VEGETATION MODIFICATION OF RAINFALL CHARACTERISTICS: IMPLICATIONS FOR RAINFALL EROSIVITY FOLLOWING LOGGING IN SABAH, MALAYSIA

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BROOKS, S.M. & SPENCER, T. 1995. Vegetation modification of rainfall characteristics: implications for rainfall erosivity following logging in Sabah, Malaysia. Modelling soil erosion following forest disturbance requires new data on a variety of parameters which control runoff generation and soil detachment. In the study area, Sabah, East Malaysia, there are no data on rainfall transformation by canopies particularly changing drop size distributions and rainfall kinetic energy at different intensities. Filter paper staining techniques were used to measure rain drop size distributions and calculate rainfall intensity and total kinetic energy for rainstorms under open sky and closed canopy conditions in an area of lowland dipterocarp forest. The results show a positive correlation between median drop size, rainfall intensity and kinetic energy for open sky situations, consistent with studies from elsewhere. Mean drop size for all samples is around 2.2 mm. For closed canopy situations there is no such relationship in rainfall parameters, all drops being around 5.5 mm in diameter regardless of rainfall intensity. With interception losses of 29 % in the study area, the modification to total kinetic energy following forest disturbance can be assessed. The results show that above rainfall intensities of 20 mm h^{-1} open sky rainfall is more erosive than that falling through the canopy. Since most rainstorms are above 20 mm h^{-1}, canopy disturbance is likely to increase erosion rates, and needs to be included when modelling soil erosion. These results provide essential inputs to new physically-based models being applied for the first time to the issue of rain forest logging effects on soil erosion in Sabah.

Key words: Rainfall characteristics - open sky - closed canopy - dipterocarp forest - drop size - kinetic energy - erosivity

BROOKS, S.M., & SPENCER.T. 1995. Pengubahsuaian tumbuhan kerana ciri-ciri curahan hujan: implikasi ke atas hakisan hujan berikutan dengan pembalakan di Sabah, Malaysia. Membuat model hakisan tanah berikutan dengan gangguan hutan memerlukan data baru mengenai pelbagai parameter yang mengawal hasilan larian dan pemisahan tanih. Di kawasan yang dikaji iaitu di Sabah, Malaysia Timur, tiada data mengenai perubahan arahan hujan yang disebabkan oleh sudur, terutamanya taburan saiz titis yang berubah-ubah dan tenaga kinetik hujan pada keamatan yang berbeza. Teknik-teknik pewarnaan kertas turas digunakan untuk mengukur taburan saiz titis hujan dan mengira keamatan curahan hujan dan jumlah tenaga kinetik untuk hujan ribut di kawasan terbuka dan dalam keadaan-keadaan sudur rapat di kawasan hutan pamah dipterokarpa. Hasil-hasil menunjukkan korelasi positif antara median saiz titis, keamatan curahan hujan dan tenaga kinetik untuk keadaan-keadaan terbuka, sejajar dengan kajian-kajian yang lain. Min saiz titis untuk kesemua sampel ialah 2.2 mm. Tiada hubungan yang serupa dalam parameter curahan hujan untuk keadaan-keadaan sudur rapat; kesemua titis mempunyai diameter berukuran lebih kurang 5.5 mm walau apapun keamatan curahan hujan. Pengubahsuaian kepada jumlah tenaga kinetik berikutan dengan gangguan boleh ditaksir dengan kehilangan pintasan sebanyak 29 peratus. Keputusan kajian menunjukkan bahawa keamatan curahan hujan yang melebihi 20 mm j^{-1} curahan hujan kawasan terbuka adalah lebih menghakis daripada curahan hujan melalui sudur. Oleh sebab kebanyakan hujan melebihi 20 mm j^{-1}, gangguan sudur mungkin menambahkan kadar hakisan dan perlu dimasukkan apabila membuat model hakisan tanah. Keputusan-keputusan ini memberikan input penting kepada model-model baru berasaskan fizik yang pertama kali digunakan untuk isu kesan-kesan pembalakan hutan hujan pada hakisan tanih di Sabah.

Introduction

The dynamics of soil erosion processes following natural and anthropogenic disturbance in rain forest catchments form a major research theme, and adopt a variety of approaches. Firstly, enhanced sediment concentrations and discharges in stream channels are being monitored (e.g. Malmer 1990, Douglas *et al.* 1992), and results indicate considerable increases in both parameters following forest disturbance. Secondly, plot-scale experiments allow direct measurement of erosion rates for different types of disturbance in a variety of environments, this being a particularly suitable approach given the diverse conditions in natural and disturbed rain forests (Brooks & Richards 1994). Thirdly, application of models provides a non-destructive technique for assessing erosion mechanisms and predicting erosion rates, as well as allowing the design of forest harvesting strategies which may not lead to accelerated erosion (Brooks *et al.* 1993). The use of models is of particular value in assessing the hydrological consequences of rain forest disturbance, given the comparative inaccessibility of many such areas, and the need to know in advance the likely problems resulting from forest harvesting. However, successful application of models depends on adopting a model structure which is suitable for accurate assessment of the complex controls on soil erosion, as well as having parameters which can be quantified accurately.

Rainfall erosivity is a major control on splash detachment, and depends on rainfall kinetic energy which varies with drop mass and rainfall intensity. Disturbance to rain forest canopies can result in large changes in rainfall erosivity (Brandt 1986). Therefore, physically-based models which are currently being developed and applied to the issue of rain forest logging for Sabah, Malaysia require values for rainfall erosivity, both under natural forest with canopy effects and for open sky situations. However, data relating to changes in rainfall kinetic energy following canopy disturbance do not exist for Sabah, East Malaysia, although data are available for rainfall interception by the canopy (Wong 1991, Sinun *et al.* 1992). To assess fully the impact of forest harvesting on total kinetic energy information on both aspects is required for open sky and closed canopy situations. The aim of this paper is to quantify rainfall energy changes which result from canopy disturbance in Sabah, Malaysia, and to compare them with similar data from other rain forest locations. The results presented in this study form part of a wider programme to consider the erosional impact of forest harvesting through the design and application of physically-based models.

The study site

The Malaysian State of Sabah (area 73 371km) comprises 10 % of the land mass of the island of Borneo. Timber extraction rates in Sabah are among the highest in the tropics due to the suitability of many of the large trees (Dipterocarpaceae) in the region. The area under undisturbed primary rain forest has been reduced from 60.1% in 1986 to 21.6% in 1992 (Marsh & Greer 1992). Annual rainfall totals are high (2822 mm per annum, 1985-1990), although rainfall can be unevenly distributed through the year. Periods of low rainfall occur. There are no data on raindrop size and rainfall energy for the region. Although detailed rainfall data exist for other tropical rain forest locations, including values for rainfall energy modification by canopies of differing structure (Vis 1986, Brandt 1986, 1989), it cannot be assumed that they are applicable to East Malaysia. Especially significant is the relative abundance of the large Dipterocarpaceae in this area, with at least 287 species (Whitmore 1990, Newbery *et al.* 1992). This produces a unique forest structure, with many tall trees and a restricted under-storey layer which allows drops to reach the ground at terminal velocity. This study focuses on the transformation of rainfall characteristics by single-layer rain forest in Sabah and provides new data which are compatible with the needs of physically-based hydrology models currently being developed as part of a larger field programme to assess the impact of commercial logging on runoff generation and soil erosion.

Assessing the effect of canopy removal on rainfall

Several factors combine to change rainfall erosivity following logging. The total volume of water reaching the ground surface is generally increased when trees no longer intercept the falling drops. For undisturbed rain forest in the Danum Valley Conservation Area, Sinun *et al.* (1992) estimated interception loss to be 29.3 %, which is consistent with other studies assessing through fall as a percentage of rainfall (Bruijnzeel 1989). For modelling erosion and runoff a single assumption of an increase in rainfall following logging is an oversimplification. It is important to consider also the transformation of drop sizes by the canopy, the alteration of the velocity at which the drops strike the ground surface and the resulting kinetic energy of the rainfall at different intensities. Kinetic energy per mm of rain is derived from the fall velocity and the mass of the falling drop. Large drops falling at their terminal velocity have more energy than an equivalent volume of rain made up of smaller drops. The forest canopy can either split drops into smaller sizes or can concentrate them into larger sizes as they drip from the ends of leaves and stems (Mosley 1982). Furthermore, drip tip mechanisms in tropical rain forests have been studied by Williamson (1981) and Williamson *et al.* (1983), where it has been suggested that they hasten drainage and so prevent the development of large drops. The processes by which rain drop sizes are transformed are complex (Herwitz 1985), but generally the forest canopy acts to concentrate drops producing significantly larger drop diameters than those occurring under open-sky rain (Wiersum 1983, Vis 1986, Brandt 1989).

Whether natural forests produce rain drops having higher or lower kinetic energy than that of natural rainfall depends on the forest structure. High, single-layer canopies enable large drops to reach terminal velocity (8 m fall required, Laws & Parsons 1943) whereas multiple-layer canopies do not provide sufficient fall height for terminal velocities to be attained. Immediately following logging all rain arriving at the ground surface is travelling at its terminal velocity. Compared with multiple-layer canopies, this will be of higher energy at most intensities. For single-layer canopies where terminal velocities can still be attained, kinetic energy will exceed that of open sky situations even at low intensities. At high rainfall intensities, however, open sky rainfall has larger drops and may therefore have higher kinetic energy compared with rainfall under undisturbed single-layer canopies. Furthermore, since more rain arrives at the ground in the absence of canopy interception, this will also contribute to any increase in rainfall energy following canopy removal. The precise intensity at which the order in the relationship switches is significant to the net effect of canopy removal on erosion, and needs to be derived. Thus in some cases rain forests increase energy compared with open sky rainfall (Vis 1986) whereas in other situations they decrease it (Armstrong *et al.* 1980). Logging also involves different degrees of soil disruption (Brooks *et al.* 1993) which interacts with variation in rain energy to determine runoff volume and erosion rate. As a first step in assessing erosion following logging the energy of open sky rainstorms needs to be quantified for different rainfall intensities and compared with that of undisturbed canopies.

Measurement of rainstorm properties

To assess rainfall erosivity it is necessary to measure the spectrum of drop sizes which occurs at different rainfall intensities. From such data median drop sizes can be found and rainfall kinetic energy and momentum calculated. It has been found that as intensity increases so does median drop size and kinetic energy of open sky rainfall (Brandt 1986). Within primary rain forest drop sizes do not vary with intensity, having their size controlled by the dripping point from which they are delivered to the ground. However, even with a wide variation in drip point characteristics (such as leaf size and shape) median drop size remains around 4.95 mm at a rainfall intensity of 20 mm h^{-1}, and 4.64 mm at an intensity of 60 mm h^{-1}, considerably larger than most drops found in open sky rainfall (Brandt 1989).

Direct measurement of kinetic energy and momentum is highly problematic since sensitive equipment is needed to pick up the small variations in these properties. Wind effects can cause inaccuracy with direct methods. However, several methods are available for measuring drop size distributions, from which energy can be found (Chapman 1948, Hudson 1981, Brandt 1989). The present study follows the paper-staining method used in Brazil by Brandt (1986) as it has been shown to work successfully in tropical locations and presents fewer practical problems than with other methods. It also permits more realistic comparisons between data derived for Manaus, Brazil and those derived for Sabah.

The method involves paper staining by falling drops. Circles of Whatman Number 1 filter paper are brushed with Janus Green dye and held over a desiccating agent until used for measurement. During rainstorms the papers are exposed at intervals, the length of exposure being precisely timed and varied according to rainfall intensity. For each sample the stain diameters are measured to the nearest 0.5 mm and converted to an actual drop size using the calibration equation derived by Brandt (1989) under controlled conditions. The combination of drop volumes measured on the papers and the time of exposure enables intensity to be calculated for each observation. Median drop diameters are also found for each intensity. Total kinetic energy is calculated from the summation of the energy of individual drops. As the density of water is approximately 1 g cm^{-1}, the volume of rain in each size class can be found by multiplying the mass of one drop by the number of drops in the class. The total kinetic energy is then found from the following equation:

$$U_k = \sum_{i=1}^{n} 0.5(0.01a)v_i^2 \text{ in J } (\times 10^{-3}) \text{ per cm rain per cm}^2 \ (= \text{J m}^{-2} \text{ mm}^{-1})$$

where U_k = kinetic energy per centimetre of rain (J)
i = drop size class
n = number of drop size classes
a = percentage of the volume of rain falling in drop size class i
v_i = terminal velocity of the drops in size class i (m s^{-1})

[N.B. The results found using the above equation are equivalent to J m^{-2} mm^{-1} (Vis 1986)].

Rainfall erosivity under open sky and single-layer forest canopy

In this study, two locations were selected for measurement, one under open sky, and the other under single-layer canopy of 50 m in height. In all 34 samples were collected over eight storms. Each sample paper contained ca. 80 drops. For each sample the drop sizes were measured, the median diameters were calculated and the results were plotted as separate histograms for open sky and canopy rainfall (Figure 1). The histogram for open sky rainfall indicates a unimodal distribution, with a slight negative skew which is consistent with results reported by Carter *et al.* (1974) and by Brandt (1989). There is a statistically significant difference between open sky rain and that experienced under the undisturbed canopy (χ^2 test; $p = 0.05$). The concentration of rain on the leaves and branches maintains a more uniform drop size with most drops being between 5 and 5.9 mm, whilst open sky rainfall has a smaller mean drop size of between 1 and 2.9 mm. There is a suggestion that the forest drop distribution is bimodal, with a small secondary mode at 2 mm. This probably relates to rain falling directly through the canopy without being concentrated on the leaves. The canopy concentration produces results in the field which are close to those obtained in the laboratory by Brandt (1989), where drops were measured under controlled conditions for a variety of leaf shapes and sizes. In laboratory research little difference has been found for different leaf configurations, with all drops having a size close to 4.5 mm (Brandt 1989). Values reported by Brandt (1986) for throughfall drop sizes are slightly smaller than those reported in this study, but the agreement is acceptably close, especially when the results of other studies are also taken into account. Vis (1986), for example, presents data which show similar values for mean drop size in Colombian forests, whereas the studies by Chapman (1948), Ovington (1954), as well as Armstrong and Mitchell (1987) indicate smaller mean drop sizes for temperate forests and agricultural crops. Results appear to be consistent between the studies conducted within rain forests.

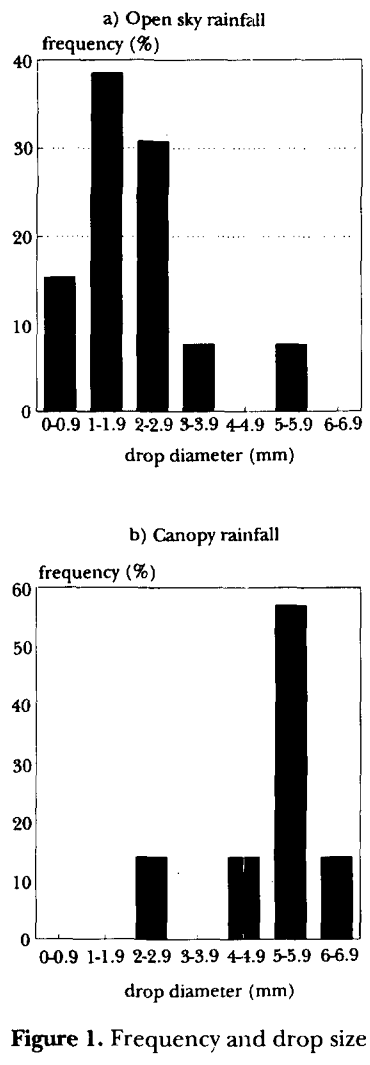

Figure 1. Frequency and drop size

The maximum drop size reached by open sky rainfall is 5.5 mm, while under the canopy drops may reach 6.8 mm. Hudson (1981) has suggested a limiting maximum drop size for open sky rainfall of around 5.25 mm due to break-up of large drops at high rainfall intensities using evidence from Zimbabwe (Hudson 1963), Thailand (Baruah 1973), Nigeria (Kowal & Hassam, 1977) and the United States (Carter *et al.* 1974). All studies indicate a levelling off in median drop size above 100 mm h^{-1}. Such effects would not be felt under forest canopies with a steady drip rate involving only large drops. The large size of drops is due to the drip point characteristics.

Differences in the median drop size for open sky rainfall occur due to variations in rainfall intensity between the samples. The relationship between rainfall intensity and median drop size can be summarised by the following general logarithmic equation:

$$D_{50} = aI^{b}$$

where D_{50} is the median drop size and I is rainfall intensity in mm h^{-1}.

The results from this study are plotted in Figure 2. Other studies have produced a variety of parameter values (Table 1), although there is close agreement about the form of the relationship. The data presented in this paper best follow the relationship derived by Laws and Parsons (1943). Thus when plotted against rainfall intensity the median drop size shows a direct relationship, as found for other studies from forest locations (Ovington 1954, Mosley 1982, Vis 1986, Brandt 1989). However, a similar pattern is not apparent for samples collected under the single-layer canopy (Figure 2). For rain falling from drip tips in the forest the median drop size remains more or less constant as intensity varies. Instead of showing a decrease in drop size at lower intensities, there are fewer drops produced mostly of a diameter around 4.5 mm. These results have implications for the energy of rainfall which depends on the mass of the rain drop. It is an important issue whether one large drop produces more energy than several smaller drops having an equivalent volume. In addition smaller drops have a lower terminal velocity than larger drops. Under this single-layer canopy all drops are at their terminal velocity when they reach the ground, but they are of a larger mass than their open sky counterparts falling at the same rainfall intensity.

Table 1. Parameter values for the relationship between drop size and rainfall intensity

Author	a	b
Laws and Parsons (1943)	1.238	0.182
Mason and Andrews (1990)	0.92	0.21
Brandt (1989)	1.416	0.123

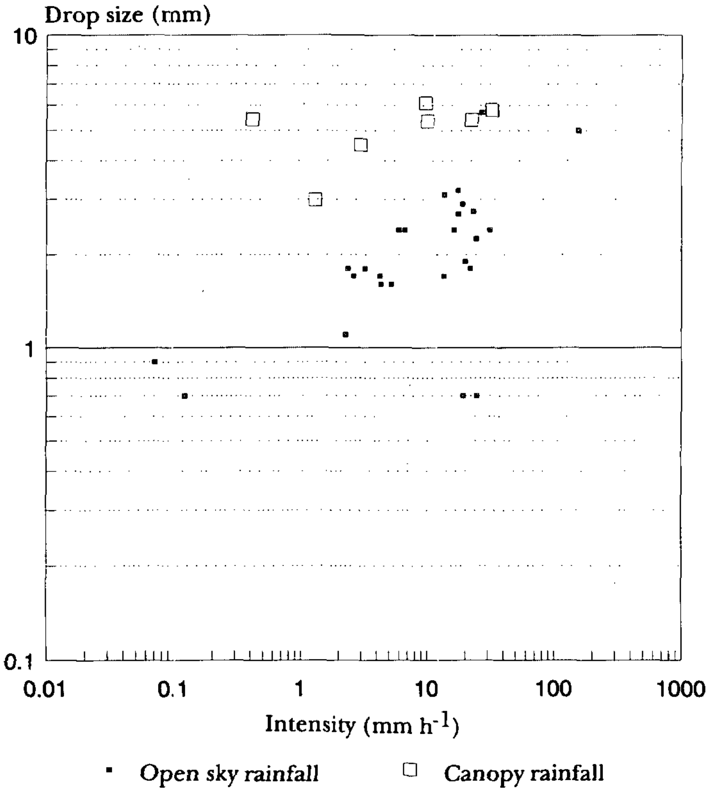

Figure 2. Drop size and rainfall intensity

For each sample the kinetic energy was calculated using the whole spectrum of drop sizes in each sample and plotted against rainfall intensity (Figure 3). This is again consistent with the findings of Hudson (1981), where there is a maximum kinetic energy of 40 J m^{-2} mm^{-1} of rain, reached at intensities of around 100 mm h^{-1}. There is a statistically significant correlation ($p = 0.99$) between energy and intensity (log) for open sky rainfall, with large intensities (150 mm h^{-1}) producing around three times as much energy as low intensities (2 mm h^{-1}). For rainfall falling from the canopy there is little association with rainfall intensity. Kinetic energy is high for all intensities, being equivalent to the energy totals associated with the highest intensity open sky rainfall. This reflects the disproportionate effect that large drops have on net kinetic energy, due to a combination of their greater mass and the greater terminal velocity, which can be reached because of the canopy height. Thus one or two large drops, while supplying the same volume of water, supply a great deal more energy than several smaller drops.

These findings are consistent with those of other studies where the concentration of rainfall into large drops by forest canopies increases its kinetic energy. The main differences between undisturbed forest and open sky rainfall are firstly, that forests generally receive a lower total volume of water, but secondly, with single-layer canopies (>13 m) this rain is no less erosive, due to its concentration into fewer larger drops. These findings need to be considered in relation to likely changes in erosion and runoff which might result from rain forest logging.

Given that most throughfall produces around 40 J m^{-2} mm^{-1} and that about 29% interception loss has been measured for the study site (Wong 1991) the results of forest harvesting on rainfall energy can be assessed for storms of different intensity. Figure 3 indicates that for open sky rainfall energy increases with intensity and it is only at intensities of around 100 mm h^{-1} that energy reaches values equivalent to that of canopy rainfall. However, with 29% loss in rainfall, typical energy received under the canopy is reduced to 25 J m^{-2} mm^{-1}. At intensities of around 20 mm h^{-1} the open sky rainfall attains higher energy and the effects of canopy removal are likely to produce higher erosion rates. For this area of Sabah, therefore, higher rainfall energy will be received at the ground surface during most rainstorms under open sky situations, and this factor should be taken into account when developing physically-based models to evaluate erosion processes following rain forest disturbance.

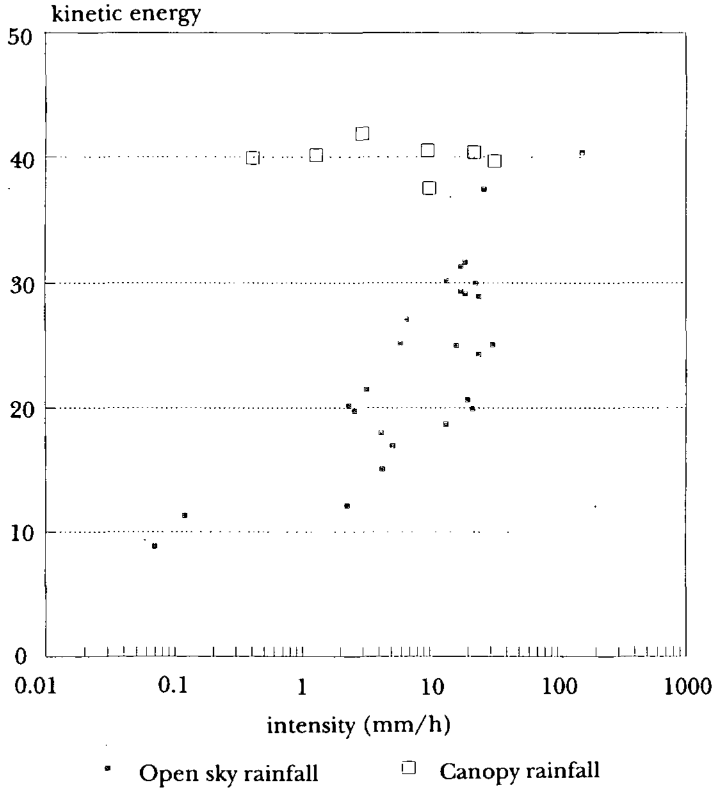

Figure 3. Kinetic energy and intensity

Implications of rainfall transformation for runoff and erosion following logging

Logging invariably involves varying degrees of disruption to different aspects of the vegetation and soil cover which make the full impact of rainfall transformation complicated to assess. The precise amount of erosion depends on the interaction between splash detachment and wash transport. Whichever has the lower value dictates the rate of sediment removal. Deforestation results in a greater volume of water arriving at the ground surface which enhances wash transport rates. It also changes the net kinetic energy of the rainfall, resulting in changed detachment rates. Both aspects need to be considered to assess fully the impact of commercial logging on soil erosion, but their relative significance varies with slope angle and the precise disruption incurred during logging (Brooks *et al.* 1993). Under the most severe disruption both soil and vegetation are considerably altered, involving greater runoff volumes and enhanced soil detachment. With a lesser degree of disturbance only the vegetation cover is affected. Without concomitant soil compaction runoff volumes do not show a similar increase. Since detachment is less dependent on slope angle than runoff, lower slope angles are more likely to be wash-limited where runoff volumes are lower, with the steeper slopes being detachment-limited.

Where the erosion process is detachment-limited the energy of the rainfall is significant. The relationship between rainfall kinetic energy (in joules per square metre per millimetre of rain) and intensity is greatly affected by the presence of a single-layer canopy. Where such vegetation is present rainfall has similar energy regardless of the intensity at which it is falling. Open sky rainfall has less energy below intensities of around 20 - 30 mm h^{-1}, with the difference increasing as intensity becomes progressively lower. Rainfall has more entrainment power when it falls through a single-layer canopy (i.e. when it can reach terminal velocity) than when falling in the open, especially at lower intensities. This is consistent with the finding that localised splash rates can be very high beneath rain forest canopies (Leigh 1982) and that localised high splash rates can be found in plantations, especially where there is no ground cover (Anderson & Spencer 1991)). However, there are several issues which complicate this in relation to the amount of erosion which will actually take place. Firstly, the forest floor is partially covered by litter or ground cover which can offer protection to the soil beneath. Although splash is found to be high in localised areas, the overall rate is likely to be low. Secondly, the rainfall is concentrated beneath drip points with areas between having either zero rainfall or receiving direct throughfall having the characteristics of open sky rainfall. Thirdly, the most erosive storms in this area of East Malaysia have intensities of around 180 mm h^{-1}. At this intensity open sky rainfall is composed of drops of a similar size to those resulting from canopy concentration (Figure 2), as well as supplying more rainfall in total. On steep-angled detachment-limited slopes which have considerable sub-soil compaction, the net effect of canopy loss is to produce high rates of erosion over the entire slope rather than in localised patches under the drip points. However, little research has considered the counter effect of understorey regrowth and reestablishment of the litter layer following harvesting. If disturbance is localised rates of regeneration can be rapid, resulting in more interception and lower fall heights. More data are required to assess the significance of vegetation regrowth to rainfall energy.

This study has shown the differences which exist in the drop sizes and kinetic energy of open sky rainfall and that falling under undisturbed rain forest canopy for Sabah, East Malaysia. The results are consistent with those found from other tropical regions. The study has also indicated that changes in rainfall energy can be significant to erosion and need to be included in physically-based models to assess the impact of rain forest disturbance on accelerated soil erosion. The data presented here represent one step towards developing a reliable data base and will help to parameterise new models which can elucidate erosion and runoff processes resulting from selective logging.

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