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Evaporation of intercepted precipitation in unlogged and logged forest areas of central Kalimantan, Indonesia

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Abstract The effect of logging practices on rainfall interception loss was monitored for 12 months and related to vegetation and rainfall characteristics at the Wanariset Sangai, Central Kalimantan. The results show that evaporation of intercepted rainfall is higher in the unlogged forest (11% of total gross rainfall) than in the logged forest (6%). These results were closely associated with the reduction in number of trees per hectare from 581 in the unlogged plot to 278 (52%) in the logged plot, or a reduction in terms of basal area from 38.6 to 13.8 m^2 ha^{-1} (65%). The evaporation rate during and after rainfall has ceased, in canopy-saturated conditions, was calculated by an energy balance method, which relied on the modified Penman equation using directly determined microclimatic and canopy structure variables as inputs. The results obtained showed that the evaporation from wet canopies in this research area is driven more by advected energy than by radiative energy. In the unlogged plot, advective energy accounted for 0.38 mm h^{-1} of the 0.50 mm h^{-1} of evaporation, whereas radiative energy accounted for only 0.13 mm h^{-1}.

Key words boundary layer conductance; energy balance equations; evaporation rate; humid tropical rainforest; Indonesia; volume balance method

INTRODUCTION

Evaporation from a wetted vegetated surface is governed by a combination of radiant energy supply, atmospheric humidity deficit, atmospheric turbulence and surface conductance (Monteith & Unsworth, 1990). These variables are the basic inputs to models of vegetation–atmosphere energy exchange and evaporation such as the Penman-Monteith equation (Monteith, 1965), in which temperature and humidity at the evaporating surface are eliminated algebraically in favour of net radiation and a surface conductance, the boundary layer conductance, when the canopy is thoroughly wetted.

The rate of evaporation of intercepted water can be measured directly as a loss of mass, e.g. by weighing (Teklehaimanot & Jarvis, 1991), by an eddy covariance method (e.g. Jensen & Hummelshoj, 1995; Moncrieff *et al.*, 1997), or by calculation using an energy balance method (Monteith, 1965). This paper deals with the calculation of rainfall interception loss using the traditional volume balance method and the energy balance method. The second approach relies on the calculation of evaporation of intercepted water using the modified Penman equation with directly determined microclimate and canopy structure variables controlling evaporation.

EXPERIMENTAL SITE

The experimental site is located in the rainforest area of Central Kalimantan, Indonesia (1°17′46″S and 112° 22′42″E). It lies in the headwaters of the Mentaya River and is a hilly area with altitude ranging from 100 to 300 m above sea level. Slopes are variable but can be as steep as 35°.

The research area is a typical lowland Dipterocarp rainforest in an area of hilly terrain. The average height of the topmost tree layer lies between 40 to 55 m and there is an understorey that usually consists of shrubs of 2–8 m height. The average depth of canopy is about 10 m. The density of trees with a dbh (diameter at breast height) over 10 cm in the unlogged plot is 581 trees ha^{-1}, while in the logged plot there are 278 trees. The basal areas in the unlogged and logged-plots are 38.6 and 13.8 m^2 ha^{-1}, respectively. Logging activities resulted in canopy gaps of about 38% of the total area and reduced the average height of the topmost tree layer to about 20 m.

The climate of this region is determined primarily by the east and west monsoons and by movement of the intertropical convergence zone. The average annual rainfall recorded at the closest national weather station was 2862 mm over 13 years of rainfall measurement (1981–1993). The annual rainfall at the research site is 3563 mm. Most of the rain is convective in origin. Storm sizes can exceed 100 mm on occasions, and rainfall intensities can average 20–25 mm h^{-1} for considerable periods.

CALCULATION PRINCIPLES

Gross rainfall, net rainfall, and interception loss

Gross rainfall was measured using three 0.2-mm tipping bucket raingauges and four simple raingauges, comprising a combination of an 18.3-cm diameter funnel and a 5-dm^3 plastic container. The tipping bucket raingauges were erected at a height of 15 m above the ground surface to reduce disturbance caused by their surrounding environment. The four simple raingauges were installed in a large gap, 1 m above the ground.

In the unlogged plot, throughfall was measured in a 100 × 40 m plot along five parallel transects of 100 m length separated by 10 m. Each transect contained 101 sampling positions at 1 m intervals, giving a total of 505 sampling positions. A total of 50 throughfall gauges were equally distributed in the five transects in which, for each transect, 10 throughfall gauges (a combination of a 5-dm^3 plastic container and a 18.3-cm diameter funnel) were randomly relocated after every rainfall event. In the logged plot, a simple stratified sampling technique was utilized, based on a grid map of canopy cover. This map was produced for a 100 × 100 m plot in which canopy cover was assessed on a three point scale as closed canopy, partial canopy and canopy gap. The grid map of the canopy was produced by dividing the 100 × 100 m plot into 10 × 10 m sections. Each section was further divided into a 5 × 5 m grid for which a gridded map of the canopy was drawn using the three point scale. The distribution of 55 throughfall gauges was based on the proportion of each crown cover in the 1 ha plot.

Stemflow for large trees was collected using composite aluminium flashing material. For small trees, a half-section plastic tube was used as a collar to channel the stemflow water down to a collector. The sampling of trees for stemflow measurement was stratified by taking the size class of the trees in each plot into account. A total of 16 sample trees in five diameter classes scattered within the area of the transect lines were measured in the unlogged plot and 20 sample trees in four diameter classes were measured in the logged plot. Overall interception loss is calculated from the difference between gross rainfall and net rainfall.

Atmospheric variables

Atmospheric variables required for the calculation of evaporation rate of intercepted rainfall were obtained by direct measurements of air temperature, relative humidity, wind speed and direction, quantum flux, and solar radiation. These micrometeorological data were collected at the research sites using two automatic weather stations. One weather station was on top of a 56-m tall tower above the unlogged forest canopy and the other station was located in the canopy gap of a logged forest.

Evaporation rate

The energy available for evaporation, λE_c, is given by (Monteith & Unsworth, 1990):

$$\lambda E_c = [sA + \rho\, c_p\, \{e_s(T_a) - e_a\}/r_a]/[s + \gamma\, \{1 + (r_s/r_a)\}] \tag{1}$$

s = rate of change of the latent heat content with respect to sensible heat content of air (Pa °C);
A = available energy ($R_n - G \cong R_n$) (J m^{-2} s^{-1});
E_c = evaporation rate from the wet canopy (mm s^{-1});
ρ = density of air (kg m^{-3});
c_p = specific heat of air at constant pressure (1010 J kg^{-1} °C^{-1});
$e_s\,(T_a)$ = saturation vapour pressure of water vapour at air temperature (Pa);
e_a = ambient vapour pressure (Pa);
λ = latent heat of vaporization of water (J kg^{-1});
γ = psychrometric constant (Pa °C^{-1});
r_a = aerodynamic transfer resistance (s m^{-1}); and
r_s = stomatal resistance (s m^{-1}).

Equation (1) is generally referred to as the Penman–Monteith equation, and is the basic formula used in simple, one-dimensional single source descriptions of the evaporation process. When the source of water vapour is a completely wet vegetation canopy, the term r_s in equation (1) is zero and the equation reduces to the Penman equation (Monteith & Unsworth, 1990) so that the resultant expression gives the rate of evaporation of intercepted water as follows (Rutter *et al.*, 1975; Jarvis, 1985):

$$\lambda E_c = [s\, R_n + \rho\, c_p \{e_s(T_a) - e_a\}\, g_a]/[(s + \gamma)] \tag{2}$$

where $E_c = I_{storm}/t_{storm} = (P_g - P_n - S)/t_{storm}$. I_{storm} is the interception loss during the storm period and t_{storm} is the duration of the storm. The canopy storage capacity, S, was obtained by separating linear regressions of gross rainfall *vs* throughfall for individual small storms following Lloyd *et al.* (1988). The value of S is given by the slope of the linear regression for zero throughfall.

Boundary layer conductance

The boundary layer conductance, g_a, is the most important property of a forest canopy determining the evaporation of intercepted water (Jarvis & Stewart, 1978; Teklehaimanot & Jarvis, 1991). In this study, g_a was calculated from re-arrangement of the Penman equation (equation 2), given the micrometeorological and evaporation data at the research sites:

$$g_{\mathrm{a}} = [\lambda E_c\,(s + \gamma) - s\,R_n]/[\rho\,c_p\,D_{vp}] \qquad (3)$$

The micrometeorological data and forest canopy properties were collected from November 1993 to April 1994 in the unlogged plot, and from June 1994 to June 1995 in the logged plot, and 32 days of collected data for each plot was used in the analysis.

RESULTS AND DISCUSSION

Evaporation rate

In the unlogged plot, the R_n component of equation (2), i.e. $sR_n/\lambda(s + \gamma)$, allows for mean evaporation during and immediately after rain of only 0.13 mm h^{-1} and varies from 0.06 to 0.2 mm h^{-1}. The result also indicates that a major part of the energy required in evaporating intercepted water is advected, i.e. $c_p\,\rho\,D_{vp}\,g_a/\lambda(s + \gamma)$. The advected energy, especially the interaction of D_{vp} and g_a components, allows for mean evaporation rate during and immediately after rain of about 0.38 mm h^{-1} and varies from 0.01 to 1.0 mm h^{-1}. Thus for a total evaporation rate of 0.50 mm h^{-1} in the unlogged plot, advective energy accounted for 0.38 mm h^{-1}, whereas radiative energy accounted for only 0.13 mm h^{-1}. A similar relationship between the major driving variables for evaporation and the rate of interception loss was also found in the logged plot for all canopy cover areas. In general, in the logged-over area the average evaporation rate accounted for by the advective energy component of evaporation was 0.35 mm h^{-1}, much larger than the evaporation rate accounted for by radiative energy of only 0.11 mm h^{-1}. These findings indicate that logging activities did not result in a great deal of change in the proportion of energy used for evaporation of intercepted rainfall.

Figure 1 shows the proportion of radiative and advective energy used for evaporation of intercepted water in both the unlogged and logged plots. The figure indicates that at low interception loss, or at the beginning of rain, radiation supplied a large proportion of the energy used to evaporate water intercepted on the canopy surface because incoming solar radiation is still an effective supply of energy. However, as interception loss increased, the combination of small r_a and the reduction of incoming solar radiation as a result of increasing cloud makes advective energy the dominant variable for evaporation.

The findings that interception loss is largely influenced more by local advective energy from air passing over the forest canopy and not by radiation confirms previous similar studies in temperate forest (e.g. Stewart, 1977; Singh & Szeicz, 1979; Pearce *et al.*, 1980; Kelliher *et al.*, 1992). Additional evidence indicating that horizontal

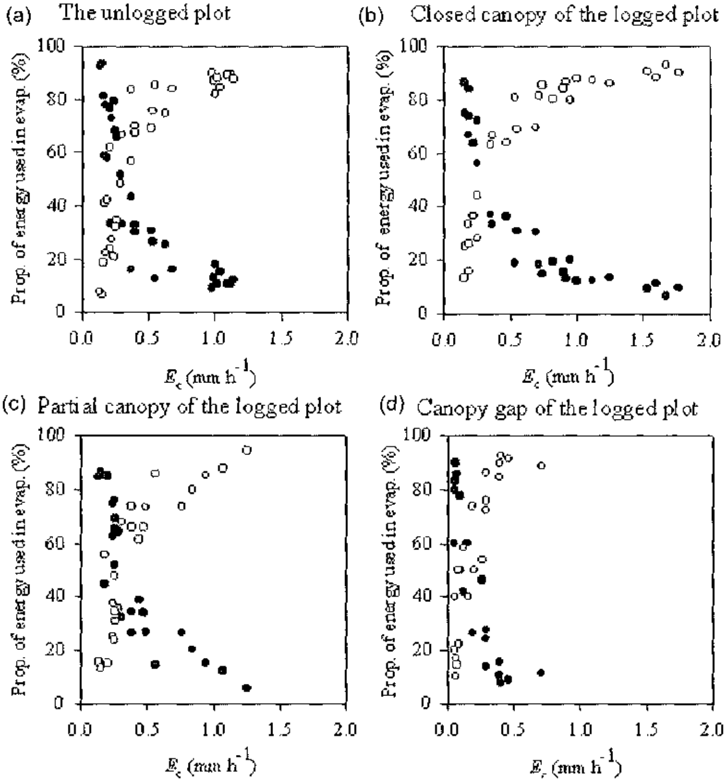

Fig. 1 Relationships between the proportions of radiative (•) and advective energy (o) used for evaporation of intercepted rainfall, E_c, in the unlogged and logged plots. The relationships are on a daily basis (during the rainfall period).

advective energy is an important driving factor for evaporation of intercepted rainfall in this study was that night-time rates of evaporation of intercepted water in the unlogged plot tended to be similar to daytime rates. In the logged plot, the night-time rates were even higher than the daytime rates, indicating that radiative energy is substantially less important than advective energy in determining evaporation rate.

The rate of evaporation in the logged plot was partitioned according to canopy cover conditions resulting from the logging activities. The mean evaporation rate in the closed canopy area was 0.7 mm h^{-1} and varied from 0.15 to 1.77 mm h^{-1}. In the areas of partial canopy and canopy gap, the mean evaporation rates were 0.45 mm h^{-1} (range 0.15 to 1.25 mm h^{-1}) and 0.22 mm h^{-1} (range 0.10 to 0.7 mm h^{-1}), respectively. The overall mean evaporation rate of intercepted water over the 1 ha logged plot was 0.46 mm h^{-1}.

On average, the mean latent heat flux used to evaporate intercepted water was slightly reduced from 328 J m^{-2} s^{-1} in the unlogged plot to 319 J m^{-2} s^{-1} in the logged plot. This reduction can be largely attributed to the reduction of mean latent heat flux to 144 J m^{-2} s^{-1} in the canopy gap area of the logged plot and was mainly caused by the reduction of average R_n from 119 to 55 J m^{-2} s^{-1} and the reduction of average g_a from 0.31 to 0.13 m s^{-1} following logging.

Boundary layer conductance

The boundary layer conductance, g_a, in the unlogged plot was calculated using equation (3) and was found to be 0.31 m s^{-1} (varied from 0.02 to 1.0 m s^{-1}).

In the logged plot, g_a was calculated for the areas of closed canopy, partial canopy and canopy gap. The averages of g_a were 0.29 m s^{-1} (range 0.02 to 0.8 m s^{-1}), 0.18 m s^{-1} (range 0.01 to 0.9 m s^{-1}) and 0.13 m s^{-1} (range 0.01 to 0.6 m s^{-1}), respectively.

Logging activities reduced g_a from 0.3 m s^{-1} in the unlogged plot to 0.2 m s^{-1} in the logged plot. This reduction of g_a leads to the reduction of interception loss from 11% of gross rainfall in the unlogged plot to 6% in the logged plot (Asdak *et al.*, 1998). The reduction of g_a seems to be attributable to the reduction of tree basal area per unit ground area, from 38.6 to 13.8 m^2 ha^{-1}. A similar result was reported from the temperate region, by Teklehaimanot *et al.* (1991) who found that boundary layer conductance per unit area of leaf declined from 0.17 to 0.07 m s^{-1} as the density of trees decreased from 2 m to 8 m spacing. As often reported, the magnitude of g_a is controlled by wind speed, u, and canopy characteristics such as plant density and height, which determine canopy roughness (e.g. Roberts *et al.*, 1993). In this experiment, boundary layer conductance was weakly related to wind speed in both the unlogged and logged plots. However, the physical environmental changes following logging were the variable heights and irregularities of the tree crowns and increase in canopy gaps. Reducing the height of some trees and creating more gaps in the logged forest leads to local variations in foliage density which would allow more wind to penetrate the canopy and, hence, increase turbulent flow. These changes that might tend to increase g_a, and hence the evaporation of intercepted water, seem to be offset by the reduction of canopy storage capacity following logging, resulting in low interception loss, especially in areas where wind speed was also considered to be low as in this research site.

The evaporation of intercepted water from wet canopies over an extensive tropical forest at rapid and consistent rates is likely to be maintained by a combination of the horizontal transport of heat and moisture (local advection) and entrainment processes. The entrainment process is the vertical movement of air from an external pressure gradient, and it involves a downwards heat flux across a stable region (Garrat, 1994). Strong local advection effects may arise in a situation where the surface energy balance is spatially variable (Rider *et al.*, 1963; McNaughton, 1976), as is assumed to be the case in this experimental area.

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