The Evaporation of Intercepted Rainfall From a Forest Stand: An Analysis by Simulation

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A model of the energy exchange between the atmosphere and a vegetated surface has been developed and used to investigate the sources of energy available for evaporation of precipitation intercepted by a forest canopy. Simulations with this model have demonstrated that a forest canopy wetted by rainfall will partition more of the absorbed radiant energy into latent heat exchange than an unwetted canopy in the same environment. This energy diversion creates a decrease in sensible heat transfer from the canopy to the atmosphere and a smaller decrease in a long-wave radiation emitted by the canopy.

Although both evapotranspiration and the evaporation of intercepted precipitation are evaporative losses, they have generally been expressed as separate terms in the hydrologic cycle because they were believed to be independent of each other. However, this concept of mutual independence has been disputed. Because evaporation is an energy dependent process and the amount of energy available for evaporation in a particular environment is limited, some investigators suggested that energy used to evaporate intercepted water must necessarily come from that which would have been used for evapotranspiration [*Leyton and Carlisle*, 1959; *Penman*, 1963].

Since this idea was first put forth, two prevailing schools of thought have developed about the role that interception plays in the hydrologic cycle. The first school suggests that the amount of energy available for evaporation under a given set of environmental conditions is a constant fraction of solar radiation, represented by the potential evaporation [*Leyton and Carlisle*, 1959; *McMillan and Burgy*, 1960; *Penman*, 1963]. Accordingly, energy used to evaporate intercepted water would not be available for evapotranspiration or the depletion of soil water. Thus this school suggests that interception loss compensates for transpiration that would have occurred and is not a loss beyond the normal evapotranspiration.

While this line of reasoning was gathering support, some experimental results indicated that evapotranspiration from unwetted forest trees was less than the total evaporation from wetted trees under similar conditions. In England, *Rutter* [1959] found that the weight of cut, wet branches decreased much faster than the weight of transpiring branches. In Germany, *Frankenberger* [1960], using turbulent transfer methods, found a total evaporation from tree stands immediately after a rain greater than that from the same stands after the foliage had dried. Later in the United States a number of experiments demonstrated that interception on tree seedlings causes only a small compensatory decrease in evapotranspiration, averaging around 10% [*Shindel*, 1963; *Harr*, 1966; *Thorud*, 1967; *Nicolson et al.*, 1968]. Lysimeter experiments by *Waggoner et al.* [1969] also have shown a total evaporation rate from a corn crop much greater immediately after wetting by spray irrigation than before wetting.

From this experimental evidence a second school has developed that although it agrees that evaporation is an energy dependent process, does not agree with the hypothesis that the amount of energy available for evaporation is fixed in a particular environment. This group of investigators believes that more energy is available for evaporation from a wet plant stand than is available from a dry plant stand under similar environmental conditions. The source of the added energy has generally been assumed to be a different allocation of the radiant input to the stand at the expense of other stand energy budget terms. However, the physical basis for this energy allocation has not been clearly defined.

We have investigated interception by developing a simulation model for the interacting physical processes that supply the energy for evaporation of the intercepted precipitation. The development of the physical basis for this model and a discussion and interpretation of some simulations with the model are the objectives of this paper. We hope that they may help to resolve some of the controversy concerning the role of interception as an evaporative process.

MODELING THE STAND ENERGY BALANCE

For simplicity, the stand that we shall model is of homogeneous vegetation with a closed canopy. We shall also assume that the stand is of large areal extent. Under these conditions, energy fluxes move primarily in the vertical direction. This allows us to look at the stand in one spatial dimension. In this 'height' dimension the upper and lower boundaries of the stand can conveniently be placed in the upper portion of the aerodynamic boundary layer and at the soil surface. Boundary conditions at the upper, atmospheric boundary are assumed to characterize the environment imposed on the stand by the prevailing synoptic and mesoscale meteorological systems.

The lower boundary (at the soil surface) is convenient because it excludes the soil, which has a large thermal lag. When the soil surface conditions are given as boundary conditions, it is possible to treat the stand as a steady state energy exchange system.

Within these boundaries it is desirable to divide the system into regions where the mechanisms for energy exchange processes are similar. Within and above a forest stand there are four such regions: (1) the aerodynamic boundary layer above the stand, (2) the canopy air space, (3) the leaf surfaces, and (4) the litter surface.

In the aerodynamic boundary layer above the stand the transfers of sensible and latent heat (evaporation) are carried on by turbulent eddies that are a product of the interaction of the momentum and heat exchange between the atmosphere and the plant canopy. Sensible and latent heat are moved

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through the stand air space by the same type of turbulent diffusion. However, the presence of sinks and sources for sensible heat and momentum in the stand space complicate the description of the turbulent fluxes within this region.

The remaining two regions are surfaces where the incoming radiant heat load is partitioned between reradiation, sensible heat flux, and latent heat flux. The leaves, other vegetative elements, and litter elements exchange latent and sensible heat through an aerodynamic boundary layer that forms near their surfaces. This boundary layer can be entirely laminar or can change to a turbulent boundary layer at some point downwind of the leading edge of the object.

The physical processes that must be considered in each of the four regions of the stand are summarized in Figure 1. The boundary conditions indicate the input information required by the model.

Previously, the one-dimensional model was developed by *Waggoner and Reifsnyder* [1968] for partitioning the measured (or estimated) net radiation within a plant canopy between sensible and latent heat exchange. However, to evaluate adequately the canopy energy balance under interception conditions, we found it necessary to utilize a model that predicted net radiation by calculating the radiation exchange within the vegetation. In addition, the model has been coupled to the atmospheric boundary layer processes to facilitate using synoptic weather information as input at the upper boundary Greater detail concerning methods for implementing the model can be found in papers by *Murphy and Knoerr* [1970, 1972]. A model similar to ours has also been proposed by *Steward and Lemon* [1969].

The set of equations that must be solved to simulate the stand energy balance can be divided into the diffusion equations for turbulent transfer of sensible and latent heat, the radiation flux divergence equations, and the surface energy balance equations. Each of these equations also demands a number of auxiliary equations to provide a closed set for which a unique solution can be found.

Turbulent transfer processes. The diffusion equations for the one-dimensional steady state case are

$$\rho c_p \, d/dz \, (K_h \, d\theta/dz) + S_h = 0 \qquad (1)$$

$$\rho L_t \, d/dz \, (K_w \, dq/dz) + S_w = 0 \qquad (2)$$

where

ρ density of air;
c_p specific heat of air at constant pressure;
L_t latent heat of vaporization for water;
θ potential temperature;
q specific humidity;
z height above ground;
S_h source strength for sensible heat;
S_w source strength for latent heat.

The values of the turbulent diffusivities for sensible (K_h) and latent (K_w) heat are derived from steady state, one-dimensional, turbulent, wind profile theory. They are generally assumed to be related to the turbulent diffusivity for momentum, K_m, which is defined as the proportionality constant relating the shear at the surface τ to the wind gradient du/dz:

$$\tau/\rho = u_*^2 = K_m \, du/dz \qquad (3)$$

For convenience, air density ρ and shearing stress τ are often grouped as a single parameter: the friction velocity u_*, squared.

Above the canopy it is usually assumed that there are no significant sources or sinks for sensible heat, latent heat, or momentum (S_h and $S_w = 0$). On these assumptions the fluxes do not change with height above the surface, and the flux equations can be solved in closed form by integrating between height z_1 and height z_2 to give the wind speed, potential temperature, and specific humidity profiles.

$$u_2 - u_1 = \frac{u_*}{k} \left[\ln \frac{z_2 - d}{z_1 - d} + (\Psi_{m_2} - \Psi_{m_1}) \right] \qquad (4)$$

$$\theta_2 - \theta_1 = \frac{T_*}{k} \left[\ln \frac{z_2 - d}{z_1 - d} + (\Psi_{h_2} + \Psi_{h_1}) \right] \qquad (5)$$

$$T_* = C/u_* \rho c_p$$

$$q_2 - q_1 = \frac{Q_*}{k} \left[\ln \frac{z_2 - d}{z_1 - d} + (\Psi_{w_2} - \Psi_{w_1}) \right] \qquad (6)$$
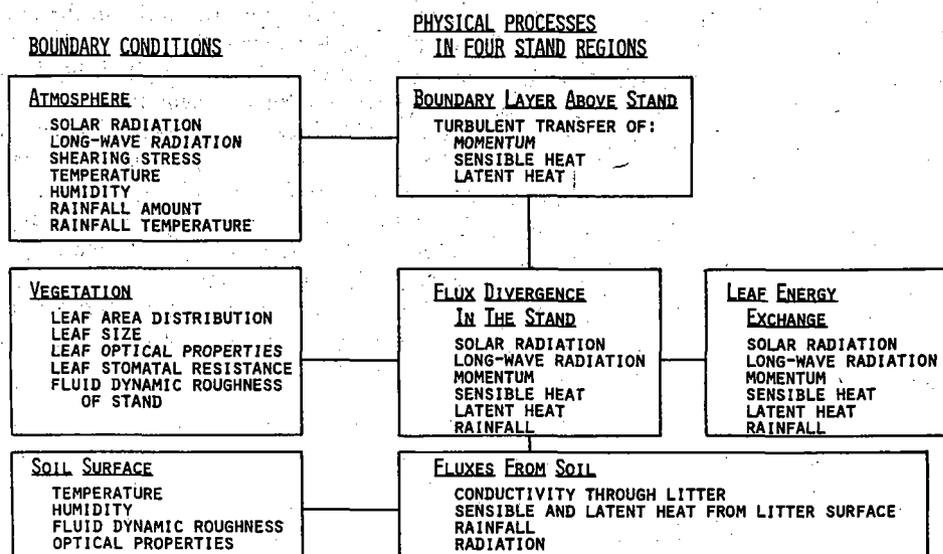
$$Q_* = E/u_* \rho L$$

Fig. 1.   Boundary conditions and energy exchange processes within each canopy region for the model of vegetation energy exchange.

where

k von Kármán's constant, equal to $\simeq 0.4$;
d displacement height of the wind profile;
C sensible heat flux;
E latent heat flux;
Ψ stability corrections for buoyancy effects on the profiles of temperature, humidity, and wind.

Detailed developments of the above relationships are given by *Fleagle and Businger* [1963] and *Lumley and Panofsky* [1964].

The above equations can be solved for the turbulent diffusivities K for the properties being transferred:

$$K_x = u_* k(z - d)/\phi_x \tag{7}$$

where x is equal to m, h, or w and ϕ is the stability correction for buoyancy effects on the gradients of temperature (h), humidity (w), and wind (m), which vary with height above the stand. *Stearns* [1968] has hypothesized that

$$\phi_h = \phi_w = \phi_m{}^{3/2} \tag{8}$$

leading to the relationships between the diffusivities of

$$K_h/K_m = \phi_m{}^{-1/2} \tag{9}$$

$$K_h/K_w = 1 \tag{10}$$

In the stand space the external surfaces of the trees are sources for sensible and latent heat exchange. These stand surfaces are also sinks for momentum. Air flow in the canopy is a complex phenomenon in which the values of the diffusivity for momentum are related to the turbulence produced by the canopy elements and are limited by the distance between these elements.

At this time no satisfactory theory for air movement in a vegetative canopy exists. However, several authors [*Geiger and Amann*, 1937; *Shinn*, 1969; *Allen*, 1967] have demonstrated that most wind profiles in the leafy part of the canopy can be fitted by

$$u_z = u_H \exp [\alpha(z - H)] \tag{11}$$

where H is canopy height and α are extinction coefficients for wind speed.

Furthermore, *Uchijina and Wright* [1964] have shown that the shearing stress in the canopy is related to canopy depth by

$$\tau_z = \tau_H \exp [\beta(z - H)] \tag{12}$$

where β is the extinction coefficient for shearing stress. From the previously given definition of the eddy diffusivity for momentum we have

$$K_m = \frac{\tau/\rho}{du/dz} = K_{m_H} \exp [(\beta - \alpha)(z - H)] \tag{13}$$

In the trunk space it is often assumed that little momentum is extracted by the trunks and that

$$K_m = u_{*_t} kz \tag{14}$$

where u_{*_t} is the friction velocity in the trunk space.

The source strengths for sensible and latent heat can be identified as the fluxes of the quantities moving toward or away from the stand surfaces. For most conditions this is approximated by the fluxes at the leaf surfaces because of the comparatively large amount of area for heat exchange provided by the leaves. The quantities of these fluxes can be determined through the following equations [*Philip*, 1964]:

$$S_h = C_h \, dA/dz \, (T_l - T_a) \tag{15}$$

$$S_w = C_w \, dA/dz \, (q_l - q_a) \tag{16}$$

where

C_h total convective heat transfer coefficient;
C_w total latent heat transfer coefficient;
dA/dz leaf area per unit ground area per unit height;
T_l, q_l values of the temperature and specific humidity of the leaves;
T_a, q_a values of the temperature and specific humidity of the air near the leaves.

The leaf specific humidity is the specific humidity at the wetted surfaces of the leaf, which are the mesophyll cell walls in normal leaves. To a good degree of accuracy this is the saturation specific humidity at leaf temperature.

The transfer coefficients are determined by the path through which the heat must travel to reach the bulk air moving through the stand. For sensible heat transfer the dominant resistance to movement is caused by diffusion through the laminar boundary layer. For the conditions simulated here the boundary layer resistance r_{bl} can be related to wind speed and leaf dimension by [*Murphy*, 1970]

$$r_{bl} = C_l(D/u)^{1/2} \tag{17}$$

where C_l is a constant, equal to about 1.6, and D is the average dimension of the leaf.

Latent heat exchange takes place at the mesophyll cell walls, where the water is evaporated. Water vapor diffusing from the cell walls to the bulk air must pass through the intercellular air space, the stomatal opening, and the leaf boundary layer. The stoma open and close in response to CO_2 concentration, leaf water stress, and light intensity. For the purposes of this paper the tree leaves are assumed to have an adequate water supply, and stomatal resistance is defined as a function of only light intensity. *Gaastra* [1959] has shown that the total leaf resistance of well-watered plants can be related to light intensity by the following equation on the assumption that there is a constant relationship between total solar radiation and the bands to which stoma respond:

$$r_l = r_{l_m} + [\gamma/(S + \beta)] \tag{18}$$

where r_{l_m} is minimum leaf resistance, γ and β are constants, and S is the intensity of solar radiation (cal/cm^2 min).

The total transfer coefficients for tree leaves, which are usually stomated on only one surface, can be expressed as series-parallel combinations of the above resistances.

$$C_h = 2c_p/r_{bl} \tag{19}$$

$$C_w = \rho L_t/(r_{bl} + r_l) \tag{20}$$

Sensible and latent heat exchange from the litter surface can be described by the turbulent transfer equations if the defining depth of the air layer for the temperature and air specific humidity profiles over the litter is large enough that any laminar sublayer will have a negligible effect on the total diffusivity for transfer.

The equations for the turbulent transfer from the litter surface are

$$C = -\rho c_p K_h \, dT/dz \tag{21}$$

$$E = -\rho L_t K_w \, dq/dz \tag{22}$$

These equations are used in the trunk space between the

canopy and the litter surface, where the turbulent transfer fluxes are constant.

Radiation transfer processes. The shortwave (S) and long-wave (L) radiation fluxes received by the vegetation are essentially constant through the depth of the surface boundary layer. The shortwave band includes the solar spectrum, whereas the long-wave band includes wavelengths greater than 4.0 μm and is made up primarily of radiation from terrestrial sources. Their magnitudes are determined by sun-earth geometry, the gross atmospheric temperature profile, and the optical properties of the air mass. For modeling purposes, typical values of these fluxes can be estimated from the climatological data for a particular geographic region and time of year. The total shortwave radiation reflected and long-wave radiation emitted from the vegetation are determined by the radiation flux divergence processes within the canopy.

The divergence of radiations in the canopy is different for the two parts of the spectrum and is controlled by the optical properties of the leaves as well as the equilibrium temperature profile in this region. For some time it has been noticed that the extinction of solar radiation with depth into the canopy was a function of the leaf area above a point or level in the stand [*Kasanga and Monsi*, 1954]. *Duncan et al.* [1967] have related this leaf area to a radiation extinction coefficient for broad-leaf species. The basic equation that they derived is

$$S_z = S_0 \exp [-A(F'/F) \sin (k_l)] \qquad (23)$$

where

S_0 radiation flux reaching the top of the stand;
A leaf area above height z;
F'/F ratio of leaf area to shadow cast; this ratio is a function of the angle between the sun and the leaf;
k_l angle of the leaf from horizontal.

With slight modifications, (23) can be used to determine the fluxes of direct, diffuse, transmitted, and reflected solar radiation. The amount of direct beam radiation absorbed is the amount intercepted S_z times the leaf absorptivity. When the diffuse radiation is calculated, the total hemispherical source for this component must be evaluated. Reflected and transmitted radiation can be estimated by keeping an account of all the radiation reflected and transmitted as it moves through the canopy and is depleted by absorption at the surfaces or escapes back toward the sky.

Long-wave radiation L transfer is complicated by the fact that this radiation is emitted (according to the Stefan-Boltzmann law) as well as absorbed by the canopy elements. For most vegetation surfaces, which have emissivities near unity, the exchange of long-wave radiation between a leaf at any depth in the stand and other leaves, the soil surface, or the sky can be described through the use of view factors and

$$L_n \doteq \sum_j F_{i \to j} \sigma(T_j{}^4 - T_i{}^4) \qquad (24)$$

where

σ Stefan-Boltzmann constant;
T absolute temperature of the material;
L_n net radiation flux between the leaves at height i and their surroundings;
$F_{i \to j}$ view factor of leaves at height i for objects at height j;
T_j temperature of the radiating objects at height j;
T_i temperature of leaves at height i.

By means of the logic that Duncan used to determine the

penetration of light into the canopy the view factor for long-wave radiation is

$$F_{i-j} = \frac{Aj}{A_i} \exp \{ - A_i(F'/F)_i/[2 \sin (k_i)]$$

$$- A_i(F'/F)_i/[2 \sin (k_i)]$$

$$- A_{i-j}(F'/F)_{i-j}/\sin (k_{i-j}) \} \qquad (25)$$

where the subscripts denote the average values for the parameters at heights i and j in the stand and for the layer between i and j ($i - j$). The flux divergence of radiation R in the canopy is then

$$dR/dz = dS/dz + dL/dz \simeq \Delta S/\Delta z + \Delta L/\Delta z \qquad (26)$$

where Δz was a small increment of stand height. Radiation exchange with the litter-covered soil is estimated by making this surface the lower boundary for the radiation flux divergence calculations.

Surface energy balances. The system of predictive equations for our model is closed by coupling the turbulent transfer and radiation flux processes through the energy balances at the leaf and litter surfaces. The leaf energy balance can be written as [*Raschke*, 1956; *Knoerr and Gay*, 1965; *Gates*, 1968]

$$\frac{dS}{dz}\left(\frac{dA}{dz}\right)^{-1} + \frac{dL}{dz}\left(\frac{dA}{dz}\right)^{-1} + C_h(T_l - T_a)$$

$$+ C_w(q_l - q_a) = 0 \qquad (27)$$

using the terms previously defined.

The energy balance for the litter-covered soil is complicated by the small conduction of heat below this surface. Since the litter is a very good insulator, its surface temperature responds quickly to the heat load produced by its environment; that is, it is not strongly coupled to the litter or soil immediately below it and may approach a quasi-steady state situation in relation to the environment. Thus one might be tempted to ignore conduction in modeling this energy balance and to set the lower boundary condition for the system at the litter surface. However, solution of the model with such a boundary condition can produce large (and unrealistic) excursions in litter surface temperature that would be difficult to predict or to control.

To overcome this problem, the lower boundary was assumed to be below a thin layer of litter, and the litter surface temperature was allowed to float in response to the steady state energy balance at this surface by using

$$\frac{dS}{dz} + \frac{dL}{dz} + \rho c_p K_h \frac{\partial \theta}{\partial z} + \rho L K_w \frac{\partial q}{\partial z}$$

$$+ \frac{k_s}{\Delta z}(T_s - T_0) = 0 \qquad (28)$$

where

$\partial \theta / \partial z$, $\partial q / \partial z$ gradient of air potential temperature and specific humidity in the trunk space near the litter surface;
k_s conductivity of the litter for sensible heat;
T_s litter surface temperature;
T_0 temperature at the lower boundary under a shallow layer of litter;
Δz small depth of litter, equal to 1 cm.

Under the conditions that are generally present during rain-

fall the litter surface specific humidity will be the saturation specific humidity at the surface temperature. Otherwise, it will be some fraction of this amount dependent on litter moisture content.

Effect of interception on the energy exchange processes. Physically, interception modifies the stand in two ways. First, the surfaces of the vegetation and the litter are partially or fully covered with a film of water. This film effectively nullifies the internal leaf diffusion resistances for the wetted areas. Second, the raindrops entering the stand have a sensible heat content, part of which may be transferred to the surfaces where they land. The amount of heat transferred will be proportional to the difference between the temperature of the drops and that of the intercepting surface.

Both of these effects can be simulated by modifications to the previously presented equations. The effect of wetting the leaves was produced by setting the leaf resistance to zero for the area of leaf presumed to be wet. For the purpose of the simulations presented here we assumed that the entire upper surface of the leaves was wet, whereas the lower surface remained dry (conditions suggested by observing the wetting of leaves during rainstorms).

The advection of sensible heat by raindrops was simulated by assuming that the initial interception pattern would be identical to the interception pattern for direct beam radiation. The transfer of energy was assumed to occur completely at the leaf that first intercepted the water. The term

$$R_0 = Q_w C_w (T_w - T_l) \tag{29}$$

was added to the leaf energy balance. The volume Q_w, the volumetric heat capacity C_w, and the temperature T_w of the water added to the leaves are the new parameters.

The optical properties of the leaves in the shortwave radiation band are also changed somewhat by wetting. However, at radiation angles less than 60° the reflectivity of a thin water film is less than 0.04, and there is an increase in absorptivity of less than 0.03. This slight increase is caused by the enhanced absorption of water in the near-infrared part of the spectrum [*List*, 1966]. Since these changes are small and are in compensating directions, the optical properties were assumed to be unchanged in the simulations. This assumption is supported by the small change in canopy albedo observed by *Stewart* [1971] after rainfall on a pine plantation. Values of the absorptivities, reflectivities, and transmissivities in the shortwave radiation band were taken from work by *Birkebak and Birkebak* [1964].

Boundary conditions and simulation methods. The foregoing development has defined the set of equations necessary to describe mathematically the stand energy balance with boundary conditions of temperature, humidity, and wind speed in the atmospheric boundary layer above the stand and at the litter surface. These boundary conditions could be replaced by values of latent heat flux, sensible heat flux, and momentum flux. In addition, values for the incoming shortwave and long-wave radiation fluxes and a quantitative description of the stand structure, i.e., leaf area and aerodynamic roughness, must be provided.

The energy balance and the microclimate in the stand were simulated by finding a unique solution for the set of equations developed in the previous section. This was done by arranging the equations so that initial estimates of certain parameters could be used to generate the values of other parameters. This procedure was continued through the given system of equations until new estimates of the parameters were calculated. These new estimates were used to restart the sequence of calculations, which continued until the results of two successive iterations were within an acceptable error.

The sequence used in this simulation began with the calculation of the flux divergence of shortwave radiation (equation (24)), which was not part of the iterative scheme and thus was calculated only once in each simulation. Then an initial estimate of the leaf temperature profile was made by assuming it to be linear with height between the value of the upper air temperature boundary and that of the lower soil surface temperature boundary. Initial estimates of the sensible and latent heat fluxes from the stand were assumed to be zero. Then the wind profile equations (4) and (12) were used to calculate a wind speed profile, and (7), (14), and (15) were used to compute diffusivity profiles. By means of the wind speed and diffusivity profiles in (18), (19), (20), and (21) the air temperature and air humidity profiles were found through (1) and (2). The exact solutions of (1) and (2) were used above the stand (equations (5) and (6)), whereas a numerical integration with respect to height after *Wachspress* [1960] was used within the stand space.

The net long-wave exchange between layers of leaves at different heights in the stand and the sky and ground was found by solving (25) for small but finite layers in the stand. This procedure provided estimates of all the parameters necessary to use (28) and (29) to make new estimates of leaf temperature and litter temperature. New estimates of the sensible and latent heat exchange for the stand were determined by summing (16) and (17) through the canopy and adding the fluxes from the litter. Under most conditions, fewer than 10 iterations were needed to reduce the error in estimating any part of the leaf temperature profile to less than 0.01°C.

RESULTS OF SIMULATIONS WITH THE MODEL

The system of equations was solved for paired sets of conditions. For each pair the boundary conditions were identical except that one solution was made with 'wet' leaves and the other with 'dry' leaves. Figures 2–6 show the stand environments predicted for one pair of simulations. The values of the input parameters used for these solutions are given in Table 1 and below.

Vegetative Parameter	Value
Height, m	31.05
Leaf area, cm²	1.85
Base of canopy, m	9

Leaf Average for Stand	Value
Size, cm	7
Angle, deg	10
Shortwave absorptivity	0.5
Shortwave transmissivity	0.2
Long-wave absorptivity	1.

Aerodynamic Parameter	Value
Zero plane displacement, m	29.08
Roughness length, cm	17
Extinction coefficient	0.0015

The environmental boundary conditions were selected to be similar to those found during periods of rainfall in the southeastern United States. The stand structure and wind profile information was taken from a study of a South Carolina coastal plain hardwood forest reported by *Shinn* [1969].

Figures 2 and 3 show the shortwave radiation, wind, and turbulent diffusivity profiles. These profiles are largely a product of the stand structure. The wind and diffusivity
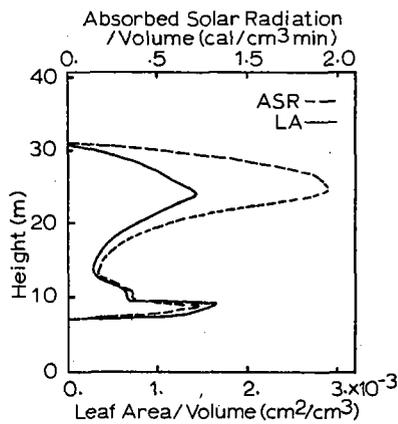
Fig. 2. Vertical distributions of leaf area (one side) *LA* and absorbed shortwave radiation *ASR* per unit of stand depth.

Fig. 4. Energetic source strengths for latent heat (solid lines), sensible heat (dashed lines), and net long-wave radiation (dotted lines) for the two conditions: interception taking place (wet) and interception absent (dry).

profiles were influenced only slightly by the stability correintrons because of the low level of energy exchange during interception conditions.

The source strengths for sensible and latent heat at different heights in the stand are depicted in Figure 4. It is evident that wetting of the stand causes an increase in latent heat exchange in the stand. Furthermore, the reader can see that the increase in energy available for latent heat comes largely from a reduction in the convection of sensible heat from the stand. Figure 4 also illustrates that a small increase of energy available for latent heat exchange is provided by a slight net long-wave radiation gain for the wet stand.

These differences between the wet and the dry stands can be explained in terms of the leaf and air temperature and humidity profiles given in Figures 5 and 6. The temperature profiles indicate that the leaf temperatures are lower when the stand is wet. Although the air temperature is also lower, the net effect is that the leaf temperature is always lowered more than the air temperature. This means that if everything else is constant, there will be less energy moving from the leaves to the air by convection of sensible heat. Furthermore, when the leaf temperature is less than the air temperature, it indicates that energy will be moving from the air to the leaf. The lower leaf temperatures also explain the net long-wave radiation gain, since emission from the leaves is proportional to the fourth power of their absolute temperature.

The effect of interception on the leaf specific humidity profile is somewhat perplexing, since the driving force for latent heat flux decreases when the leaves are wet, but the flux in-
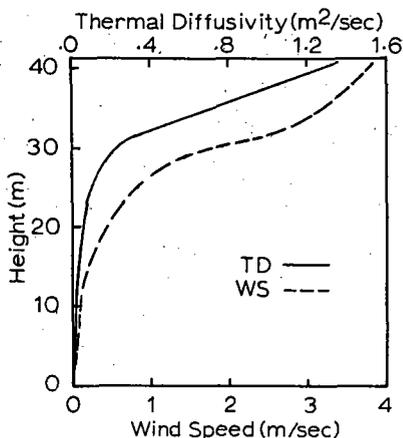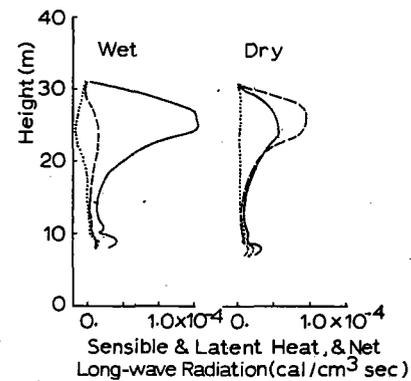
creases. The reason for this apparent inconsistency is that the diffusive resistance for water vapor transport is less for the wet leaf than for the dry leaf. Although the specific humidity at the evaporating surface, which we defined as the saturation specific humidity at leaf temperature, has decreased because of the lower leaf temperature, the evaporation from the wetted leaves takes place from the leaf surface, and the internal leaf resistances are no longer in the diffusion pathway.

The integrated effect of interception on the stand energy balance is an increase in the latent heat exchange at the expense of the long-wave radiation and sensible heat exchange. The amount of increased latent heat exchange depends on the environmental conditions under which the comparison of wet and dry leaf conditions is made. Figures 7 and 8 show ratios of wet to dry evaporation for a variety of environments where the simulations were made by varying the parameters indicated on the figures and leaving the other input parameters as they are listed above and in Table 1. These simulations indicate that evaporation from wet leaves may be from 1½ to more than 2 times the transpiration from dry leaves under similar environmental conditions. Thus interception can only partially compensate for expected transpiration losses.

At this time it is impossible to test rigorously the complete model used for the above calculations. Such a test would involve a very intensive micrometeorological field experiment currently beyond our capability and would require solving the problem of measuring radiation exchange during periods of rainfall. *Stewart and Thom* [1973] have made calculations based on solving for the resistances in the simple Penman-

Fig. 3. Vertical distributions of windspeed *WS* and the turbulent diffusivity for sensible heat transfer, *TD*.
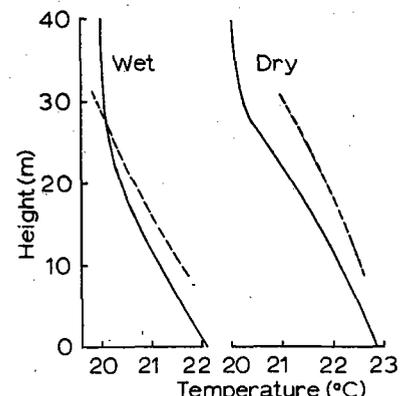

Fig. 5. Leaf temperature (dashed lines) and air temperature (solid lines) profiles for the two conditions: interception taking place (wet) and interception absent (dry).
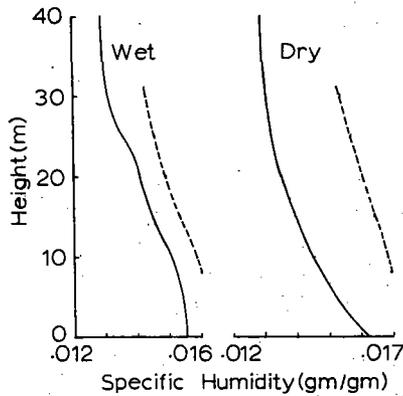
Fig. 6. Leaf specific humidity (dashed lines) and air specific humidity (solid lines) for the two conditions: interception taking place (wet) and interception absent (dry).

Monteith combination equation [*Penman*, 1963], using Bowen ratio data collected during days when interception was not present and assuming that the resistance remained the same during interception conditions except that the surface resistance to evaporation was equal to zero. They predicted ratios of evaporation of intercepted water to transpiration of up to 5:1 under similar environmental radiation supplies and specific humidities. These ratios agree fairly well with the ratios of more than 2:1 calculated by the model presented in this paper.

McNaughton and Black [1973] have made Bowen ratio estimates of evaporation during rainy days. On the basis of their measurements they estimated that the intercepted water evaporated no more than 20% faster than the same amount of transpiration. However, their own measurements indicate that evaporation from the Douglas fir forest is 95% of the predicted free water evaporation on the only day with sufficient rainfall to wet the canopy thoroughly, whereas evaporation averaged 18% of the predicted free water value on all the other days. Thus their measurements also agree reasonably well with the results of our simulations.
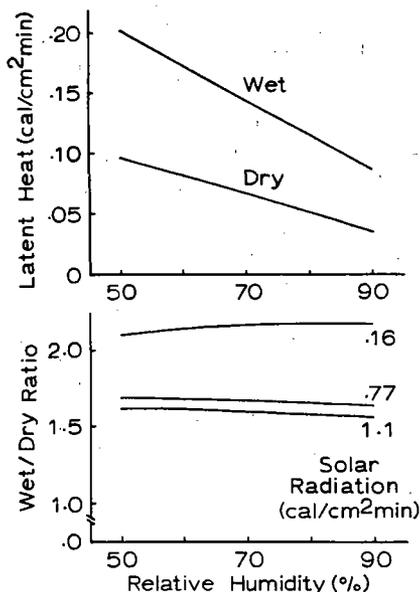

Fig. 7. (Top) Effect of relative humidity on latent heat transfer from wet and dry stands. (Bottom) Effect of relative humidity and solar radiation input on the ratio of latent heat transfer from a wet stand to latent heat transfer from a dry stand.
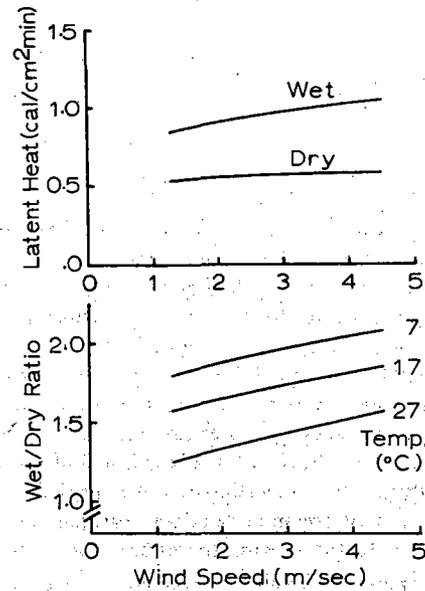

Fig. 8. (Top) Effect of wind speed on latent heat transfer from wet and dry stands. (Bottom) Effect of wind speed and air temperature at the upper boundary (41 m) on the ratio of latent heat transfer from a wet stand to latent heat transfer from a dry stand.

Another test that can be made is a comparison between the evaporation rate during periods of rainfall, as estimated from interception accumulation curves, and the latent heat exchange estimated by the model. *Helvey and Patric* [1965] found that the regression

$$I = 0.083P + 0.036 \text{ (in.)} \qquad (30)$$

would predict cumulative interception I from cumulative rainfall P for a large number of eastern forest stands of deciduous species. The slope of this curve is often assumed to be the interception capacity made available by evaporation during the storm. If we use a moderate rainfall rate of 0.007 cm/min, then the evaporation rate needed to match the above equation will be 0.00058 cm/min, or approximately 0.3 Ly/min. Given the conditions listed above and in Table 1, which were selected to approximate the average conditions during rainfall in the eastern United States, we find that the predicted latent heat exchange is 0.075 Ly/min.

The fact that the predicted latent heat exchange during the rainfall period is less than that predicted by the interception equation should not be surprising. The storage capacity of the canopy for intercepted water is not filled immediately. In fact, it is probably never filled completely for many storms. Therefore the slope of the interception curve is not just the evaporation during the storm but is the evaporation plus the accumulation in the more slowly filled part of storage capacity, such as the bark storage on the tree branches and stems.

TABLE 1. Environmental Parameters

Boundary Values*	Temperature, °C	Relative Humidity, %
41 m	20	90
1 cm	20	95

The shortwave radiation was 0.16 cal/cm² min, the sky temperature was 293°K, and the wind speed at about 41 m was 3 m/s.
*Approximate.

CONCLUSIONS

From this analysis it is clear that precipitation intercepted by vegetation evaporates at a greater rate than transpiration from the same type of vegetation in the same environment. These theoretical results are corroborated by the experimental results of Shindel [1963], Thorud [1967], Harr [1966], Nicolson et al. [1968], Waggoner et al. [1969], and McNaughton and Black [1973] as well as the calculations made by Stewart and Thom [1973], based on the simple combination equation. Our analysis also allows us to identify the energy source for the more rapid evaporation of the intercepted water as being an increase in net radiation through a decreased long-wave reradiation and a decreased or even negative sensible heat flux. Furthermore, the model demonstrates that the enhanced evaporation of intercepted water can occur for forests of large areal extent, where horizontal advection may be negligible. Thus it reaffirms the conclusions from empirical experiments that interception of precipitation does represent a loss of water to the soil and to the streamflow under field conditions.

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