Impact of mechanized selective logging of rainforest on topsoil infiltrability in the Upper Segama area, Sabah, Malaysia

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Abstract Measurements of topsoil (0-30 cm) bulk density and steady-state infiltrability were made in undisturbed lowland rainforest and in forest that was selectively logged 12 years ago in the Upper Segama area, Sabah, Malaysia. In the logged-over forest, measurements were made on former tractor tracks and in adjacent recovering forest. Average bulk densities increased with depth in both forests (range in undisturbed forest: 0.98-1.26 g cm^{-3}; logged-over forest outside tractor tracks: 1.11-1.35 g cm^{-3}). Variation was much less for the sparsely vegetated tractor tracks (range: 1.31-1.37 g cm^{-3}). Topsoil bulk density (0-18 cm) was highly correlated with steady-state infiltration rates. Average values for the latter were 88 (undisturbed forest), 73 (recovering forest), and 15 mm h^{-1} (12-year-old tractor tracks). A comparison of 15-minute rainfall intensities with average saturated infiltrabilities and average infiltration curves (Philip's equation) predicted a substantial increase in the frequency and volume of infiltration-excess overland flow on the former tracks. These results indicate that natural regrowth is not always capable of mitigating the negative impacts of currently practised logging methods. Some suggestions for improvement are offered.

INTRODUCTION

The dipterocarp forests of southeast Asia are under extreme pressure by mechanized logging. Exploitation is often done under some variant of the Malaysian Uniform System which involves the extraction of all saleable timber above a prescribed diameter, relying on seedlings and saplings to produce the next harvest after a period of 60-80 years (Whitmore, 1990). Damage to the vegetation associated with this approach is considerable, with typically 40-60% of trees larger than 10 cm dbh (diameter at breast height) killed or seriously injured and similar losses amongst seedlings. In addition, 10-30% of the soil surface may be laid bare in the form of logging roads, skidder tracks and log landings (Bruijnzeel, 1992). The use of heavy equipment tends to compact topsoil in these places, setting in motion a negative spiral of reduced infiltrability and increased frequencies of overland flow and sheet erosion, thereby rendering the establishment of a new protective cover of vegetation and litter more difficult. Malmer & Grip (1990) and Hendrison (1990) reported very low infiltration rates on former tractor tracks that were still heavily compacted 6-8 years after their last use. Hence, such tracks may remain a source of direct runoff and sediment for considerable lengths of time. There does not seem to be any information about the time needed for the soils of these disturbed areas to recover fully, although work in temperate areas suggests that at least 20 years might be needed (Hatchell & Rallston, 1971).

This paper examines the effects of mechanized timber extraction on topsoil bulk density, sorptivity and steady-state infiltrability in the Upper Segama area, Sabah, Malaysia. Observations of the above parameters were made for undisturbed conditions, in forest that had been logged 12 years ago, and on former tractor tracks dissecting the recovering stand. Rainfall intensities over the period January-March 1990 were used to assess the influence of reduced infiltrability on the volume and frequency of infiltration-excess overland flow (Horton, 1933).

STUDY SITE

The Upper Segama area is situated in the southeastern part of Sabah, Malaysia, about 80 km west of Lahad Datu. The region experiences a humid tropical climate without a distinct dry season. Average annual rainfall is 2500-3000 mm, most of which falls as convectional storms of relatively high intensity (Abdul Razak, 1985). The undisturbed reference forest was located in the Danum Valley Conservation Area, one of the few remaining large expanses of undisturbed lowland dipterocarp forest in Sabah, at an elevation of 208-220 m a.m.s.l. The undulating terrain with moderate slopes (10-35°) was underlain by the Kuamut Formation (mudstones, sandstones and miscellaneous rocks), in which a clayey ultisol had developed (particle size distribution at 30 cm: 38% clay, 36% silt, 26% sand; Van der Plas, 1992). The forest was dominated by tall trees belonging mainly to the Dipterocarpaceae, Lauraceae, Burseraceae and Fagaceae families but a relatively open undergrowth of smaller trees, saplings and shrubs was also present. The forest floor was covered by a litter layer of variable thickness, showing a tendency to become thinner or discontinuous on steep slopes and under a relatively open canopy (Burghouts *et al.*, 1992). The logged-over site (100-140 m a.m.s.l.) was located 12 km to the east at the intersection of Bole River and the main logging road to Lahad Datu. Here, about 100 m^3 ha^{-1} of timber had been removed by crawler tractors 12 years ago, leaving 36 large stumps in an area of 2.5 ha. Former tractor tracks were covered with a vegetation dominated by grasses, herbs and *Macaranga* trees, with relatively little litter accumulation and occasional bare patches of soil, particularly tracks that were aligned perpendicular to the contour. Tractor tracks made up about 10% of the surface area in the experimental plot. The forest outside the tracks consisted of several large trees of non-economical species (e.g. *Koompassia excelsa*), various commercial species that were too small at the time of logging, and fast growing *Macaranga*, rattan, strangling figs, lianas and bamboo. The ultisol of the logged-over forest was somewhat less clayey than that of the undisturbed forest (grain-size distribution at 30 cm: 30% clay, 37% silt, 33% sand), reflecting a less complete weathering of the substrate.

MEASUREMENTS AND DATA PROCESSING

Field measurements of infiltration were made using a portable double-ring infiltrometer (diameters of inner and outer rings 14 and 21 cm, respectively; Hills, 1970). At each test site, litter and superficial roots and fibre mats were removed. The infiltrometer was driven 5 cm into the ground by hammering a wooden platform placed on top of the device. Great care was taken to minimize soil disturbance. At the start of each experiment the inner and outer rings were filled simultaneously to give a ponding depth of approximately 2 cm. In the inner ring a constant head was maintained by a system of two plastic pipes protruding from a 3-litre bottle, while water was added manually to the outer ring at regular intervals. Cumulative infiltration and elapsed time were noted down for about 2 h to ensure that steady-state infiltrability had been attained.

Sixteen tests were performed in the undisturbed forest, distributed over five sites representing the diversity in topography, vegetation cover and litter accumulation throughout the research plot (Burghouts *et al.*, 1992). Six infiltration tests were run on former tractor tracks in the selectively logged forest, five in the adjacent regenerating forest and four in recovering forest on a somewhat more massive brown inceptisol in the northern part of the plot. At each of the 31 test points, five core samples were taken at 6 cm intervals down to a depth of 30 cm. The cores (volume 100 cm^3) were analysed for soil moisture content, dry bulk density, and porosity (Black, 1965). Daily charts from the rainfall recorder at the Danum Valley Field Centre provided data on rainfall patterns for the period January-March 1990.

An infiltration experiment yields a series of cumulative infiltration values *vs.* time from which instantaneous infiltration rates can be calculated by differentiation. As infiltration proceeds, the gradual saturation of the profile results in a reduction of the suction head, finally leaving gravity as the only remaining force to allow vertical flow. As a consequence, the initially high infiltration rate decreases and asymptotically approaches a constant level which is usually referred to as saturated or steady-state infiltrability. The time dependence of ponded infiltration is described by several mathematical expressions, among which Philip's two-parameter equation is the most commonly employed (Philip, 1957, 1958). The equation is relatively easy to use and gives reasonable predictions of field-measured infiltration rates (e.g. Sharma *et al.*, 1980; Berndtsson, 1987). Furthermore, its parameters can be derived from experimental infiltration data by means of regression analysis without additional measurements. According to Philip (1957, 1958) the amount of infiltrated water through a ponded surface is given by:

$$I_t = St^{0.5} + At \qquad (1)$$

where:

I_t = cumulative infiltration at time t (L);
S = sorptivity of the soil ($LT^{-1/2}$);
A = a constant related to the hydraulic conductivity at the soil surface (LT^{-1}).

By differentiation the expression for the instantaneous infiltration rate i_t is found:

$$i_t = 0.5St^{-0.5} + A \qquad (2)$$

Boundary conditions are:

$$i_t \rightarrow \infty \text{ as } t \rightarrow 0$$

$$i_t \rightarrow A \text{ as } t \rightarrow \infty$$

In the case of strictly vertical infiltration into a uniform soil, A is approximately equal to saturated conductivity K_s, whereas sorptivity is a measure of the uptake capacity under unsaturated conditions largely determined by the suction gradient. Inherent to the above boundary conditions, the value of A as obtained by least-square curve fitting is an underestimation of the actual final infiltration rate. In the present case the latter was usually reached within 30-90 minutes. Therefore, experimental steady-state infiltrability was evaluated from the (straight) slope of the cumulative infiltration graph after 90-120 minutes.

Although the statistical distribution of infiltration test results often remains ambiguous (particularly for small sample populations; Keisling *et al.*, 1977), all parameters will be presented as arithmetic rather than geometric means. Significance of the results was determined using parametric (Student's t) and non-parametric (Mann & Whitney) tests (Seyhan, 1980).

RESULTS AND DISCUSSION

Under forest cover, average dry bulk density increased considerably with depth in the top 30 cm of soil (Fig. 1). Values ranged from 0.98 to 1.27 g cm^{-3} under undisturbed forest, and from 1.11 to 1.35 g cm^{-3} under selectively logged-over forest. Bulk densities for the latter were significantly higher at each depth interval, probably due to a less complete weathering of the sandstone substrate. On the former tractor tracks bulk density remained relatively constant with depth with values ranging between 1.31

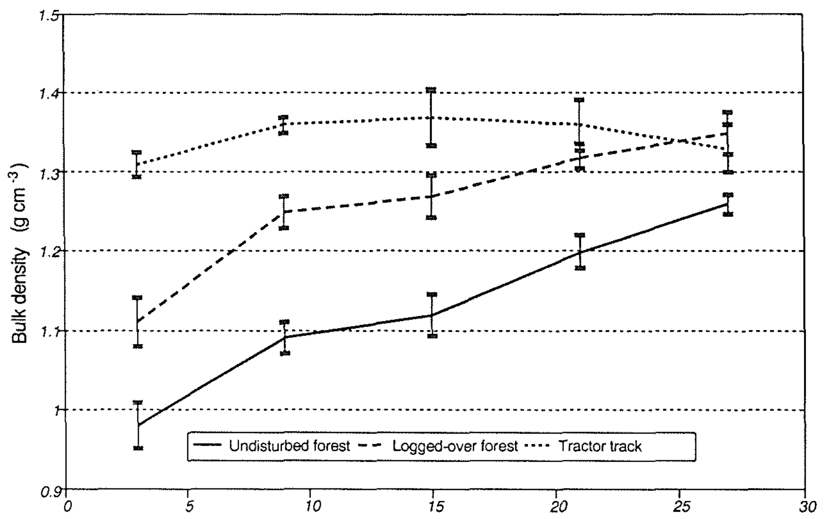

Fig. 1 Soil bulk density *vs.* depth under (–) undisturbed and (--) logged-over forest and (...) 12-year-old tractor tracks.

and 1.37 g cm^{-3} and a maximum around 12-18 cm (Fig. 1). Bulk densities for the upper 18 cm were significantly higher compared to the soils of the adjacent forest, indicating that twelve years of natural regeneration had not neutralized topsoil compaction (cf. Malmer & Grip, 1990; Hendrison, 1990). Measurements of porosity in the top 30 cm indicated a decrease with depth under undisturbed forest (from 57% to 50%) and logged-over forest (from 53.5% to 46.5%). As with bulk density, porosity was quite constant with depth below tractor tracks (47-48.5%).

The highest infiltration rates were found under undisturbed forest: mean steady-state infiltrability (i_s) was 88 mm h^{-1} (range 12-178; SD = 45.6), while mean sorptivity (S) was 55 mm $h^{-1/2}$ (range 5-192; SD = 54.9). Relatively low average values for saturated infiltrability were obtained for two sites with a rather open canopy, a thin organic layer, and a moderately dense root system (57 and 59 mm h^{-1}). On the three locations characterized by a closed canopy, a thick organic layer and a dense root mat, average values were almost twice as high (104-109 mm h^{-1}).

Average values of the respective infiltration parameters derived for the recovering forest outside the former tractor tracks of the logged-over site did not differ significantly from those for primary forest: i_s = 73 mm h^{-1} (range 17-112; SD = 37.3), and S = 45 mm $h^{1/2}$ (range 14-75; SD = 26.5). On the other hand, infiltrability of the former tractor tracks was poor: i_s = 15 mm h^{-1} (range 0.5-45; SD = 17.8), and S = 30 mm $h^{1/2}$ (range 0.8-119; SD = 44.0). Except on one occasion, steady-state infiltrability was reached within 15 minutes.

Average infiltration curves (according to Philip's equation) for the three surface types are presented in Fig. 2. Despite the large ranges and high standard deviations that are commonly associated with infiltration studies (Keisling *et al.*, 1977) and the limited number of replications, the differences between the infiltration capacities of both forests and the twelve-year-old tracks proved significant at the 95% confidence

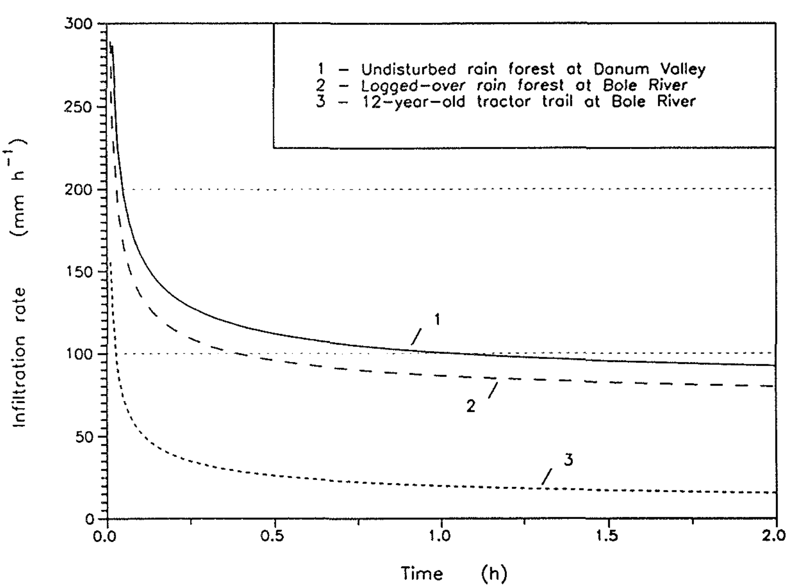

Fig. 2 Average Philip infiltration curves for the three surface cover types of Fig. 1.

level, both for parametric and non-parametric tests. Regression analysis on bulk density and porosity data (upper 18 cm only) *vs.* final infiltration rates yielded correlation coefficients of 0.871 and 0.925, respectively (Van der Plas, 1992).

An initial assessment of the impact of reduced infiltrability on amounts of overland flow in logged-over terrain was attempted by comparing data on 15-minute rainfall intensities for the first three months of 1990 with average steady-state infiltrability rates for the three cover types (Figs 2 and 3). During this period a total of 632 mm of precipitation was recorded (January: 357 mm; February: 120 mm; March: 155 mm). It has been shown that at high rainfall rates, throughfall intensities are only marginally lower than rainfall intensities (Hutjes *et al.*, 1990). As such, the use of gross rather than net rainfall intensities will not be of much consequence. Subtraction of i_s from the rainfall intensity yields the intensity of excess precipitation, which, by definition, equals the rate of Horton overland flow (HOF). The frequency distribution of potential HOF rates for each surface cover type during the period January-March 1990 is given in Fig. 3. In the undisturbed forest, saturated infiltrability was exceeded by 0-5 mm h^{-1} only once. Therefore, potential HOF under these conditions would amount to a mere 0.8 mm or 0.13% of total precipitation. The saturated infiltrability of the logged-over forest was exceeded during two 15-minute intervals yielding a potential HOF depth of 8.3 mm or 1.3% of total precipitation (still a low value for tropical lowland forests; Bruijnzeel, 1990). With saturated infiltrability being exceeded during forty-seven 15-minute intervals and a potential amount of HOF of 170 mm (27% of total precipitation), the expected frequency and volume of infiltration-excess overland flow was substantially higher on the former tractor tracks. The use of a smaller intensity interval (e.g. 5 minutes) would have enlarged the above runoff depths and frequencies even. However, one should bear in mind that the presently followed procedure contains a "worst case" element in that it assumes the soil to be saturated

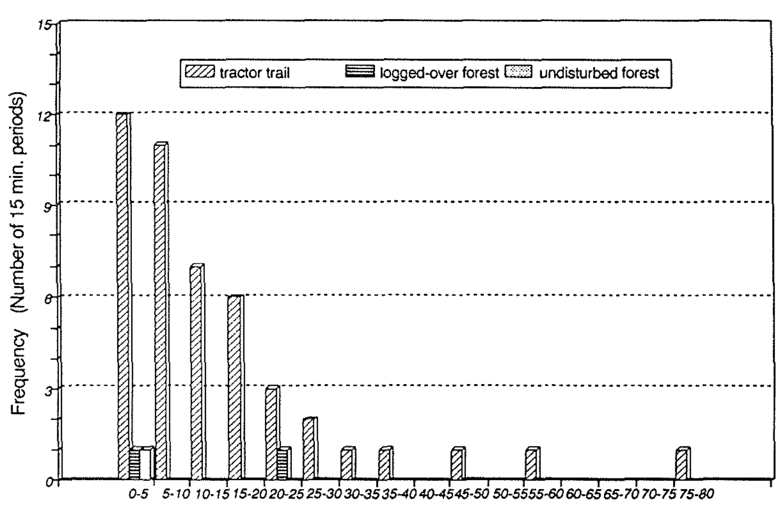

Fig. 3 Predicted frequency of occurrence of Horton overland flow during the first 3 months of 1990 on each of the surface cover types of Fig. 1.

soil. Information on antecedent moisture conditions would be necessary to enable a more realistic prediction of the magnitude of HOF.

An alternative approach is that advanced by Wierda *et al.* (1989). Infiltration rates during non-saturated conditions are taken into account by plotting an overlay of infiltration rates (expressed as a function of cumulative infiltration in mm) and mean rainfall intensities *vs.* cumulative amounts of rainfall for individual storms (Fig. 4). Applying the method to the same data set suggested an absence of HOF in the two forest covered areas, and the occurrence of HOF during eight storm events on the former tractor tracks (Fig. 4). A major drawback of the second method is the use of mean rainfall intensities which tends to produce underestimates and which leaves short-lasting high intensities unidentified, particularly if these occur during large or long events. Despite the shortcomings of the two methods, it is clear that HOF was a frequent process on the tractor tracks, whereas it has to be considered to be of minor importance in undisturbed or regenerating forest where soils got less compacted.

At the catchment level, if it is assumed that all HOF produced on the tractor tracks does reach the stream during the rainfall event, then the contribution to storm discharge may be considerable at the prevailing rainfall intensities. Naturally, the actual impact of logging on peakflows will depend on the dominant runoff mechanism before disturbance. Permeameter measurements made on core samples taken down to a depth of 1.5 m from the soil of the undisturbed forest indicated that vertical hydraulic conductivity decreased rapidly with depth (Van der Plas, 1992). Therefore, a throughflow dominated runoff mechanism is plausible (as was demonstrated independently by the observations of Sinun *et al.*, 1992). As reviewed by Bruijnzeel (1990), the largest changes in peak discharge and sediment yield are to be expected following a shift from a throughflow-dominated flow regime to a HOF-dominated one. Figure 5 presents the potential increases in peak discharge that may accompany logging in the Upper Segama area as a function of a) instant rainfall intensity,

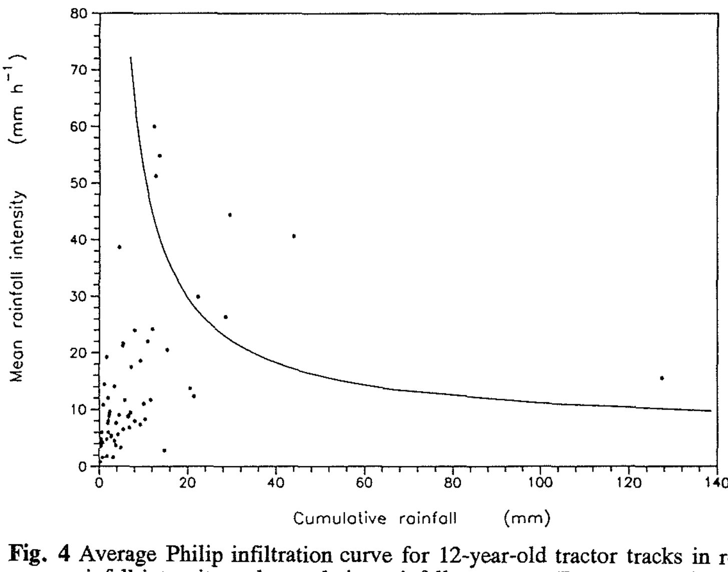

Fig. 4 Average Philip infiltration curve for 12-year-old tractor tracks in relation to mean rainfall intensity and cumulative rainfall per event (January-March 1990).

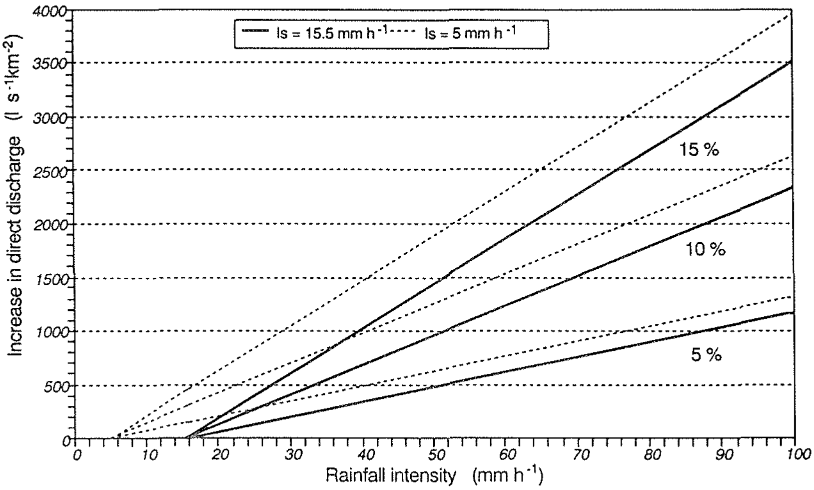

Fig. 5 Potential increase in direct discharge after logging as a function of rainfall intensity, proportion of area compacted by machinery, and final infiltration rates.

b) average saturated infiltrability of tractor tracks (two representative values shown), and c) percentage of area occupied by tracks. As an example, the nomogram would predict a rise in discharge of about 1000 l sec^{-1} km^{-2} of logged area for a rainfall intensity of 50 mm h^{-1} in combination with a relative area occupied by tractor tracks of 10%, having a saturated infiltrability of 15 mm h^{-1} (Fig. 5).

Perhaps the most striking aspect of our findings is that the impact of mechanized forest exploitation on topsoil characteristics (and by inference on basin runoff response) is still considerable after 12 years of forest regeneration. The use of heavy machinery tends to involve the creation of heavily disturbed areas that are prone to continuous degradation, thereby remaining sources of direct runoff and sediment for many years. To prevent such increased peakflows and erosion, areas laid bare during timber extraction should be located properly with respect to the contour and drainage patterns, i.e. away from streams and steep hillside sections. Additional measures that would help to minimize soil damage during the operation include: timing of road construction to conform to periods of least rainfall and allowing sufficient time for earthworks to stabilize before intensive use; providing adequate drainage to roads and tracks; yarding of logs uphill rather than downhill, using winch ropes rather than having tractors/skidders clear an approach to every log; directional felling into existing gaps; minimizing the number of tractor passes on tracks by dragging several logs to the landing at one haul; raising the leading end of the log to keep it from ploughing into the soil; suspending tractor traffic during wet periods to avoid excessive compaction; and maintaining adequate streamside buffer strips (Pearce & Hamilton, 1986). After completing the logging operation, additional treatment of compacted areas (notably landings), for example ripping and/or grass seeding, construction of cross-drains) may be indispensable for the development of a new protective cover of vegetation and litter.

Acknowledgements This research was supported by the Netherlands Foundation for the Advancement of Tropical Research (WOTRO) under project no. W84-253. We thank the Socio-economic Research Unit of the Federal Government of Malaysia and the Danum Valley Management Committee for permission to carry out the work. Dr Tony Greer (University of Manchester) and Encik Waidi Sinun (Danum Valley Field Centre) kindly provided us with rainfall data. Marco van der Plas thanks Theo Burghouts (Free University Amsterdam), Tony Greer and DVFC employees and staff for information, suggestions, assistance and company during his stint at Danum Valley. This paper is Number A/061 of the Royal Society's South-east Asian Rain Forest Research Programme.

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