

Sediment Discharge through Buffer Zones in a Tropical Rainforest of Peninsular Malaysia

Yasuhiro OHNUKI^{1,4*}, Abdul Rahim NIK², Shoji NOGUCHI^{3,5} and Shozo SASAKI^{3,6}

¹ Department of Forest Site Environment, Forestry and Forest Products Research Institute (FFPRI) (Tsukuba, Ibaraki 305–8687, Japan)

² Forest Research Institute of Malaysia (Kepong 52109, Kuala Lumpur, Malaysia)

³ Forestry Division, Japan International Research Center for Agricultural Sciences (Tsukuba, Ibaraki 305–8686, Japan)

Abstract

To prevent soil runoff from logging roads and skid trails, buffer zones are commonly established along both sides of streams. These buffers range in width from 10 to 100 m from the center of the stream, depending on stream width, (from 1 to > 40 m) as dictated by the Reduced-Impact Logging Guidelines for Lowland and Hill Dipterocarp Forests in Indonesia. In the Bukit Tarek Experimental Watershed in Malaysia, sediment accumulations were observed along narrow streams after logging despite the presence of 20-m-wide buffer zones, double the width set out in the guidelines. Thus, we examined erosion-accumulation depths on different slopes in 20-m-wide buffer zones to clarify the spatial effects on sediment discharge, particularly as it relates to the microtopography and the vegetation cover, including fallen trees. Some of the accumulation depths at lower elevations and along streams were small, whereas on steep concave slopes and hollows that extend to streams, large accumulations were observed 1 year after logging. These findings indicated that, although a 20-m-wide buffer zone may be partly effective at preventing sediment discharge, it is not adequate on concave slopes (lower side-hollows and channel walls) where surface flows often converge. We compared several physical properties of the surface soil in accumulated areas relative to undisturbed areas and demonstrated that bulk density was larger and total porosity and coarse porosity were smaller in the accumulated soils, especially on lower side-hollows. These results indicate that soils accumulated on concave slopes would accelerate the occurrence of surface flow. Tree distribution was not dense in the buffer zones, but fallen trees and the relatively dense understory vegetation including rattans and palms partly prevented the discharge of sediment into streams. Our findings suggested that 20-m-wide buffer zones with dense fallen trees and understory vegetation are partly sufficient to prevent sediment discharge; however, along steep concave slopes and hollows where rain water converges, wider and thicker buffer zones are needed.

Discipline: Forestry and forest products

Additional key words: fallen tree, physical property, soil runoff, vegetation cover

Introduction

Selective logging has been practiced in many tropical regions in order to decrease the negative impact of tree felling on flora and fauna^{7,8,12,14,16–18,30,32}. Several studies have been conducted in Sabah, Malaysia, relating to the

discharge of sediment following selective logging^{3,9,10,11,31}. However, in these areas, the most negative ecological impact of sediment discharge was not from tree felling, but from the construction of bulldozer paths³¹.

The construction of logging roads and skid trails significantly accelerates sediment yield^{5,6,21,34,37}. For example, the surface erosion rates of skid trails and general har-

Present address:

⁴ Kyushu Research Center, FFPRI (Kumamoto 860–0862, Japan)

⁵ Tohoku Research Center, FFPRI (Morioka 020–0123, Japan)

⁶ Hokkaido Research Center, FFPRI (Sapporo 062–8516, Japan)

*Corresponding author: e-mail bhankan@affrc.go.jp

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vesting areas were measured using a rainfall simulator⁶. Surface soil compaction did not recover after more than 5 years after construction of the harvesting areas, whereas surface infiltration rates on the skid trails increased and erosion rates declined.

To prevent sediment discharge from logging roads and skid trails, buffer zones are commonly established along both sides of streams, especially in humid tropical regions^{22,35,39}. These buffers range in width from 10 to 100 m from stream center, depending on stream width, which ranges from 1 to > 40 m, in accordance with the Reduced-Impact Logging Guidelines for Lowland and Hill Dipterocarp Forests in Indonesia³⁵. In the tropical rainforest of Bukit Tarek Experimental Watershed (BTEW) in Peninsular Malaysia, sediment accumulations were observed along narrow streams after logging, despite the existence of 20-m-wide buffer zones^{15,34} double the width dictated in the guidelines. Thus, we examined erosion-accumulation depth, particularly as it relates to microtopography, on varying shaped slopes in 20-m-wide buffer zones to clarify the spatial effects on sediment discharge using the erosion pin method^{1,4,29}. We discuss the relationships among the microtopography, physical properties of soils and the effects of vegetation cover, including fallen trees and understory vegetation, on sediment discharge to the streams.

Study area

The Forest Research Institute Malaysia (FRIM) and Forest Department (FD) established the BTEW in 1989 with the goal of clarifying the effects of forest management on the hydrological aspects of the forest³³. The BTEW is located in Selangor Darul Ehsan, Peninsular Malaysia (latitude: 3° 31' N, longitude: 101° 35' E, altitude: 48–213 m; Fig. 1), and is divided into three catchments designated C1, C2 and C3²⁵⁻²⁷. Catchments C2 and C3 were logged in November 1999^{15,34}, and C3 was cleared from December 2003 to January 2004³⁸. Among the three catchments, only C2 (area: 34.26 ha, altitude: 53–213 m) includes 20-m-wide buffer zones on both sides of streams to prevent sediment discharge caused by logging roads and skid trails. From logging roads and skid trails, some sediment lobes reach and partly intrude into the buffer zones (Fig. 1: stippled area). The average slope in C2 is 34.3°, and that of the buffer zones is 27.7°. The microtopographical units of the buffer zones are upper sideslope, lower side-hollow, lower sideslope, footslope, channel wall, and bottomland, after Tamura³⁶ (Fig. 2). Lower sideslopes, lower side-hollows, and channel walls have mostly steep inclinations, 30.8°, 30.2°, and 33.7° on average, respectively. In contrast, the inclinations of upper sideslopes, footslopes, and bottomlands are gentle, with average slopes of 23.4°, 16.1° and

5.2°, respectively.

The vegetation in the three catchments is dominated by *Koompassia malaccensis*, *Eugenia* spp. and *Canarium* spp., and a variety of palms and rattans dominate the understory vegetation. Along the streams in C1 and C3, the vegetation is dominated by *Euphorbiaceae* spp., *Rubiaceae* spp., *Burseraceae* spp., and *Lauraceae* spp.²⁸.

Geologically, the area consists primarily of metamorphic rocks including quartzite, quartz mica schist, graphitic schist, and phyllite from the Arenaceous Series³³. Based on the Food and Agriculture Organization of the United Nations (FAO) classification¹³, the soils are Acrisols²³. Average precipitation between 1999 and 2002 was 2,573 mm, with monthly peaks that occurred during the SW monsoons of April and the NE monsoons of November²⁴.

Methods

To clarify the effects of the buffer zones on soil runoff, we established four plots (Figs. 1 & 2) with different types of slopes designated RG (rectilinear gentle slope, average inclination: 24.9°), RS (rectilinear steep slope, average inclination: 26.8°), V (concave steep slope, average inclination: 31.3°), and X (convex gentle slope, average inclination: 27.8°). Soil accumulation-erosion depths were measured using the erosion pin method^{1,4,29} after each plot was sectioned into approximately 5-m grids. Erosion pins were placed at the intersections of the grid lines so that plots RG, RS, V, and X contained 38, 35, 42, and 40 pins, respectively. The pin number differences were primarily the result of the varied distribution of bushes and fallen trees in each plot. The topography of the plots was surveyed using laser equipment and electronic compasses (Laser Technology, Inc., Centennial, Colorado, USA), and topographical maps with 1-m contour lines were used. The overall layout of the experimental site showing the sediment discharge areas in relation to the logging roads and skid trails is summarized in Fig. 1.

In January 2001, we conducted a vegetation survey of the four plots to obtain information on the types and locations of trees, fallen trees and understory vegetation. The distribution of trees and understory vegetation including palms and rattans at the buffer zones is shown in Fig. 3.

The stainless steel erosion pins were 350 mm long and 2 mm in diameter (Fig. 4). Different tapes were wound from the top of the pins to 30 to 50 mm and 100 to 150 mm to facilitate their accurate placement in the soil such that the lower end of the lower tape (50 mm wide) marked the surface level. To monitor soil erosion and accumulation, we measured the distances above or below the soil surface, respectively, to the lower end of the tape

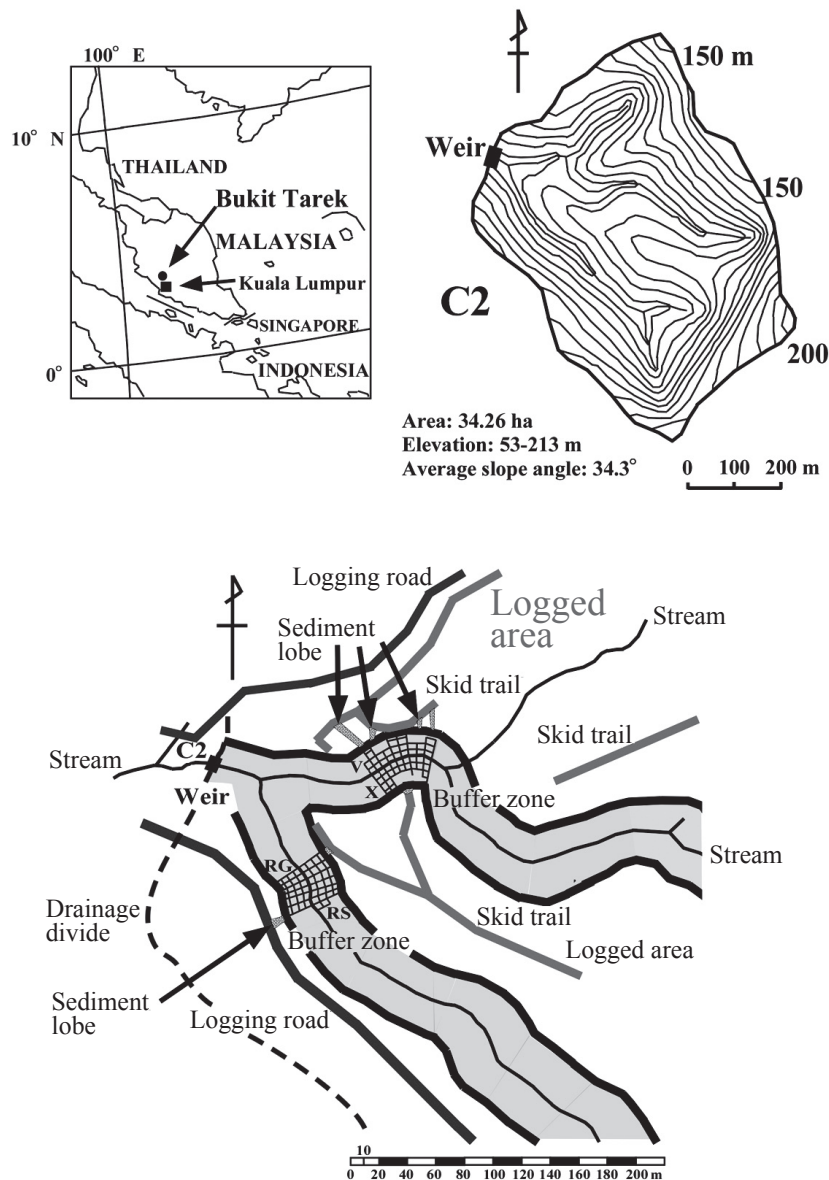


Fig. 1. Location and topographic map of catchment C2; buffer zone and measuring plots in the lower reach of C2, Bukit Tarek Experimental Watershed, Malaysia

RG: Plot RG (38 points), RS: Plot RS (35 points), V: Plot V (42 points), X: Plot X (40 points), Stippled area: Discharged sediment lobes from logging roads and skid trails.

every 2 months between March 2000 and January 2001. This method is less accurate than the Universal Soil Loss Equation (USLE) because it cannot actually trap transported soil mass; however, it can measure the change in surface level at many points. If a point is covered by disturbed-accumulated soils, it is clear that sediment transport reaches at least to that point, although the quantities of sediment discharge cannot be determined.

Soil physical properties including bulk density, total porosity, coarse porosity, fine porosity, and soil water retention were measured after collecting undisturbed cy-

lindrical surface soil samples (400 cm^3) from four erosion-accumulation plots in the buffer zones. Samples were collected from eight points, including four points in the undisturbed area and four points in the area of accumulation (hereafter "accumulated area"). The bulk density was measured using the method of Blake and Hartge². Total porosity and soil water retention were measured using a sand box with a suspended water column (0–50 cm H_2O ; 0–5 kPa) and a pressure chamber (50–1584 cm H_2O ; 5–155 kPa)¹⁹. Total porosity was divided into coarse porosity (0–500 cm H_2O ; 0–50 kPa) and fine porosity (> 500 cm

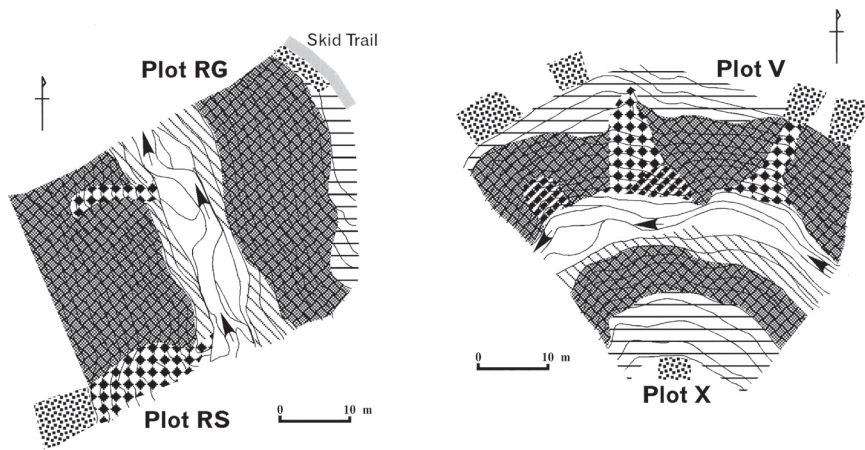


Fig. 2. Classification map of microtopographical units associated with plots RG, RS, V, and X
 Each microtopographical unit is classified after Tamura³⁶.
 □ : Upper sideslope, ▤ : Lower side-hollow, ▥ : Lower sideslope, ▧ : Footslope,
 ▨ : Channel wall, □ : Bottomland, ▩ : Sediment lobe.

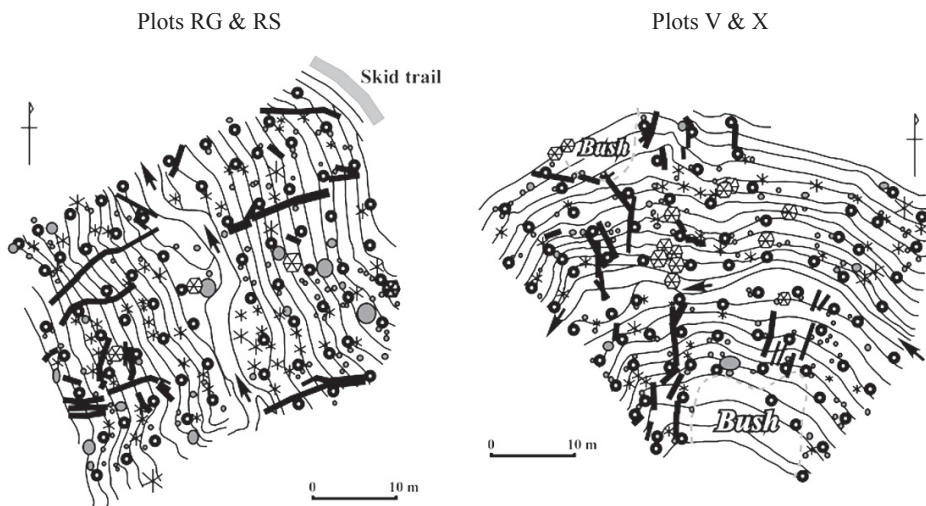


Fig. 3. Location of trees and understory vegetation in each plot
 ● : Trees, * : Rattans, ⊗ : Palms, | : Fallen Trees.

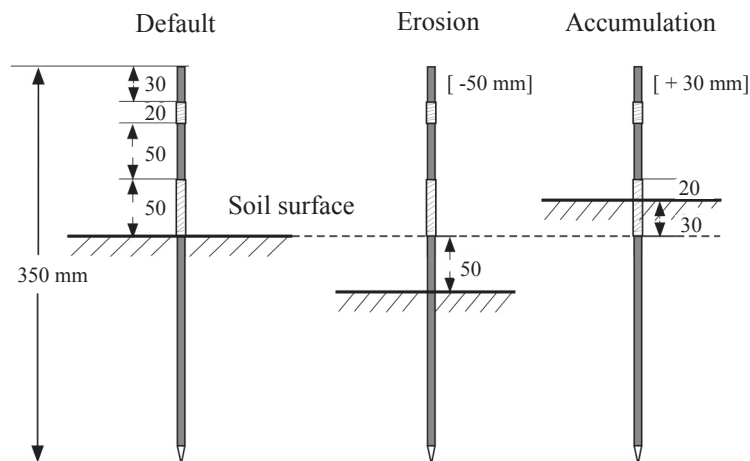


Fig. 4. Erosion pin method used in the buffer zones

H₂O; > 50 kPa).

The vegetation cover in the buffer zones or the percentage of canopy openness in plots RS and RG (73 points) and plots V and X (82 points) was measured in February 2003 from whole-sky photos using a digital camera. Hemispherical photographs were taken at 1 m above the ground using a Nikon fisheye lens (FC-E8) mounted on a digital camera (Nikon Cool Pix 950), and canopy openness was calculated using Gap Light Analyzer (GLA) software (School of Resource and Environmental Management, Simon Fraser University, British Columbia, 1999).

Results and discussion

1. Erosion-accumulation depth in the buffer zones

We collected measurements from 16 March 2000 to 19 January 2001. Precipitation was observed on approximately 63% of the days in this period (rainy days/total days: 133/210). Total rainfall for this period was 2,395 mm, less than the 1999–2002 average of 2,573 mm.

Over the course of the study period, over half of all points in plots RG and RS (Fig. 5, left side) were eroded less than 20 mm, and accumulation was observed at only 21 points. At a hollow (area **a**), large accumulation depths were observed from just below a sediment lobe to the middle of the hollow. Although we do not have any data for the lower slope near the stream, the sediment could have flowed into the stream through the hollow. Near the skid trail in plot RG, large accumulation depths over 20 mm were observed at several points. In contrast, no accumulation was observed in a small hollow where thick leaf litter had accumulated (area **b**).

From March 2000 to January 2001 (Fig. 5, right side), over half the points in plot V exhibited accumulation, especially on the under-slope side of the plot. The points with

the largest accumulation depths were located on the lower part of the sediment lobes from the skid trails (Fig. 1). In the middle reach of plot V, apparent convex-shaped mounds (areas **c** and **d**; Fig. 5, right side) were observed with rather small erosion-accumulation depths. These mounds were not discharged from the new skid trail, but from an older road that had existed previously at this same location. In plot X, over half of the points showed deposition, but no large accumulation depths were observed despite proximity to the end of a skid trail (Fig. 1). Along the stream, three-quarters of the points were covered by accumulated soils from the upper part of the slopes (plot V) and upstream (plot X).

2. Erosion-accumulation depth and microtopography

According to the Reduced-Impact Logging Guidelines³⁵, a buffer zone of 10 m is enough to trap sediment discharge for streams with bank widths of 1–10 m. Indeed, Lacey²² found that 10-m buffers of undisturbed forest (slope angle: 21°) result in 80–90% less runoff and a > 95% reduction in sediment produced by logging skid tracks. Ziegler et al.³⁹ showed that some sediment derived from road runoff was deposited on the fillslope leading to a 10-m riparian buffer in a disturbed headwater basin in a montane forest in northern Thailand. The relatively flat headwater basin in that area trapped 80% of discharged coarse sediments and reduced the transport capacity.

In our study area, however, 20-m forest buffers were not adequate to prevent sediment discharge from logging roads and skid trails through hollows and steep concave slopes from reaching streams (Fig. 5). As seen in Figs. 2 and 5, sediment depositions were observed at lower side-hollows in plots RS and V, at concave lower sideslopes in plots RG and V, and at a channel wall in plot V. Ta-

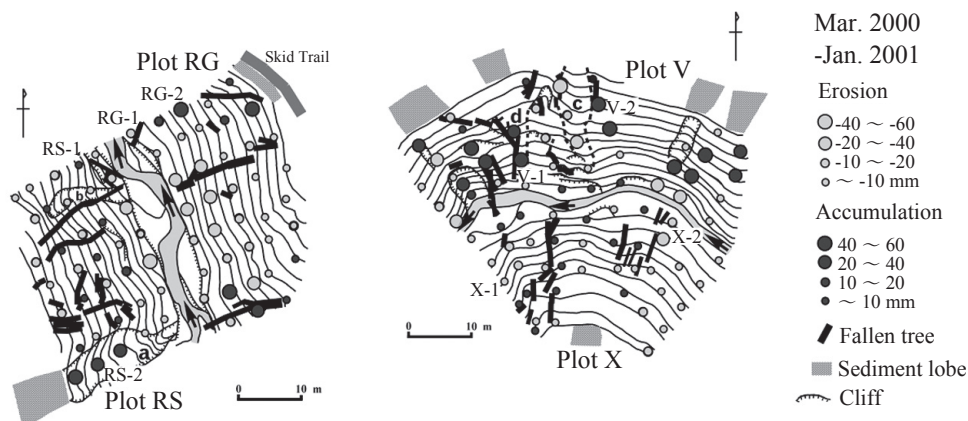


Fig. 5. Erosion-accumulation depths in each plot
a and **b**: Hollows on the slope,
c and **d**: Mounds (several decades old).

ble 1 shows average slope inclinations and average erosion-accumulation depths for each microtopographical unit. Ordinarily in the slope process, erosion is prevalent on steeper slopes and accumulation dominates on gentler slopes. However, in this area, accumulations were found at channel walls and lower side-hollows where slopes are steep. Both microtopographical units have concave cross sections and a converging surface flow; thus, the sediment discharge could have occurred during heavy rains. Also, in the *Ls-V* sub-unit (lower sideslope in plot V, Fig. 2), which has a concave cross section and can converge overland flow, the average accumulation was rather deep.

In contrast, surface erosion in bottomlands and on footslopes, which have gentle inclinations, was considerable (Table 1). Floods occurred often in bottomlands¹⁵, and deposited sediment would have been transported downstream during and after rainfall events. On footslopes, despite the gentle slopes, little accumulation occurred because sediment lobes and lower side-hollows are not located on their upper slopes (Fig. 2). The *Ls-X* sub-unit (lower sideslope in plot X), which has a convex cross section, showed small values of erosion depth similar to those of bottomland; a dense bush could trap a sediment lobe

(Figs. 2 & 3). Upper sideslopes also showed small erosion depth values; although two sediment lobes were located on these upper slopes (Fig. 2), dense bushes may have controlled the sediment discharge (Fig. 3).

3. Physical properties of soils and sediment discharge

The bulk density and total, coarse, and fine porosity of surface soils in the erosion-accumulation plots are shown in Table 2. The bulk density and total porosity were highly inversely correlated; the correlation coefficient in accumulated areas was -0.9932 , and that in undisturbed areas was -0.9982 . Bulk density was lower in undisturbed areas (mean = 0.73 Mg m^{-3}) and higher in accumulated areas (mean = 1.06 Mg m^{-3}). The total porosity in undisturbed areas (mean = $0.71 \text{ m}^3 \text{ m}^{-3}$) was higher than that in accumulated areas (mean = $0.59 \text{ m}^3 \text{ m}^{-3}$). The total porosity difference could be attributed almost entirely to the difference in coarse porosity, because the average fine porosity was nearly identical in both areas (undisturbed areas: $0.27 \text{ m}^3 \text{ m}^{-3}$, accumulated areas: $0.28 \text{ m}^3 \text{ m}^{-3}$), but the average coarse porosity was ~ 1.5 times higher in the undisturbed areas (undisturbed areas: $0.44 \text{ m}^3 \text{ m}^{-3}$, accumulated

Table 1. Slope inclination and erosion-accumulation depths in each microtopographical unit

Microtopographical unit	B1	Fs	Cw	Ls	<i>Ls-V</i>	<i>Ls-X</i>	Lsh	Us
Number of points	18	20	3	92	20	22	12	10
Average slope inclination (°)	5.2	16.1	33.7	30.8	35.0	30.5	30.2	23.4
Average erosion-accumulation depth (mm)	-4.3	-11.2	+22.8	-0.5	+7.5	-3.8	+15.4	-6.0

B1: Bottomland, Fs: Footslope, Cw: Channel wall, Ls: Lower sideslope, *Ls-V*: Lower sideslope in plot V, *Ls-X*: Lower sideslope in plot X, Lsh: Lower side-hollow, Us: Upper sideslope, +: Accumulation, -: Erosion.

Table 2. Physical properties of surface soils in the buffer zones

Microtopographical unit	Accumulated area					Undisturbed area				
	[A-1]	[A-2]	[A-3]	[A-4]	Mean	[U-1]	[U-2]	[U-3]	[U-4]	Mean
	RG-2	RS-2	V-1	V-2		RG-1	RS-1	X-1	X-2	
	Ls	Lsh	Lsh	Ls		Fs	Ls	Ls	Fs	
Bulk density (Mgm^{-3})	0.93	1.21	1.15	0.94	1.06	0.67	0.59	0.85	0.82	0.73
Total porosity ($\text{m}^3 \text{ m}^{-3}$)	0.65	0.52	0.53	0.64	0.59	0.73	0.75	0.67	0.68	0.71
Coarse porosity ($\text{m}^3 \text{ m}^{-3}$)	0.30	0.32	0.27	0.32	0.30	0.47	0.52	0.35	0.43	0.44
Fine porosity ($\text{m}^3 \text{ m}^{-3}$)	0.35	0.20	0.26	0.32	0.28	0.26	0.23	0.33	0.25	0.27

Ls: Lower sideslope, Lsh: Lower side-hollow, Fs: Footslope.

areas: $0.30 \text{ m}^3\text{m}^{-3}$). With respect to the microtopographical units, RS-2 and V-1 in the accumulated areas located in lower side-hollows in plots RS and V, respectively, had higher bulk densities and lower total porosities than the other points; they also had lower fine porosities than RG-2 and V-2, located lower on sideslopes. These results indicate that the accumulated soils on lower side-hollows are firmer than the soils in undisturbed areas. Furthermore, accumulated soils with lower fine porosities become saturated more readily after heavy rains and therefore generate surface flow.

The soil water retention curve (Fig. 6) supports the ideas mentioned above. In plots RG and RS, the inverse proportion curves also indicated higher soil porosity in undisturbed than accumulated areas where inclined *S*-shaped curves suggested lower porosity for the low water retention zones (10^0 – $10^1 \text{ cm H}_2\text{O}$). Inclined *S*-shaped curves at all points also indicated that the low water retention zone was of lower porosity in plots V and X than in plot RG; V-1 and V-2 points in accumulated areas showed lower porosity in the low water retention zone than X-1 and X-2 points in undisturbed areas (Fig. 6). In addition, with respect to the microtopographical units, RS-2 and V-1 in the

accumulated areas on lower side-hollows in plots RS and V, respectively, had the lowest porosities, $10^0 \text{ cm H}_2\text{O}$ and $10^3 \text{ cm H}_2\text{O}$, respectively; this indicates that they may have not only lower water permeability but also lower porosity in high water retention zones.

As mentioned above, firm accumulated soils had high bulk density and low total and coarse porosity. Furthermore, soils located on lower side-hollows had lower fine porosity than soils on lower sideslopes. These results suggest that accumulated soils on steep concave slopes may accelerate the occurrence of surface flow. Noguchi et al.²⁵ showed that saturation overland flow may not be dominant in the C1 forest catchment (an undisturbed basin), but subsurface flow must play an important role in stormflow generation. In C2 catchment buffer zones, especially on steep concave slopes, lower side-hollows, and channel walls, low fine porosity could decrease the subsurface flow, and low coarse porosity may accelerate the generation of surface flow; the discharged sediment would therefore be transported into streams.

4. Erosion-accumulation depth and vegetation cover

We conducted a vegetation survey in January 2001, the results of which are summarized in Figure 3. The most abundant and diverse family was *Euphorbiaceae* spp.; the other main families were *Rubiaceae* spp., *Lauraceae* spp., *Rhizophoraceae* spp., *Burseraceae* spp., and *Leguminosae* spp. The *Euphorbiaceae* spp. had 25 m in maximum height and 32 cm in maximum DBH. The maximum tree height was 35 m in *Lauraceae* spp.; the maximum DBH was 90 cm in *Leguminosae* spp. A vegetation survey was also conducted along the streams and the riparian zone for the adjacent catchment basins C1 and C3²⁸; C3 was logged most recently, between November 1999 and February 2000.

In our four plots, we also measured openness of the canopy using a fisheye lens at 155 points (Fig. 7). In plots RS and RG (73 points), canopy openness ranged from 2.5 to 14.1% (mean = 9.0%, variance = 6.45, SD = 2.54). In plots V and X (82 points), openness ranged from 4.1 to 15.3% (mean = 8.6%, variance = 5.10, SD = 2.26). In plots RS and RG, canopy openness was particularly small on the left bank of the stream. The values of measured canopy openness in both plots did not correlate with the erosion-accumulation depths measured from March 2000 to January 2001. This means that the gaps, which have open areas of $> 6.3 \text{ m}^2$ in the buffer zones in this area, do not have a severe effect on the erosion-accumulation depths. Konishi et al.²⁰ also mentioned that throughfall ratio per gross rainfall was weakly correlated with the openness of the canopy. With respect to these results, gaps could accelerate erosion owing to the increase of canopy

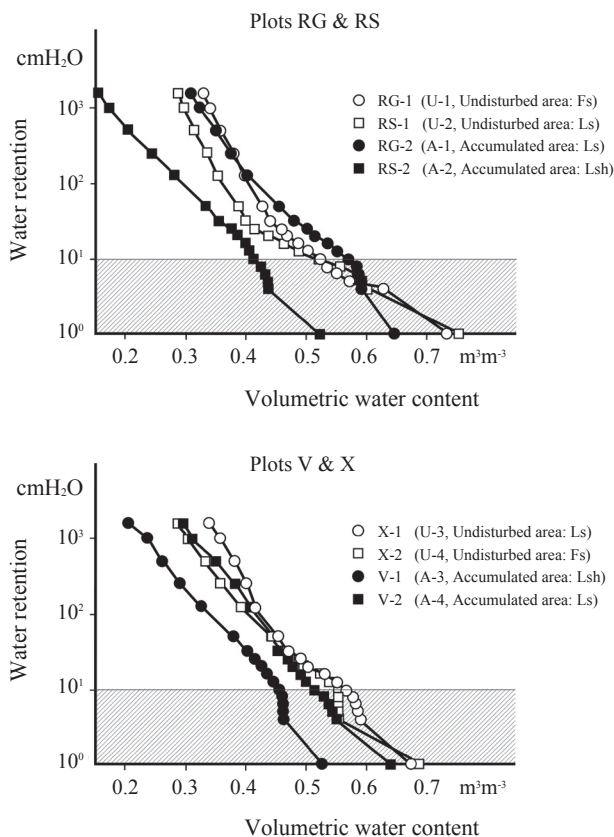


Fig. 6. Soil water retention curves of surface soils in the buffer zones

Hatched line: Low water retention zone (10^0 – $10^1 \text{ cm H}_2\text{O}$).

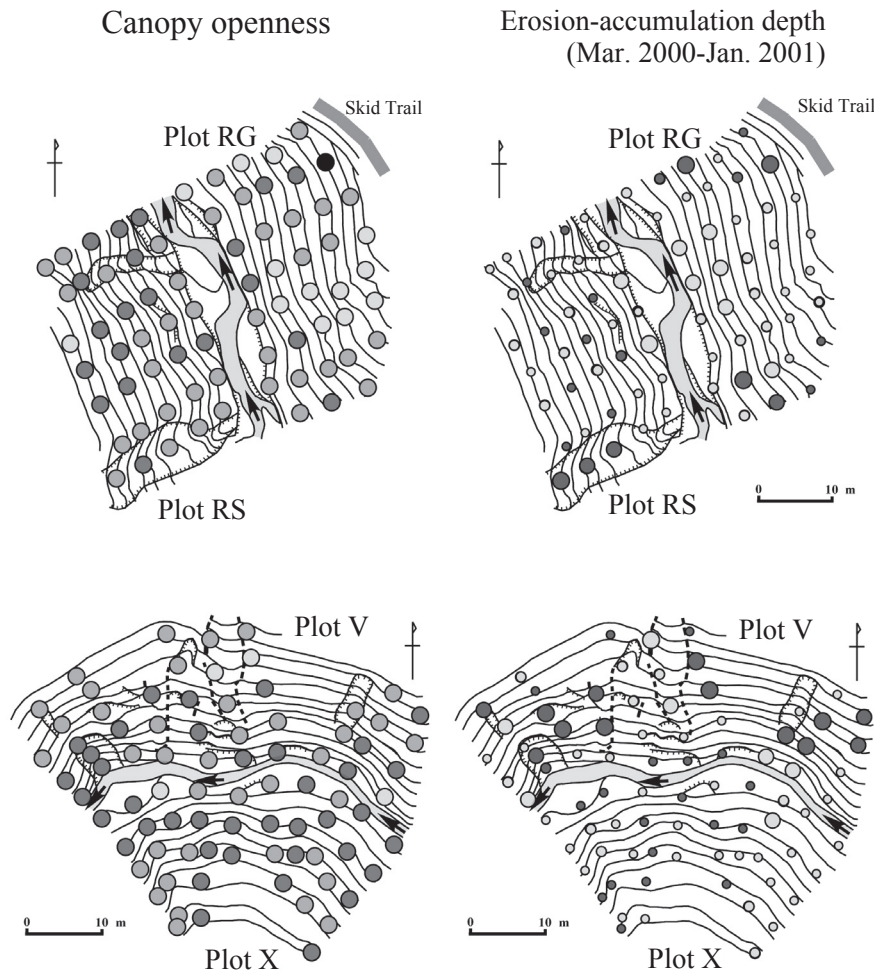


Fig. 7. Canopy openness and erosion-accumulation depths
 ● : 0~4%, ● : 4~8%, ● : 8~12%, ○ : 12~16%.
 Legend of erosion-accumulation depth is as per Fig. 5.

throughfall volume; however, less erosion volume would be observed if thick understory vegetation and thick litter covered the gap surface.

In addition to the effects of microtopography, vegetation cover played an important role in decreased erosion and sediment discharge in this study area (Figs. 3 & 5). In particular, the understory vegetation that consisted of bushes and fallen trees on the slopes effectively controlled the sediment discharge in the buffer zones. As mentioned above, bushes were located just below the skid trails in plots V and X (Fig. 3), and in plot X, in particular, sediment discharge was hardly observed at the upper sideslope adjacent to the bushes. In plot V, points adjoining the bushes showed small accumulation depths (Figs. 3 & 5).

Fallen trees (Figs. 3 & 5) also controlled sediment discharge and surface erosion. Despite the steeper slope in plot RS, accumulation depths in this plot, with the exception of the lower side-hollow (Fig. 5a), were small. Thus, it appeared that the many fallen trees in plot RS trapped

the sediment in incremental steps coinciding mainly with the contours. The tree length per 100 m² was 27.55 m in plot RS and 18.15 m in plot RG, and when the fallen trees were orthogonal to the contours, there was little effect on sediment discharge. Apparent sediment control effects were confirmed at the lower reach of plot V (Fig. 5). The fallen trees adjoining the bushes (d) also trapped much sediment so that discharge hardly reached the stream (Fig. 5). Furthermore, short fallen trees just below the old sediment lobe had been trapping the soils for many years (under slope of c). At the lower reaches of plot X, the sediment discharge was small because of the favorable effect of the bushes and the fallen trees that trapped the sediment from the end of the skid trail (Fig. 1). Tree length per 100 m² was 13.99 m in plot V and 21.25 m in plot X.

In all BTEW catchments, large and fine wood pieces provided sediment storage after harvesting in the streams¹⁵. Thus, sediment storage effects of wood in the streams, the contribution of microtopography effects in the buffer

zones, and the understory vegetation consisting of bushes and fallen trees all contribute to the control of sediment discharge and surface erosion. Here, it was clear that the 20-m buffer zone partly controlled the sediment discharge not only by vegetation cover but also by fallen trees on convex and linear slopes; however, on steep concave slopes and hollows (microtopographical units: lower side-hollows, channel walls, and concave lower sideslopes; Fig. 2), sediments would have easily flowed into streams after heavy rains. Thus, in these danger zones where rain water converges, wider and thicker buffer zones and trapping systems made from cut fallen trees, branches, and leaf litters are needed.

Conclusion

We monitored erosion-accumulation depths, soil physical properties, and trees and understory vegetation in buffer zones in the C2 catchment of Bukit Tarek Experimental Watershed. The 20-m-wide buffer zones could not stem the sediment discharge from logging roads and skid trails to the streams; large sediment discharge was observed on the steep concave slopes and hollows near the streams where soils would have low permeability and surface flow would be easily generated. In contrast, sediment discharge and surface erosion were primarily controlled by the understory vegetation including bushes and fallen trees in the other microtopographical units on convex and linear slopes. Our findings suggest that, although 20-m-wide buffer zones may be adequate to prevent sediment discharge in some areas of convex and linear slopes, wider and denser buffer zones are needed on steep concave slopes and hollows where rain water converges.

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