. 4	0.00	2.88	-2.14	-0.74
Aug. 4- Aug. 14	0.00	2.07	-0.90	-1.17