

Energy flux studies in a coniferous forest ecosystem

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Abstract

The fluxes of thermal energy between the atmosphere and a young Douglas-fir forest were measured during two contrasting summer days, one cloudless and one overcast. The energy budget components were evaluated by the Bowen ratio method, with ceramic-wick psychrometers at the 26.16 m, 28.16 m, or 31.16 m levels. The maximum height of the tallest trees was 28 m, and the general level at the top of the closed canopy was about 22 m. Daily totals of the energy budget components (cal/cm^2) under cloudless skies on July 29, 1971, were: solar radiation, 584; net radiation, 410; change in storage, 5; convection, -135; and latent energy, -280. The albedo was 0.09 on both the clear and the overcast day. Analysis of the overcast conditions of July 31, 1971, yielded the following values: solar radiation, 171; net radiation, 134; change in storage, 6; convection, -39; and latent energy, -102.

Problems of measurement and analysis are discussed. These include the storage term in the biomass, and the small gradients of potential temperature and vapor pressure above the canopy. Clear day gradients at noon, for example, were in the order of $-0.03^\circ\text{C m}^{-1}$ and -0.03 mb m^{-1} . Techniques are presented for minimizing measurement errors.

Introduction

The level of biological activity at the surface of the earth is closely associated with cycles of energy and mass. The cycles of mass and of energy are virtually interchangeable concepts. Indeed, the transpiration and photosynthetic components of the mass cycle can be studied through examination of the cycle of energy, with the energy required to change the phase of H_2O and CO_2 serving as the connecting link.

The magnitudes and phase relationships of the mass and energy cycles are affected by the characteristics of the surface, and by the state of the atmosphere. The properties of vegetation, particularly of low, cultivated ecosystems, have been investigated thoroughly in a variety of studies that have clearly demonstrated many advantages for energy budget evaluations of transpiration and photosyn-

thesis (Baumgartner 1965). The advantages include sensitivity, mobility, and the benefits to be gained by use of a nondestructive technique. The application of these techniques to the forest ecosystem appears feasible and useful. A number of studies have already been reported, but in general the effects of forests upon the cycles are not yet well known (Baumgartner 1971, Tajchman 1971). Coniferous forests, as a class, are good absorbers of solar radiation. The roughness of coniferous crowns also appears to effectively enhance mixing in the atmosphere near the top of the canopy. These factors, combined with the large surface area of canopies, make forests into very efficient exchange surfaces for water vapor, carbon dioxide, and energy.

Studies of the fundamental cycles of energy and mass have begun at the Cedar River site in the Coniferous Forest Biome. A variety of interrelated studies are planned in coopera-

tion with physiologists, soil scientists, hydrologists, and meteorologists. The work reported here is of preliminary research into the exchange of thermal energy between a young Douglas-fir forest and the atmosphere. The energy exchange processes have been evaluated during two contrasting conditions: the first during clear, warm weather characterized by a large energy input to the forest, and the second during cool, overcast conditions with a relatively small energy input to the forest. The objectives are to define the energy transfer characteristics of the young forest under conditions of both high and low rates of transpiration. Study of these contrasting conditions will help us to understand the processes that control the exchange of energy and water vapor between the forest canopy and the atmosphere.

Experimental Methods

The evaluation of thermal energy exchange in the forest is simple in concept, requiring that appropriate boundaries be defined about the forest site, that the quantities of energy crossing the boundaries be identified, and that appropriate measurements be made at periodic intervals. The periodic samples can then be combined to yield estimates of energy exchange for the desired time interval. The selection of an appropriate model is an important step in evaluating the thermal energy exchange.

Energy Transfer Models

Several review articles have discussed the application of various energy transfer models to the problem of evaluating the exchange between the forest and the atmosphere (Baumgartner 1965, Federer 1970, Fritschen 1970).

The basic problem concerns the transformation of energy by the forest from radiant to nonradiant forms. The total energy thus transformed is called net radiation, Q^* ; this equals the quantity of radiation of all wavelengths absorbed at the surface, minus the radiation lost by reflection and emission. The

net radiation is transformed into either a change in stored heat in the soil and biomass, G ; a flow of convective (sensible) energy between the forest and the air, H ; or a flow of latent heat, λE , that is associated with a flux of water vapor E . The amount of energy transformed in photosynthesis, P , is of great importance in productivity. However, since it amounts to only a few percent in terms of the net radiation flux over the forest (Denmead 1969), P will be neglected in this study.

The rate and direction of energy transfer depends upon the relative energy states of the canopy and the atmosphere and upon the availability of radiant energy which is derived primarily from the sun. The state of energy is determined by temperature and by vapor concentrations. Motion of the atmosphere may also enhance energy transfer. Energy transfer models thus use measurements of temperature, vapor concentration, wind, and radiant energy in order to determine the flow of energy between the forest and the atmosphere.

The "Bowen ratio" model was selected for use in this study because of relative simplicity in analysis and application, and because of its general acceptance based upon tests over other types of vegetation. The method was first derived by Bowen (1926), and has been adapted for energy transfer studies by a number of workers (Fritschen 1965, Tanner 1960).

The Bowen ratio model has been thoroughly described elsewhere, but a short discussion here will help to place its application into perspective. First, we must sum the thermal energy fluxes active in the forest in accordance with the principle of conservation of energy, to obtain

$$Q^* + G + H + \lambda E + P = 0. \quad (1)$$

The polarity convention considers fluxes to the surface as positive. After neglecting photosynthesis, equation 1 can be solved for latent energy to yield

$$\lambda E = -(Q^* + G) / (1 + \beta) \quad (2)$$

where β is the Bowen ratio of convective heat to latent heat ($H/\lambda E$). The Bowen ratio can be written

$$\beta = H / \lambda E = \gamma \Delta\theta / \Delta e \quad (3)$$

where γ is the psychrometric constant ($\gamma \approx 0.66$ mb/ $^{\circ}$ C at sea level) and $\Delta\theta$ and Δe represent the measured differences in potential temperature and in vapor pressure at two levels in the atmosphere above, but near, the surface.

The Bowen ratio model thus provides a rationale for partitioning the measured supply of thermal energy into convection and latent heat, based upon measurements of temperature and vapor concentration at only two levels above the canopy surface. Wind measurements are not required for the analysis, although they are often useful in interpretation of the results. The supply of thermal energy ($Q^* + G$) is measured, so limits are placed on the estimates of convection and latent heat with this method.

The disadvantages of the model are primarily associated with instrumentation; accurate measurements are required in order to measure the small gradients in temperature and vapor found near the forest canopy. In addition, the basic relationship in equation 2 becomes undefined whenever $\beta = -1$. This normally occurs infrequently, and ordinarily only for short periods near dawn or dusk when the amount of available energy is limited. The magnitude of H and λE will normally be small at such times.

Site Conditions

The energy exchange studies were carried out in the broad, flat valley of the Cedar River, near Seattle, Washington. The soil and stand conditions have been described by Fritschen (1972). The stand is second-growth Douglas-fir approximately 35 years old, with an average of 570 trees per ha. The stand canopy is relatively level; the height of the tips of the tallest trees in the vicinity of the experimental site is about 28 m. The site is adjacent to the lysimeter tree described by Fritschen (1972). A series of energy transfer studies are planned at this site in the future, using the lysimeter tree, meteorological towers, and a variety of models for evaluating energy exchange processes.

Field Measurements

Net radiation, stored heat, and temperature and vapor pressure measurements were obtained with a mobile data acquisition that has been described by Gay.¹ The truck-mounted system includes sensors and supports, cabling, and a digital data logger with resolution of 0.001 percent (0.1 microvolt on a 10 millivolt scale). Ceramic wick, wet-bulb psychrometers of the basic design of Lourence and Pruitt (1969), as modified by Gay (n.d.), were used for the temperature and vapor pressure measurements.

The sensors were mounted on a 33.5 m (110 ft) tall, triangular TV tower about 0.3 m (1 foot) in width. Wind, temperature, and vapor pressure measurements were made at six levels, respectively, 26.16, 27.16, 28.16, 29.16, 30.16, and 31.16 m above the forest floor. The radiation budget components were measured from a height of 30.66 m above the floor. The tip of the tallest tree in the vicinity of the tower extended to 28 m, though the bulk of the crowns were below 24 m, and the general level of crown closure was about 20 to 22 m above the floor. Five soil heat flux disks were installed at the -2 cm level, just beneath the surface of mineral soil on the forest floor.

Observations began on July 27 and continued through August 1. The sensors were sampled at 5-minute intervals during the day, and at 10-minute intervals at night. The observation period spanned a range of weather conditions that included one clear and one completely overcast day. The data acquisition system performed well during this period.

Problems in Forest Energy Budget Analyses

A variety of measurement problems are encountered in energy budget studies. In addition, forests have unique characteristics of scale and mass that affect the application of

¹L. W. Gay. An environmental data acquisition system. National Conference on the Forest, Weather, and Associated Environment, Atlanta, Georgia, May 18-19, 1971. Mimeo., 8 p. Abstracted: Bull. Am. Meteor. Soc. 52: 202-203.

the basic energy budget model given in equation 2. The gradients of temperature and vapor above the rough, porous forest canopy are very slight, and measurement difficulties increase with small gradients. Another major problem is related to the difficulty of measuring changes in stored energy in the biomass of the forest. These problems will be placed into perspective at the Cedar River site, for they affect the analyses and the subsequent interpretation of the results.

Evaluation of Gradients

Gradients of temperature, vapor concentration, and wind are small above forest canopies, even though the transfer of energy and mass may be proceeding at high rates. The small gradients result from mixing induced by the mechanical turbulence created by the rough canopy surface. In addition, the exchange surfaces are distributed through a considerable canopy depth so that the sources of heat and vapor are diffuse, rather than being concentrated as in the dense canopies of crops or other low vegetation. The small gradients above the forest require that extreme care be taken in the development of suitable instrumentation, and in the experimental design controlling the deployment of sensors.

The Bowen ratio model assumed that steady state conditions prevail, i.e., the values of the variables do not change with respect to time during the period of analysis. This is partially satisfied by averaging the values over the period of an hour before applying the model. Integration into hourly means also reduces the small random component of error associated with the measurements. It does not, however, reduce biases that are introduced by small differences among sensors. Such biases can be a source of serious error, particularly with small gradients that exist above the forest. Bias errors must be handled by techniques other than averaging.

Two approaches have been used to cope with the problems involved in the measurement of small gradients above forests. In the first approach, the two levels of measurement required for the Bowen ratio are separated by

a relatively large distance (10 m) in order to increase the differences that are being measured to a level commensurate with the sensitivity of the data system (Galoux et al. 1967, Storr et al. 1970). In the second, reversing sensors have been used to cancel the effect of any small biases that may exist between sensors (Black and McNaughton 1971).

A large vertical separation of the sensors introduces questions of the representativeness of the measured gradients which should represent the effect of the underlying surface. It is quite possible that a sensor placed 10 m above the canopy may be measuring properties of the atmosphere that are derived from a surface other than the one under investigation. In contrast, a pair of reversing sensors, placed near the canopy, offers an excellent means for evaluating small gradients. However, the reversing mechanism introduces new problems of design for operation and support in tall forests.

A graphical approach was used in this study to minimize sensor errors in the gradient measurements used for the Bowen ratio analysis. Initially, the mean hourly values of potential temperature were plotted against the associated values of vapor pressure to yield 24 plots (1 per hour) for each day, with each plot containing six points (one for each measurement level). The plots will be straight lines if similarity exists between the gradients of potential temperature and vapor concentration, providing there are no errors of measurement (Tanner 1963). Since similarity is an assumption of the Bowen ratio method, these plots were used to separate out the instrument levels that exhibited small offsets throughout the day and to identify those levels appropriate for use in the Bowen ratio analysis.

The similarity plots for July 29 are shown for levels 1, 4, 6 in figure 1A, and for levels 1, 2, 3 on July 31 in figure 1B. The potential temperature (θ) scale on the ordinate differs between the 2 days. The vapor pressure (e) scale is shown in the legend. Note that the plot for each hour has been normalized by subtracting the θ and e value at the bottom level from the observations at each of the other levels. Therefore each plot actually shows the incre-

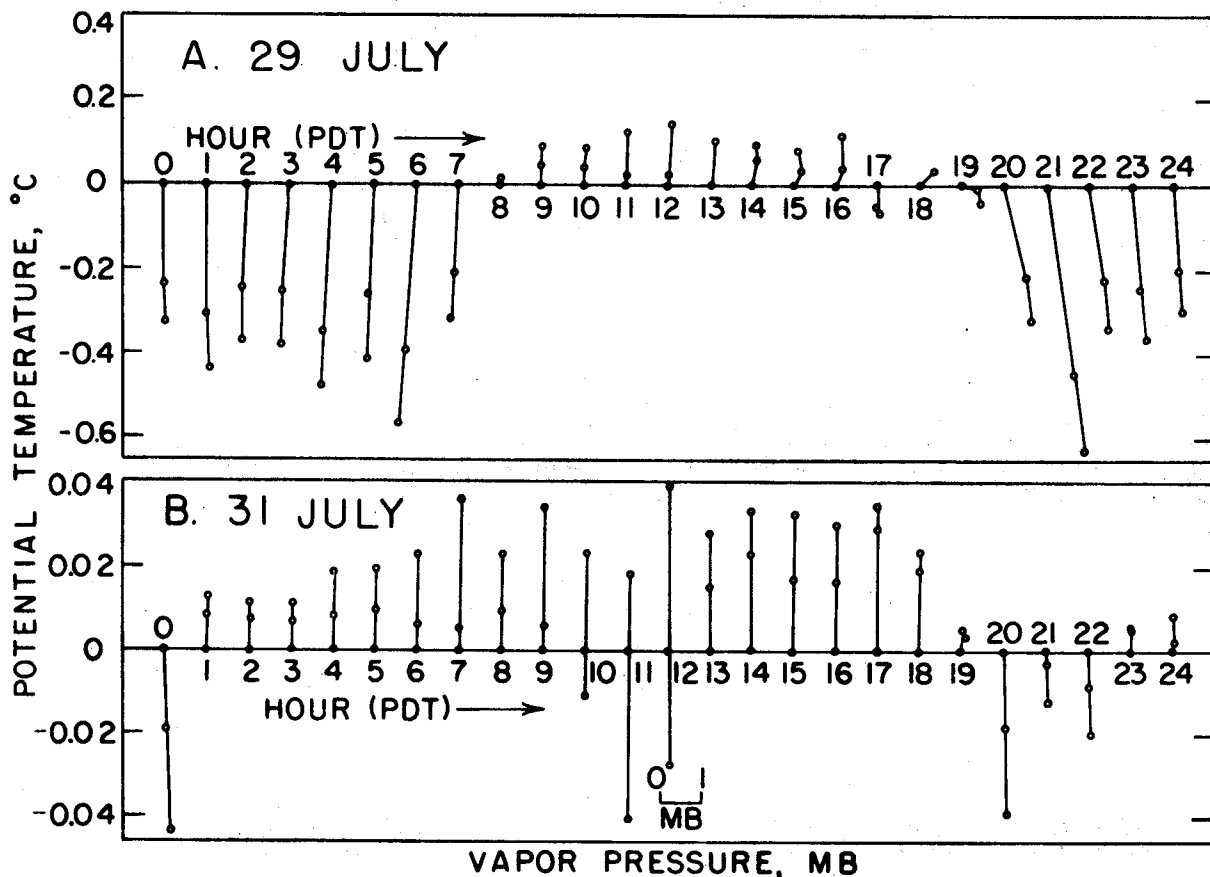


Figure 1. Similarity between gradients of potential temperature and vapor pressure. A. Clear weather on July 29, 1971. Levels 1, 4, and 6. B. Overcast weather on July 31, 1971. Levels 1, 2, and 3.

ment of θ and e with respect to the first measurement level near the canopy.

Though several points can be deduced from such similarity plots, the most important conclusion concerns adequacy of data. The linearity at the selected levels confirms their acceptability for the Bowen ratio model, although an unexplained offset is evident at level 2 during the 1000-1200 hours on July 31.

Once the data is judged acceptable, one notes that the slope of the lines is $\Delta\theta/\Delta e$; this is directly proportional to β , the Bowen ratio, as shown in equation 3. Thus the relative slope of the similarity plots is an index to the way that the surface is partitioning the net energy supply into convection and evaporation. Further, the quadrant of each hourly plot indicates the sign of β , and the direction

of the H and λE fluxes.

For example, as plotted in figure 1A and 1B, both fluxes will have the same sense in quadrants I and III where the slope is positive ($\beta > 0$). In quadrant I, H and λE are both directed away from the surface and are negative by the sign convention adopted earlier. In quadrant III, H and λE are both positive, as their sense is toward the surface. The slope and the β coefficient are negative in quadrants II and IV. In quadrant II, H is toward the surface (advection) while λE is directed away, while the fluxes in quadrant IV have the opposite sense. The similarity plots can thus provide three things: a ready indication of the magnitude of the Bowen ratio; an indication of the direction of the H and E fluxes; and an identification of levels suited for the Bowen ratio analysis.

Evaluation of Stored Heat

Application of the Bowen ratio model to forest measurements reveals a problem in measuring the stored heat term in equation 2 that is a direct consequence of the nature of the forested surface. The scale of the forest elements makes the change in heat storage in the biomass difficult to measure, and many studies (Baumgartner 1956) have treated these changes as negligible. This is certainly true on a daily basis, but an appreciable amount of energy appears to move into storage (-G) in the biomass in the early morning, and out again (+G) in the early evening. These amounts ordinarily will balance when totaled over the day, but comparisons among hourly totals may be in error unless the energy storage changes are estimated for the biomass as well as for the soil.

The estimates of biomass storage change were derived here by an indirect method that may prove useful in other situations as well. First, application of the Bowen ratio model to data collected during the early evening hours frequently resulted in positive estimates of latent energy (condensation) when the vapor gradient clearly indicated that evaporation was taking place. This apparent anomaly in the Bowen ratio estimate of λE could occur as a consequence of underestimating the storage term G. In order to obtain the proper sign on λE under these conditions, the estimate of G must be increased to a positive value that exceeds the absolute value of the negative net radiation.

Estimates of the minimum probable value of G were obtained in this manner for the hours between sunset and the time near midnight when the vapor gradient changed direction, indicating the beginning of condensation. As a second step, the crossover points between release (+G) and uptake (-G) of stored energy were then estimated from my experience and that of others (Grulois 1968) as being about 1 hour after sunrise and 3 hours before sunset. The release of stored heat (+G) is then defined by the two crossover points and by the magnitude during the early evening hours. The third and final step was to estimate the magnitude of the gain in

storage (-G) during the morning hours so that the daily integral approximately balanced. The final result is a much better estimate of hourly changes in stored energy than could be obtained by direct measurement of the soil storage component alone. The magnitude of the stored energy change will be investigated further during future studies.

The major problems in application of the Bowen ratio model to the forest appear to be associated with adequate precision of the measurements. The similarity tests demonstrated here appear useful in eliminating errors from the data. Further, the changes in stored energy can be estimated by an indirect method, based upon gradient measurement and knowledge of the time at which the stored heat flux reverses sign.

The Forest Energy Budget

Energy budget analyses were developed for 2 days that represent quite different amounts of available energy. The solar energy input to the forest was large on July 29, 1971, a day characterized by clear skies and a warm mean temperature (24.4°C). In contrast, July 31, 1971, was completely overcast with reduced levels of incoming solar radiation and a relatively cool mean temperature (17.4°C). Examination of the energy budgets under such contrasting conditions will improve our understanding of the basic processes that govern energy transfer between the forest and the atmosphere.

The diurnal energy budget will first be examined with respect to daily totals; a discussion of the relationships among hourly values of the energy budget components will then follow.

The Diurnal Energy Budget

The daily energy budget totals are presented for the separate periods of daylight (13 hours) and night (11 hours) and for 24-hour totals in table 1. Dividing the daily totals into daylight and night portions enhances future comparisons that may be made with data collected under different daylengths at Cedar River or elsewhere.

Table 1.—Diurnal energy budget components¹

Period	July 29—clear				July 31—overcast			
	Q*	G	H	λE	Q*	G	H	λE
----- cal/cm ² -----								
Daylight	454	-43	-143	-263	141	-7	-38	-96
Night	-44	48	8	-17	-7	13	-1	-6
Daily total	410	5	-135	-280	134	6	-39	-102

¹Totals are given for the daylight hours, 0630-1930 PDT; night hours, 1930-0630 PDT; and the full day, 0000-2400 PDT.

There is a large difference in the radiation supply on the 2 days, as net radiation totaled 410 cal/cm² under the clear skies of July 29, and only 134 cal/cm² for the overcast conditions of July 31. These totals include a steady net loss of radiation at night, amounting to -44 cal/cm² under clear skies, and -7 cal/cm² under the overcast conditions.

The net radiation term represents the energy converted from radiative to nonradiative forms by the forested surface. The short-wave radiation from the sun makes up the largest component of the net radiation. During the 13 hours of daylight on the clear day, the forest received 584 cal/cm² of solar radiation and reflected 55 cal/cm². Under overcast skies, the forest received 171, and reflected 16, calories/cm². The albedo was 0.09 on both days.

Since the gain and loss of longwave radiation also enters into the supply of radiant energy, it is not helpful to calculate a short-wave/net radiation ratio as an index of efficiency of conversion. However, the low albedo value (0.09) emphasizes the efficiency with which the Douglas-fir canopy absorbs solar radiation. This low reflectivity is similar to values reported for other coniferous canopies (Stewart 1971), and is much lower than the 0.2-0.25 albedo values that commonly prevail over crops and other low vegetation (Monteith and Szeicz 1961). As noted by

Baumgartner (1971), forests are effective absorbers of solar radiation.

The changes in stored energy (G) tabulated in table 1 for the 24-hour period are near zero, which is in accord with observations reported elsewhere. This term represents the changes in heat storage of both the biomass and the soil. Most of the storage changes are attributed to the biomass; the indirect methods used² to estimate the changes in storage have been described in an earlier section.

I estimate that -43 cal/cm² went into storage during the daylight hours on the clear day and that 48 cal/cm² came out of storage during the night. The storage changes on the cloudy day proceeded in a similar direction, but the magnitudes were much smaller.

The storage term at Cedar River appears large because of the large quantity of the biomass there. The biomass is as yet unmeasured, however. Attempts will be made to measure the storage flux directly in future experiments.

The convective flux for the clear day totaled -135 cal/cm², directed away from the forest into the atmosphere. A slightly larger amount, -143 cal/cm², was lost during daylight, but 8 cal/cm² was gained by the canopy at night when the canopy temperatures dropped below that of the air. Under overcast sky conditions, -38 cal/cm² were lost over the full day.

Latent energy was the largest dissipation term on each of the days, totaling -280 cal/cm^2 for July 29 and -102 cal/cm^2 on July 31. There was a net loss of latent energy by night, as well as by daylight, for both days. The evaporation equivalent of the latent energy total was about 0.5 cm on July 29, and 0.18 cm on July 31.

The Bowen ratio ($\beta=H/\lambda E$) is a measure of how the surface partitions the energy supply between sensible and latent heat. The mean daily value of β was 0.48 for the clear day, and 0.38 for the overcast day. The difference in β between days is not large, but it suggests that the forest partitioned more of the energy supply into convection on the clear day than on the overcast day. From another viewpoint, the ratio of $\lambda E/Q^*$ was 0.67 on the sunny day, and 0.76 on the overcast day. This is in the direction that one might expect for a stand of vegetation that receives a large input of energy.

Hourly Energy Budgets

The phase relationships among the energy budget components can be examined with the

aid of figure 2 which shows the hourly values on July 29, and figure 3 which shows the hourly values on July 31. Each plotted point represents the midpoint of an hourly mean. The daytime, night and daily totals in table 1 were integrated from the rates shown in these two figures. The 2 days exhibit different characteristics, so they will be discussed separately.

The symmetry of the bell-shaped net radiation curve on July 29 confirms that the skies were cloudless on that day. The maximum intensity occurred during the hour centered on 1300 hours PDT, which closely corresponded with solar noon. The net radiation values became positive about 1 hour after sunrise and remained positive until shortly before sunset, indicating the hours in which there was a surplus of energy that might be dissipated through the other energy budget components. The net radiation was negative throughout the night, as the surface lost energy to the atmosphere. The greatest net radiation loss occurred at 2200, about 1 hour after sunset at a time when the forest was rapidly losing the absorbed solar radiation that had been stored during the day.

The phase of the fluxes is also of interest,

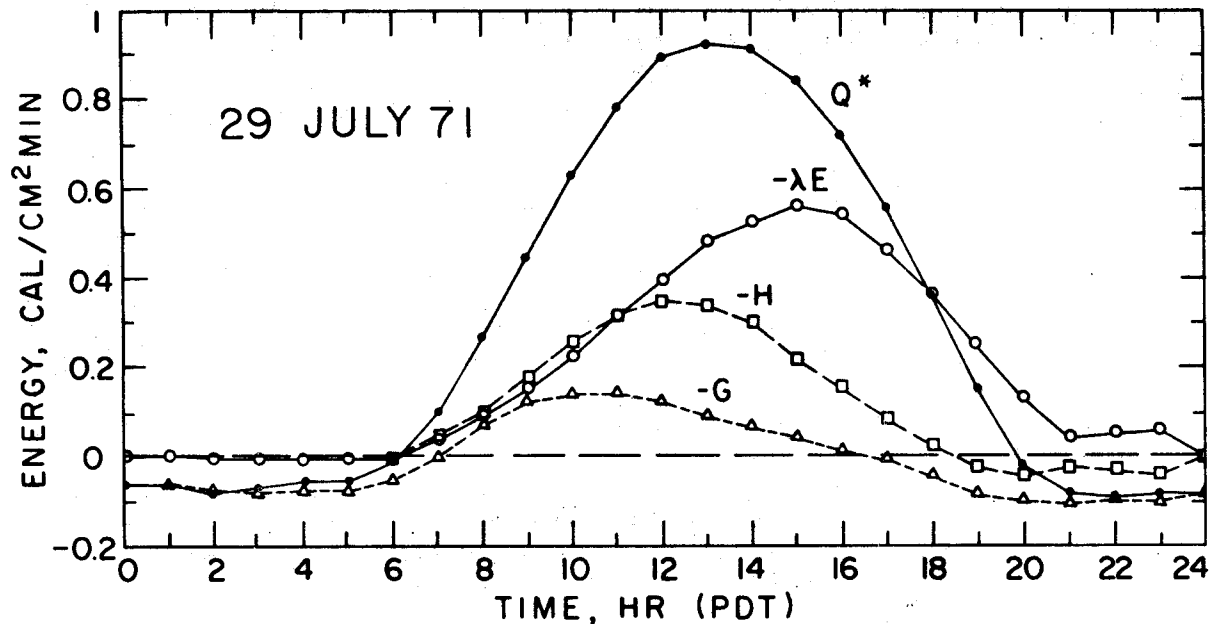


Figure 2. Energy budget components under clear skies. Symbols: net radiation, Q^* ; change in heat storage of soil and biomass, G ; convection, H ; latent energy, λE .

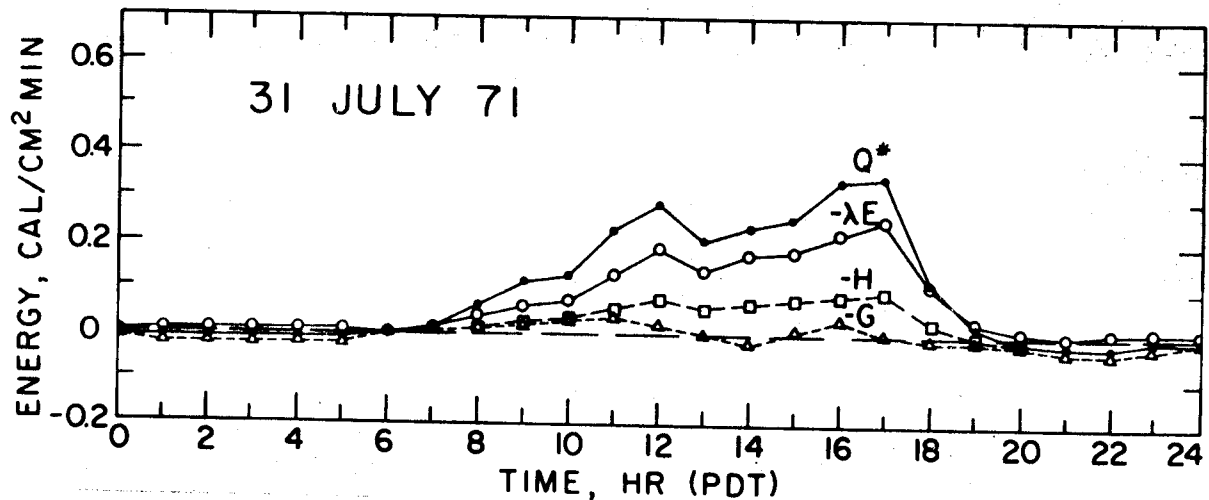


Figure 3. Energy budget components under overcast skies. Symbols: net radiation, Q^* ; change in heat storage of soil and biomass, G ; convection, H ; latent energy, λE .

as G , H , and λE all lag behind Q^* . Let us consider the stored heat flux first. It reaches its peak flow into the biomass and soil ($-G$) in midmorning, and reverses to flow out of the biomass ($+G$) in the late afternoon and early evening. The change in stored heat appears to provide a significant source of energy to the surface throughout the night.

The sensible heat flux, H , reaches its maximum about two hours after G , but still an hour before solar noon. Sensible heat is directed away from the surface during daylight ($-H$), but reverses in direction as convection begins to provide energy ($+H$) to the surface during the night. During this period, the canopy cools below air temperature due to longwave emission.

The latent energy flux reached its maximum about two hours after solar noon. Evaporation continued well into the night; only during the early morning hours did a rather small amount of condensation take place.

The marked phase shift between sensible and latent energy is of interest, as many studies have shown these two fluxes to be in phase with net radiation (Baumgartner 1956, Denmead 1969, Rauner 1960). The Douglas-fir forest, in contrast, partitioned the energy available at the surface into sensible and latent energy on a preferential basis. This partition was on a 1:1 basis during the morn-

ing, but latent energy was apparently favored at the expense of sensible energy during the afternoon. A similar pattern is evident in measurements over a young Douglas-fir forest near Vancouver, B.C. (Black and McNaughton 1971), and over a mixed hardwood forest (Grulois 1968).

The phase shift in latent energy into the afternoon is probably related to a vapor pressure deficit which has an afternoon maximum on clear days. Stewart and Thom² have concluded that the latent energy flux from their pine forest site in England is controlled more by the vapor pressure deficit than by the supply of available energy. This conclusion is based upon their evaluation of the interplay between the relatively large internal resistance to transfer and a small external resistance; the ratio for the pine site was in the order of 20:1.

Conclusions

The observations reported here are an initial contribution toward the problem of evaluating the flow of energy and mass between the atmosphere and the young Douglas-fir forest at the Cedar River site.

²J. B. Stewart and A. S. Thom. Energy budgets in pine forest. Institute of Hydrology, Wallingford, Berkshire, U. K. Unpublished manuscript, 1972.

Forested surfaces are generally considered to be effective energy exchange surfaces. The results confirm that this young stand has a high absorptivity for solar radiation, with an albedo of 0.09 for both clear and overcast conditions. This high absorptivity contributes to the large net radiation values that were measured under clear skies.

The role of the forest in dissipating the net radiation is of particular interest. The porous, aerodynamically rough canopy is effective in transferring sensible and latent energy into the atmosphere. The large quantity of forest biomass may also involve an amount of stored thermal energy that is of significance during short periods, even though the daily totals are small. Summed over a 24-hour period, evapotranspiration was about 280 cal/cm² min (0.5 cm water equivalent) or about two-thirds of the net radiation that was transformed under clear skies. Evapotranspiration was relatively larger on an overcast day, about three-quarters of net radiation, although the total amount of latent energy (102 cal/cm² min, or 0.18 cm water equivalent) was considerably lower.

These results provide initial estimates of the amounts of energy transferred during extreme conditions under cloudless and under overcast skies. The exchange of energy and mass depends not only upon the energy input to the forest, however, but also upon the physiological response of the vegetation. Now that the instrumentation system and the analysis model have been tested at this site, subsequent research will include a range of environmental conditions. Instrumentation development and model testing will continue in cooperation with the lysimeter installation and eddy flux system of cooperating investigators. Ultimately, analysis and interpretation of the energy transfer studies must include physiological as well as physical characteristics of the stand.

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