Runoff and Soil Erosion in Selectively-logged Over Forest, Danum Valley Sabah, Malaysia

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ABSTRACT This study on soil loss and runoff using bounded runoff plot was carried out in selectively-logged over forest in Danum Valley Lahad Datu Sabah. The purpose of this study was to quantify the effect of forest cover disturbance and recovery on runoff and sediment production within the forest patches, and to better understand the key controlling factors. Runoff plots were set up in forest areas which experienced different levels of logging disturbances and recovery that has been logged 28 years prior to this study, i.e. logged hillslope, skid trail, and patches of undisturbed/control hillslope area. The magnitude of runoff and soil loss from skid track plot was found to be the highest (2.72 t ha-^{1} yr^{-1}), followed by logged slope (2.56 t ha^{-1} yr-^{1}) and control plot (0.13 t ha^{-1} yr^{-1}). Physical properties of soil (ie: soil compaction) appeared to be important factor that determine the magnitude of soil loss

KEYWORDS: Soil loss, runoff, selective-logged, soil compaction logging disturbances

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INTRODUCTION

Soil is a key to life on the land, affecting life and affected by it. Of all the earth's crustal resources, the one human take most for granted is soil due to the fact that it is a renewable resource. Though soil forms continuously, the rate is usually very slowly (Fitzpatrick, 1986). Changes in land cover, particularly deforestation, can have significant effect on watershed hydrology. In forest conditions, vegetation protects soil from eroding in various ways. Firstly, vegetation affects the amount of rain water reaching the forest soils via canopy rainfall interception (Chappell *et al*., 2001; Nunes *et al*., 2011; Asdak *et al*., 1998; Bidin *et al*., 2003). This will reduce the amount of surface runoff generated that influences the rates of soil erosion (Zhang *et al*., 2015; Li *et al*., 2014; Wakahara *et al*., 2008; Miyata *et al*., 2009; Zuazo & Pleguezuelo, 2008; Tsiko *et al*., 2012; Elliot *et al*., 1996). On the other hand, vegetation reduces the erosive power of impacting raindrops (Nunes *et al*., 2011;Chang, 2012). The loss of protective vegetation either through natural or human induced makes soil vulnerable to being swept away by wind and water. Various studies have demonstrated the occurrence of high soil losses due to forest disturbance (Suryatmojo *et al*., 2011; Fahey & Marden, 2005; Douglas, 2003; Kasran, 1988).

Typical effects of forest disturbances on productivity often results from the forest management activities including road construction, logging operation or fire. Studies reported the impacts of road construction in logging areas have led to much soil compaction and soil erosion (Douglas *et al*., 1992; Douglas, 2003; Pinard *et al*., 2000; Luckow & Guldin, 2007; Jusoff, 1988;Rivera *et al*., 2010). Other researchers reveal significant increase in water yields and storm flow volume resulting from forest clearance or conversion (Suryatmojo *et al*., 2011; Gerold, 2010; Rahim, 1988; Hartanto *et al*., 2003). In addition to soil losses, large amounts of soil nutrients are removed with runoff, resulting in less productivity of soil and deterioration of downstream water quality (Nepal *et al*., 2014; Douglas *et al*., 1999).

Monitoring of soil loss is very important as it provides valuable information about soil erosion risks caused by logging operations. By reducing soil erosion, sustainably managed forests contribute significantly to the systems providing and maintaining the Earths supplies of clean water, while also ensuring a balanced water cycle. The purpose of this study is to quantify the effect of post-logging disturbance and forest recovery on runoff and sediment production in the study area, and to better understand the key controlling factors.

METHOD

Study Site

The study was conducted in secondary tropical rainforest at Danum Valley Forest Complex or DVFC. . It is located at 117 ^{0}48.75' E and 5^0 01' N in the eastearn Sabah, Malaysian Borneo. This area is covered by natural forest which is classified as 'lowland dipterocarp rainforest' (Hazebroek *et al*., 2012; Whitmore, 1984). It is also part of the high-biodiversity area known as the heart of Borneo. The area was selectively logged in early 1989 using bulldozers and high-lead yarding (Marsh & Greer, 1992), leaving the complex structure of forest patches with different level of disturbance (eg: undisturbed forest fragments, moderately impacted and highly damaged rain forest) (Nussbaum 1995). Previous record of mean annual rainfall at the DVFC from year 1986-2012 was 2873 mm (Annammala, 2014). Hazebroek *et al*. (2012) describe the rainfall patterns at DVFC are include many brief showers of low-intensity rain, but also high intensity showers, short duration storms and occasional multi cell, complex, persistent heavy rain over hundreds of square kilometers for many hours. Temperatures vary little throughout the year, with a mean of 26.7^{0}C, (Marsh & Greer, 1992). The soils around the study site are mostly occupied by the Kuamut mélange Formation. The mélange consists of a variety of rock assemblages like sedimentary and volcanic rocks with inter-bedded sandstone, mudstone and tuffs, known collectively as slumped breccia (Gasim *et al*.,1994; Hazebroek *et al*., 2012). The most widespread rocks are ultrabasic, basic and intermediate igneous rock as well as sedimentary rocks (Hazebroek *et al*., 2012).

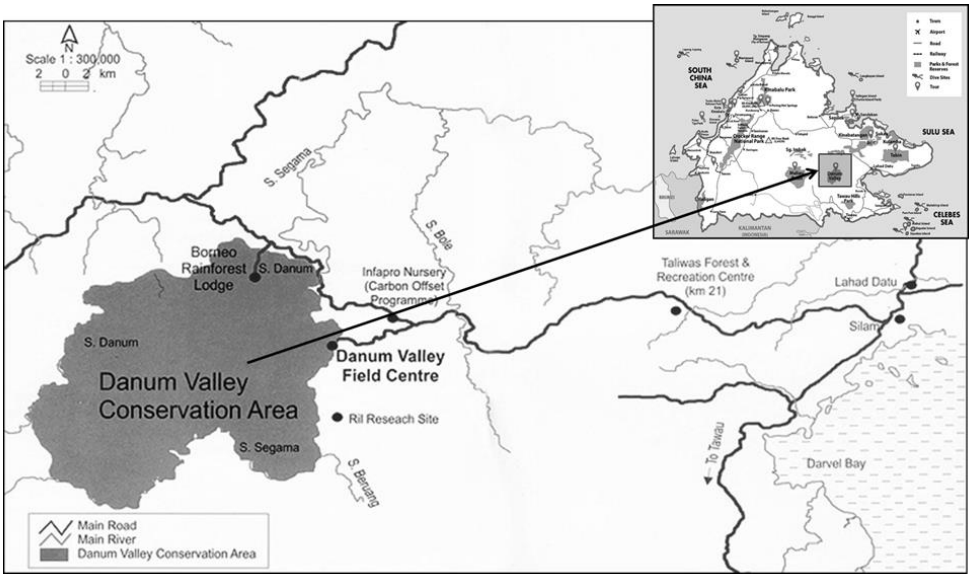

Figure 1. Location of study area

Field observation and analysis

The runoff plots (1 m x 2 m; 15 cm high boundary wall) were installed on the field with different slopes. These 1 m x 2 m plots were aligned with the slope of the unit (unit treatment or harvest unit). The plots are representative of undisturbed soil, disturbed soil and skid track (based on above ground biomass (AGB) index). Control plot was undisturbed, logged slope was represent a highly damaged area, and another plot was installed on skid track. The plots were bounded with aluminum strips. Runoff from each plot was passed through a channel into a collection tank placed in a trough. Both the collecting channels and the troughs were covered with plastic sheets to ensure that only the runoff from the plots entered the tanks and also to minimize evaporation. The runoff collected was measured with a calibrated bucket and recorded. Through-fall for each rainfall event was determined from data derived from the gauge placed around each plot, and analyzed following the method derived by Morgan (1979). Hydraulic conductivity was measured using mini disk infiltrometer by Decagon. Standard methods were applied to investigate particle size distribution (United States, 1951). Soil texture was classified according to the FAO (1990). The majority of investigated soils were loam. The general characteristics of experimental plots are described in Table 1.

Table 1. General characteristic of experimental plot

Location	General description	n	Vegetation density (t ha^{-1})	Soil Texture	Slope angle (degree˚)
Logged slope	Disturbed sloped/thick undergrowth following several small tree falls/ small canopy gaps	4	*250.47	clay loam	19 - 33
Skid track	Heavily disturbed log feeder road /small canopy gaps	4	*257.65	loam	16 - 24
Control plot	Undisturbed slopes/ control/no harvesting/ no sign of animal disturbance	1	*663.87	Silt loam	12

Source: Hue, 2017 (unpublished data).

RESULTS AND DISCUSSION

Basic physical properties of investigated soil

The soil texture were categorized as silt loam, clay loam and loam for control, logged slope and skid track, respectively. Bulk density varies within the study sites, ranged from 0.77 – 1.18 g cm^{-3} at the surface, 0.92 – 1.20 g cm^{-3} at 10 cm depth and 0.98-1.31 g cm^{-3} at 15cm depth. Mean dry bulk density amounted to 0.89 g cm^{-3}, 1.16 g cm^{-3} and 1.23 g cm^{-3} for plot undisturbed, disturbed and skid track respectively. These figures are broadly similar to the previous studies at the same site (Nussbaum, 1993; Clarke, 2002; van-der Plas & Bruijnzeel, 1993). Table 2 shows the bulk density value from different post logging period in the same study site.

Table 2. Bulk density (g cm^{-3}) of soil taken from different post logging period

Period after logging	Bulk density (g cm^{-3})			Reference
	Undisturbed slope	Logged slope	Skid trail	
18 months		1.07	1.44	Nussbaum (1995)
12 years	0.98-1.26	1.11-1.35	1.31-1.37	Van-der Plas & Bruijnzeel, (1993)
15 years		1.13	1.20	Clarke (2002)
28 years	0.77-0.98	1.0-1.27	1.18-1.31	*This study*

Values of bulk densities on the heavily disturbed sites are still significantly higher than in undisturbed area. Clarke (2002) noticed that the difference of bulk density value in Danum area is not significant even after 10 years of the study. This result agrees with Hakansson and Lipiec (2000) which indicated that compaction of top soil, required a long period to neutralize and tend to be permanent. Also, Alexander (2012) reported that 40 years after logging has not produced significant difference in soil compaction.

The value of bulk density often associated with penetration resistance of soil. Average figures of resistance obtained from the study sites in the study site are shown in Table 3. Likewise, the value of mean resistance is higher in skid track compared with other sites. The average dry bulk density increased considerably with depth in the top 15 cm of soil. Bulk density typically increases with soil depth since subsurface layers are more compacted and have less organic matter, less aggregation, and less root penetration compared to surface layers, therefore contain less pore space. Average values of soil bulk density associated with the difference disturbance elements within the logged forest. This study observed that vegetation density is lower on high compacted compared to non-compacted soil. Whether compaction was sufficiently severe to decrease root penetration or reduce tree growth is unknown. Additional research is clearly needed in this area to quantify the consequences of soil disturbance for tree performance.

Table 3. Average soil strength in the study site (resistance to penetration)

Plot	n	Mean resistance (Kpa)	St.d
Control plot	24	71.1	10.2
Logged slope	22	72.7	13.8
Skid track	28	88.1	25.5

Hydraulic conductivity

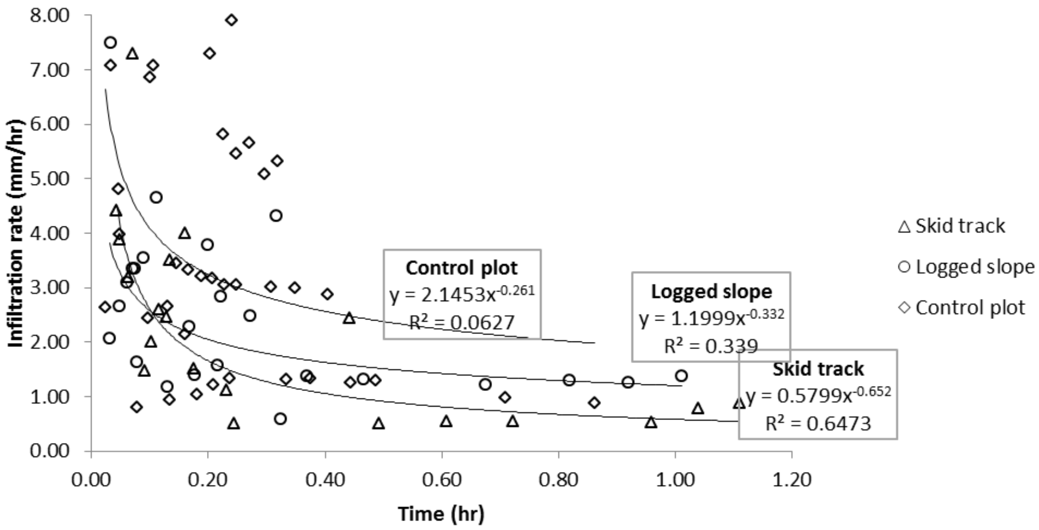

Figure 2. Changes in infiltration rates with time in different disturbance

Hydraulic properties of soil are one of the most important agents controlling soil infiltration rates and runoff generation (Blanco-Canqui *et al*., 2002). Logging operation can decrease the soil's ability to infiltrate and distribute water into forest soils (Ziegler *et al*., 2006) yet few thorough studies have been reported from tropical region. Measurements of infiltration rates were made on undisturbed forest soils and on adjacent soils, which were severely disturbed by the passage of skidders during timber harvesting. The highest infiltration rates were found on control plot; hydraulic conductivity (K_s) was range from 0.22 to 2.54 cm hr^{-1} in average. Relatively lower K_s value for the logged slope and skid track that ranged from 0.36 to 2.05 cm hr^{-1} and 0.16 to 0.83 cm hr^{-1} respectively. Infiltration curve for the different surface types are presented in Figure 2.

Table 4. Comparison of saturated hydraulic conductivity (K_s) measured by different methods

K_s range (cm hr^{-1})	Method	Reference
0.14 -2.53	Mini disk inflitrometer (Decagon devices)	*This study*
15.6 – 30.5	Talsma ring permeameter	Bidin *et al.*,(1993)
1.5 – 8.8	Double ring infiltrometer	Van-der Plas & Bruijnzeel, (1993)

As shown in Table 4, the results from different measuring method are varied. This variation can be explained by the different method used to measure hydraulic conductivity in the field (Mohanty *et al*. 1994). Also, it has been demonstrated by numerous study that the infiltration rates are greatly affected by the properties of the soil (eg: Leiveci *et al*., 2016; Zemke, 2016; Jadczyszyn & Niedźwiecki, 2005). For example, Mazaheri and Mahmoodabadi (2012) found that the increasing percentage of sand have intensified influence on final infiltration rate, while silt and clay content have the reverse influence. This also agrees with Haghnazari et al. (2015) who reviewed that soil texture determines the average pore size which water can infiltrate into the soil. While soil textures in the studied plots are generally comparable, it is important to consider other soil characteristic, for example, soil compaction (Table 2). In this study, lowest infiltration rates were found in skid track plot where the bulk density is the highest. This study agrees with Luckow and Guldin, (2007) who indicates that the increasing of bulk density resulting in a much lower water infiltration rate into soil. Also, study elsewhere in Sabah reported a reduction of infiltration capacity after tractor passes (Malmer & Grip, 1990). Lower rates of soil infiltration, will produce more surface runoff and direct soil loss (Jadczyszyn & Niedźwiecki, 2005). Sinun *et al*. (1992) reported that surface runoff from abandoned track is markedly increase ten times higher compared with that in undisturbed forest.

Rainfall and runoff

In an average year, the climate of this tropical forest is very humid because of all the rainfall. There is a little variation in the amount of rainfall throughout the year. Rainfall amount varies from 2874.2 mm in 2014 and 2199.6 mm in 2015, with the total of 202 rainy days in 2014 and 204 rainy days in 2015. The percentage of throughfall catches from 3354.68 mm of gross rainfall was 64.8 %, 80.7% and 76.4% in control, logged slope and skid track respectively (Table 5). Throughfall percentage was found highest in the lowest vegetation density. The variation of throughfall percentage is often linked with the vegetation density.

Table 5: Vegetation density and throughfall amount

Plot	Vegetation density (t ha^{-1})	Crown area (m^2)	% Throughfall
Control	*663.87	*5819.3	64.8
Logged slope	*250.47	*3342.9	80.7
Skid track	*257.65	*3241.1	76.4

*Source: Hue, 2017 (unpublished data).

A number of observational studies reported that forest canopy affect the amount of rainfall reaching forest soils (Chappell *et al*., 2001; Nunes *et al*., 2011; Asdak *et al*., 1998; Bidin *et al*., 2003). Other studies reported that other vegetation characteristic such as total leaf area, leaf area index and total surface area correlated with amount of rainfall intercepted (eg: Li *et al*., 2016; Xiao & McPherson, 2011). Forest floor interception is also an important mechanism that precedes infiltration or runoff (Tsiko *et al*. 2012; Gerrits & Savenije, 2011).

Figure 3 shows the relationship between rainfall and runoff in the study site. Notice that precipitation value of each plot site may vary due to the spatial variability of rainfall. As expected, runoff was generally higher from logged slope than from either of the other plots. The total runoff volume from each plot in the period under study were 307.38 L, 667.97 L and 778.08 L for control, logged slope and skid track respectively. These represent runoff depths of 153.7mm, 334 mm and 389 mm for control, logged slope and skid track plot respectively, produced by a total gross rainfall of 3354.68 mm. It was observed in the present study that stemflow constituted a small percentage (2%) of gross rainfall on average; therefore it was treated as minor component in this study.

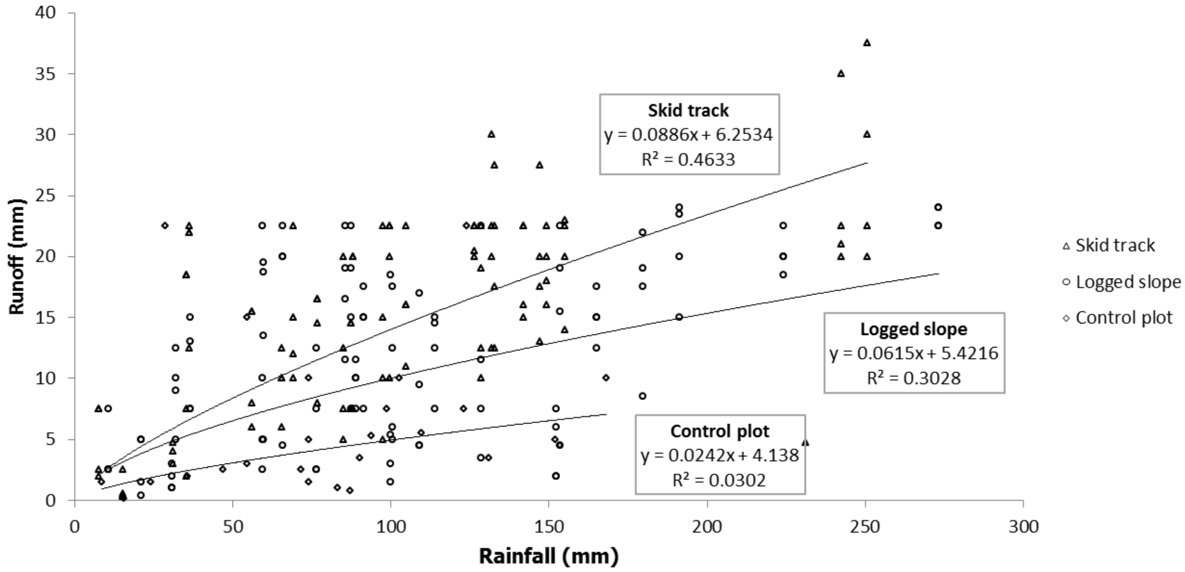

Figure 3. Runoff generated from rainfall

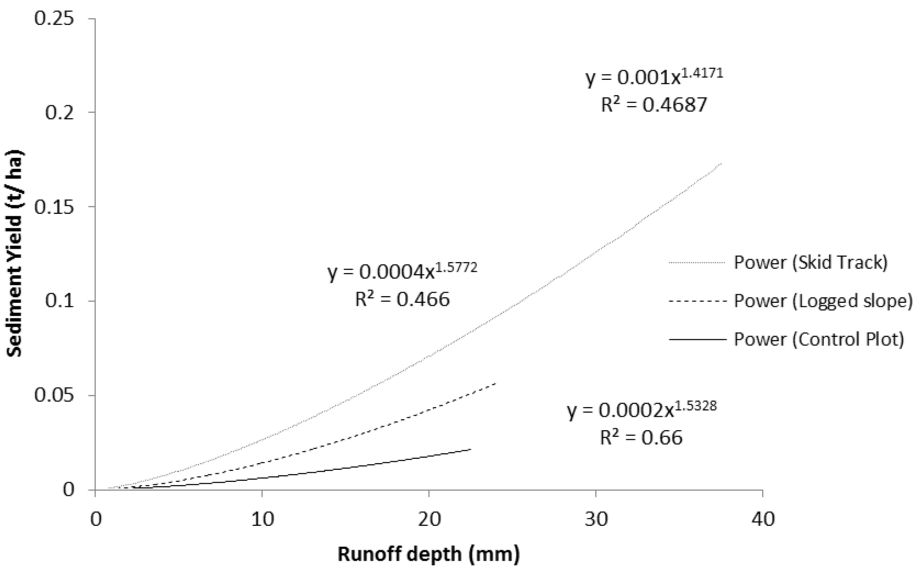

Figure 4. Relationship between runoff depth and sediment yield computed in this study.

Runoff is increasing with the increased value of rainfall. Runoff and rainfall does not show a significant relation due other factor that may influence the value of runoff depth. Each plot has different characteristic that influence the rates of runoff generation. According to Thanapakpawin *et al*.(2007), steep hillsides with slopes exceeding 25% tend to have higher rates of soil erosion which prevents advanced soil development, thus soils at these area have relatively shallow and have limited water holding capacity. Other studies also reported the significant effect of slope on runoff and soil losses (Khan *et al*., 2007; Lal, 1988).While this is not the case, as the highest runoff volume in this study was not from the steepest angle. Supposedly, disturbed slope (28°) produced more runoff than skid track (16°) if slope angle were taken into account, but it was found that the highest yield were resulting from skid track even though there is a big different of slope degree. The impact of runoff generation on sediment yield calculated using simple linear regression is presented in Figure 4.

Soil losses ranged 8.0 x 10^{-5} t ha^{-1} to 0.99 t ha^{-1}. Sediment yield reached its maximum value (0.99 t ha^{-1}) in November 2015 when the highest precipitation occurred (327 mm). The lowest sediment yield was recorded in February 2016 reaching in control plot. The magnitude of runoff and soil loss from individual skid track plot was found to be the highest (2.72 t ha^{-1} yr^{-1}), followed by logged slope (2.56 t ha^{-1} yr^{-1}) and control plot (0.13 t ha^{-1} yr^{-1}). The rates of soil erosion in undisturbed plot (control) appear lower than previous findings that obtained at the same study site. Earlier, Sinun *et al.* (1992) obtained value of sediment loss ranged from 0.2 t ha^{-1} yr^{-1} to 0.29 t ha^{-1} yr^{-1} in undisturbed plot. Similarly, rates measured on skid track and logged slope during the research period are much lower than the previous findings at the same catchment. For instance, Douglas *et al*. (1992) noted that during main logging phase, erosion rates reported was 55.8 t ha^{-1} yr^{-1}. The rates decreased to 11.2 t ha^{-1} yr^{-1} one year after logging. During pre-logging period in 1989, short-term investigation using bounded plots on skid trails showed that unprotected skid trail plot had a sediment yield of 190.5 t ha^{-1} and after a year, the rate reduced to 10.5 t ha^{-1} (Douglas, 2003). The differences between soil erosion rates in this study and previous studies, suggests that soil erosion is slowly reduced, but not yet fully recovered even after 27 years since logging ceased.

Soil surface conditions of the study site may play an important role in determining the rate of erosion between the run off plots (Haghnazari *et al*., 2015). In this study, highest sediment yield occurred in skid track which also has the highest value of bulk density (1.23 g cm^{-3}) and resistance to penetration (88.1 Kpa). Whilst the lowest yield occurred in control plot which has lowest bulk density (0.89 g cm^{-3}) and resistance to penetration (71.1 Kpa). In a separate study, Anand *et al*. (2015) reported regenerating logged forest has lower sediment yield in medium to large storms compared to the undisturbed forest, indicating the important role of understory vegetation for erosion protection. Likewise, Sinun *et al*. (1992) observed that vegetative cover, soil organic matter and soil faunal activity could be an important factor that leads to higher erosion rates within plots. Also, the amount of sediment that ran off the plots in the study period could be varied according to the amount of runoff, as well as the intensity and duration of rain (Jadczyszyn & Niedźwiecki, 2005).

CONCLUSION

This study shows that soil surface conditions are one of the major factors controlling the rates of erosion. It was observed that rates of soil losses are higher in the area with high compacted soil. Higher compacted soil increase the resistance of penetration of soil, thus reduce the infiltration rates of soil, resulting high amount of runoff generated and sediment yield. Also, even with the high amount of rainfall of a given surface disturbance, other factors may interplay to cause a significant difference in rates of soil erosion. Large-scale surveys of soil losses may be useful for predicting adverse changes in the forest environment. Furthermore, these results should be viewed as preliminary because there was other research treatment that is not included and with lack of primary forest data.

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