Soil erosion in disturbed forests and agricultural plantations in tropical undulating terrain: *in situ* measurement using a laser erosion bridge method

N. A. Mohamad, A. Nainar, K. V. Annammala, D. Sugumaran, M. H. Jamal and Z. Yusop

ABSTRACT

The rapid growth of agricultural plantations and climatic extremes has raised concerns pertaining to enhanced soil erosion. Soil erosion studies are still relatively limited in Malaysia. In this study, soil erosion in four sites such as high conservation value forests (HCVFs), logged forest (LF), mature oil palm (MOP), and mature rubber (MR) within the Kelantan River Basin was measured. A total of 3,207 measurements were conducted via the Modified Laser Erosion Bridge in all sites over 1 year. Results of soil erosion are 87.63, 25.45, 8.44, and 5.90 t ha^{-1} yr^{-1} for the HCVF, LF, MOP and MR, respectively – classified as very severe (HCVF), very high (LF), moderate (MP) and slight (MR) according to the Indian condition classification. Steep slope gradient (significant positive correlation to erosion) and logging are the main factors attributed to the high erosion rates. This is to be further explored in the future and more detailed studies should be conducted on the HCVF and LF areas, respectively. Mitigation measures and sustainable agricultural practices should be planned to control and reduce soil erosion.

Key words | agricultural plantation, erosion, forest, land use, logged forest, slope gradient

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INTRODUCTION

Soil erosion, although a naturally occurring process, may be accelerated by human-induced activities. A land-use change alters slope topography, soil properties, and vegetation cover, thus accelerating soil erosion. Changes in topography, vegetation, and land cover directly affect hydrological dynamics (Duan *et al.* 2015; Nainar *et al.* 2018), erosion rates (Clarke & Walsh 2006; Walsh *et al.* 2011), and ecological processes (Luke *et al.* 2017) by altering the exposure of ground surfaces (Jeloudar *et al.* 2018). Besides changes in ground cover, significant changes in soil characteristics that lead to soil loss and degradation have also been documented (Giang *et al.* 2017). Although many erosion-related investigations have been conducted throughout the world, studies from Malaysia are still limited (Hashim *et al.* 1995; Walsh *et al.* 2011; Annammala *et al.* 2012).

Annually, Southeast Asia loses over 900,000 ha of forests to logging, conversion to agriculture and urbanisation – one of the highest rates of land-use change in the world (Catacutan *et al.* 2017; Luke *et al.* 2017). In Malaysia, 74,000 ha of permanent forest reserve were converted to new timber latex clone rubber plantation between 2005 and 2009 (Lim 2013). Within the last two decades, oil palm has been the main crop of interest in this country where the total planted area increased by 1.3% from 5.47 million ha in 2016 to 5.81 million ha in 2017 (Malaysia Palm Oil Board 2018). A large proportion of this is located

doi: 10.2166/wcc.2019.063

in Peninsular Malaysia (2.7 million, 46.6%), while the states of Sabah and Sarawak have 1.56 million (26.8%) and 1.55 million (26.6%), respectively (Malaysia Palm Oil Board 2018). To date, the Lebir catchment, the area of focus in this paper, consists of oil palm plantations and land conversion is still actively ongoing.

Besides land-use changes, the relationship between erosion and climate change, especially that of rainfall regime (amount, intensity, and distribution), has been increasingly garnering interest in recent decades. Although having an equatorial climate without extreme temperatures, Malaysia is at times subjected to monsoonal storms as a result of two major monsoon periods in the subtropics – northeast monsoon and southwest monsoon (Loo *et al.* 2015). Rain during these periods is known to have triggered episodic floods and landslides (Billa *et al.* 2004). One of the worst incidents is during the 1967 Kelantan flood. A total of 636,700 people were affected, including loss of lives, property, and farmland (Tuan & Hamidi 2013; Alias *et al.* 2016).

This paper aims to quantify the soil erosion rate in different land uses in the east coast of Peninsular Malaysia (Kelantan state) over the period of one year – covering both high and low rain periods as affected by the monsoon. Erosional impact of forest conversion to agricultural plantations and slope gradient will also be analysed and discussed.

Study area

The state of Kelantan is located in the eastern region of Peninsular Malaysia. It is situated between latitude (4°–6°N) and longitude (101°–103°E). The Kelantan river originates from northeast of Peninsular Malaysia. It is divided by two major rivers which are Galas and Lebir. The study was conducted in the Lebir catchment that drains an area of approximately 2,500 km^2 (Figure 1). The climate is hot and humid all year round with a mean annual precipitation of more than 2,500 mm between 1975 and 2004 (Alias *et al.* 2016; Tan *et al.* 2017). Distinct long droughts and wet periods do not occur, but higher rainfall (amount, duration, and intensity) occurs between mid-October and mid-January, whereas March to May receives relatively less rainfall as affected by the regional monsoonal cycle. The general geology is complex, but mainly comprises (i) interbedded sandstone, silts and shale from the Triassic group, (ii) intermediate to basic volcanic which are mainly pyroclastic, and (iii) a smaller extent of phylliate, slate and shale with subordinate sandstone and schist from the Permian group (Ibbit *et al.* 2002). Land use is mainly dominated by agricultural plantations (timber latex clone rubber, oil palm, and paddy) at the lower reaches, but the headwaters and steep mountainous areas are still forested (classified as Permanent Reserved Forest and Virgin Forest Reserve). At present, land-use changes from logged forests (LFs) to the agricultural plantation of either rubber or oil palm are still taking place at some parts of the Lebir catchment.

METHODOLOGY

Experimental design

Soil erosion rates were measured and monitored from March 2017 to February 2018 at four different sites: (a) high conservation value forest (HCVF) – an area of forest where harvesting activities are prohibited. This site is similar to a primary forest and acts as a control site; (b) LF – an area that was left to regenerate after logging without any restoration measures; (c) mature oil palm (MOP) plantation – planted in 2009 (10 years old); and (d) mature rubber (MR) plantation – planted in 2006 (13 years old) (Figure 1). Palm trees are considered to have achieved a mature state at 3 years of age while rubber at 7. The MOP site and the MR site are the two most abundant tree crops in Malaysia.

Characteristics of the monitored sites are summarised in Table 1. The mean bulk density for forests is less than 1.0 g cm^{-3} while that of agricultural plantations is more than 1.0 g cm^{-3}. The highest mean slope was found in HCVF (33°) followed by LF (30°), MOP (22°) and MR (16°). From March 2017 to March 2018, the mean ground cover for HVCF and MR decreased by 21% and 17%, respectively, while it increased by 13% in both the LF and MOP. The mean canopy cover for the same period increased in all sites – 9% (HCVF), 40% (LF), 35% (MOP) and 18% (MR).

Erosion transects were installed and numbered from top to bottom of a hillslope in ascending order (Figure 2). All transects were randomly placed on hillslopes except in HCVF where extreme slopes (>30°) were selected. This was done because erosion results from the normal slope

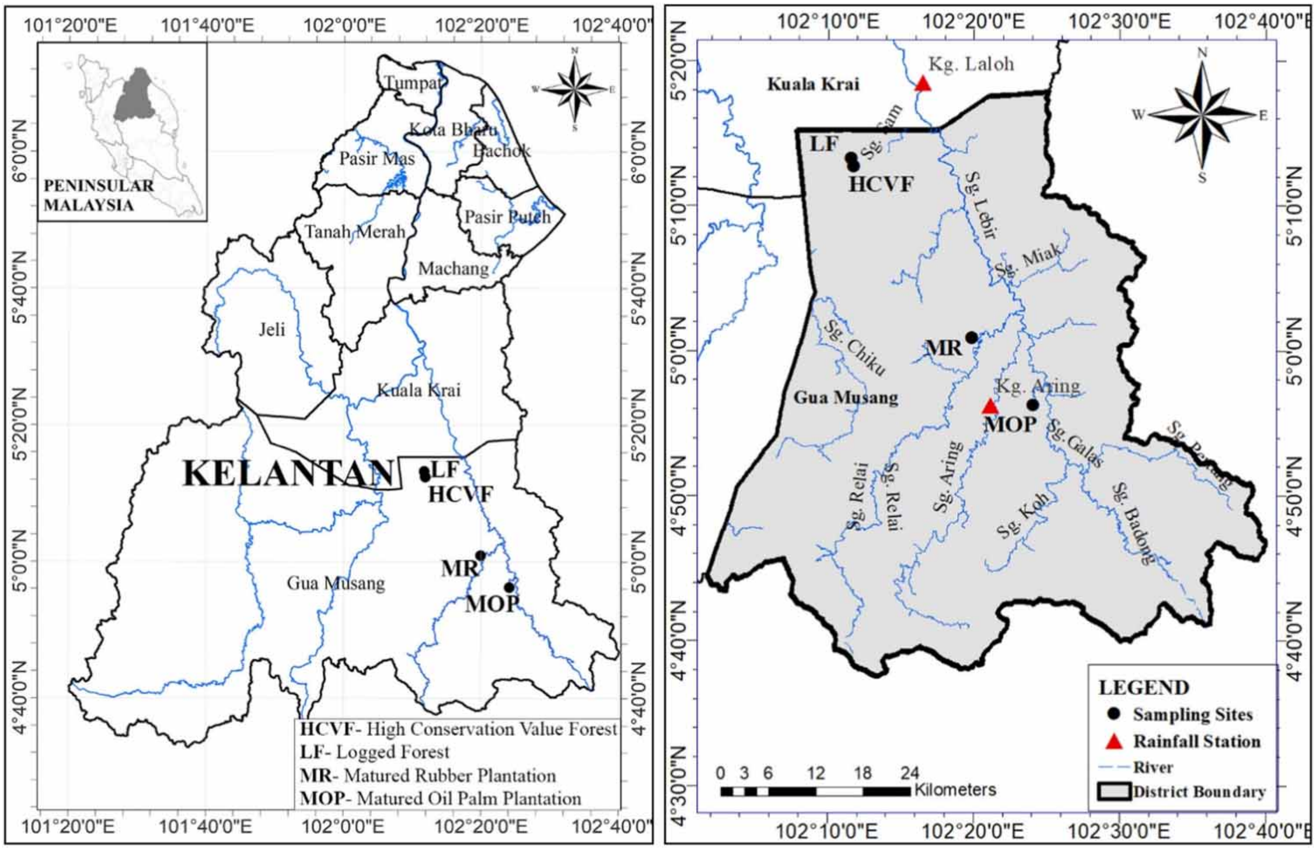


Figure 1 | The Lebir catchment and location of transect sites.

Table 1 | Summary of characteristics of the soil erosion observation sites

Site ID	*n*	μBD (g cm^{-3})	μ slope (°)	μ ground cover (%) 1[a]	μ ground cover (%) 2[b]	μ canopy cover (%) 1[a]	μ canopy cover (%) 2[b]
HCVF	16	0.91	33	27	6	86	95
LF	17	0.84	30	10	23	53	93
MOP	27	1.26	22	16	29	50	85
MR	47	1.18	16	17	0	53	71

n = Number of transects.
[a]March 2017.
[b]February 2018.

(0–25°) in pristine forests have been documented in the past (Walsh *et al.* 2011, 2017; Annammala *et al.* 2012;), but those in extreme gradient slopes remain less explored. At each site, several soil samples were collected to determine the soil bulk density that was determined using the 3B4a code method (Burt 2004).

Data acquisition

Measurements of ground lowering were carried out using the Modified Laser Erosion Bridge (MLEB) technique, as shown in Figure 3 (Mohamad *et al.* 2018 modified after Annammala *et al.* 2012). The erosion bridge is 3 m in length, marked with a scale of 10 cm intervals (30 points in total). This erosion bridge was affixed in-between two permanent poles (balance was checked using a bubble leveller) driven firmly into the ground. Net changes in the ground level (whether erosion or deposition) were measured every 3 months by means of a microprofiler and averaged. Ground-lowering rates in the study area were then converted to erosion rates with the unit of ton per hectare per year (t ha^{-1} yr^{-1}) by using the following equation:

$$ER(\mathrm{t\,ha^{-1}\,yr^{-1}}) = 10BD \times GL \quad (1)$$

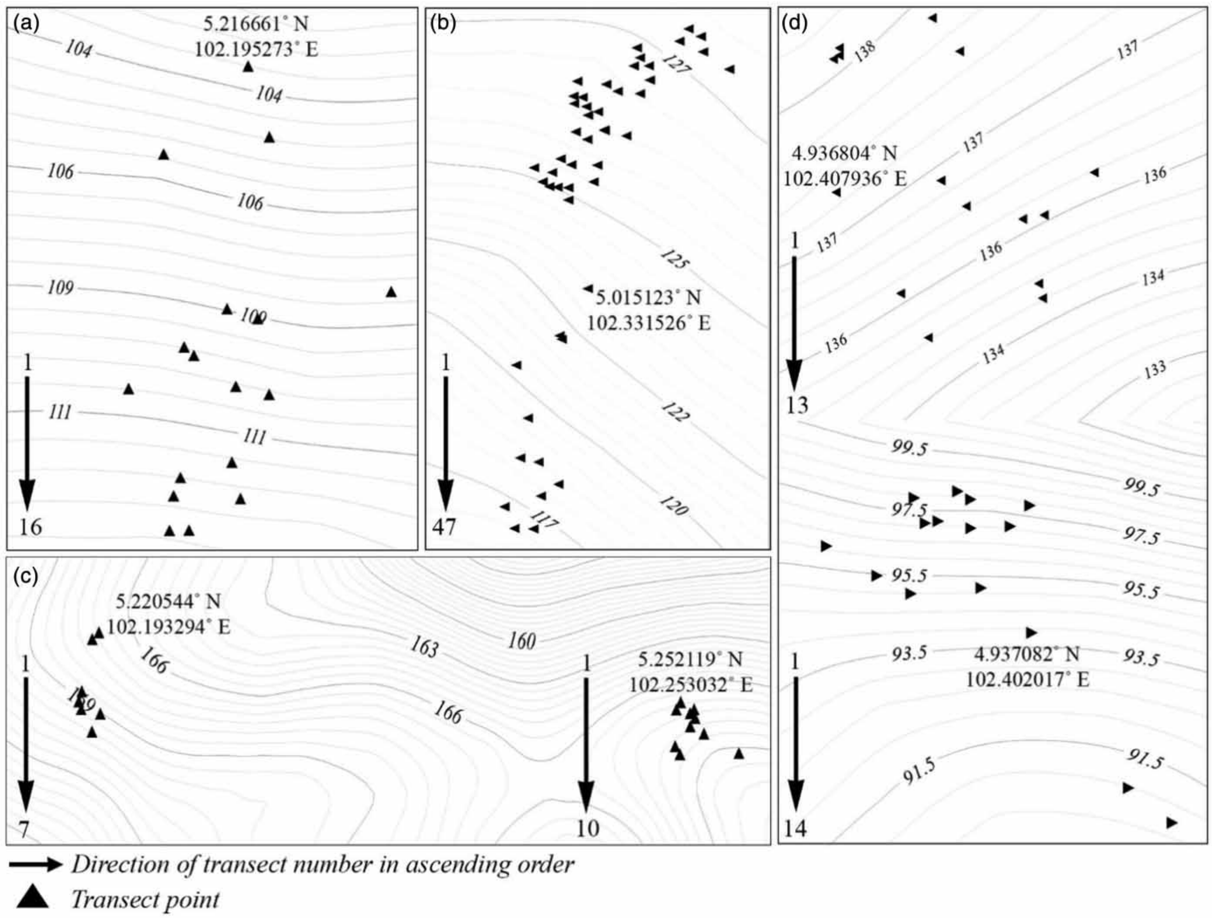


Figure 2 | Transect points in each site. (a) HCVF, (b) MR plantation, (c) LF and (d) MOP plantation.

where BD is the bulk density in g cm^{-3} and GL is the erosion rate in mm yr^{-1} (Clarke & Walsh 2006). The mean soil bulk density data are given in Table 1 for different land uses.

Monthly rainfall data from two nearby rainfall stations, Kg. Aring (4.9375°N, 102.3528°E; near MOP and MR) and Kg. Laloh (5.30833°N, 102.275°E; near HCVF and LF), were acquired from the Department of Irrigation and Drainage.

Statistical analyses

The Shapiro–Wilk test was first performed to test for the normality of data. Following this, the non-parametric Kruskal–Wallis H test was used to evaluate the differences in the erosion rate among different land uses ($\alpha = 0.05$). In addition, Spearman's rho correlation analysis was used to examine the relationship between soil erosion and slope gradient. All statistical analyses were performed using SPSS V.24.

RESULTS AND DISCUSSION

Rainfall over the monitored period

Annual rainfall recorded from March 2017 to February 2018 is 2,107 and 2,082 mm for Kg. Aring and Kg. Laloh, respectively (Figure 4) – both of which are lower than the mean annual rainfall for Kelantan. High rainfall occurs in June to January, and the highest rainfall was in November (387 and 536 mm for Kg. Aring and Kg. Laloh, respectively). February and March were relatively dry months. Differences in rainfall amount between the

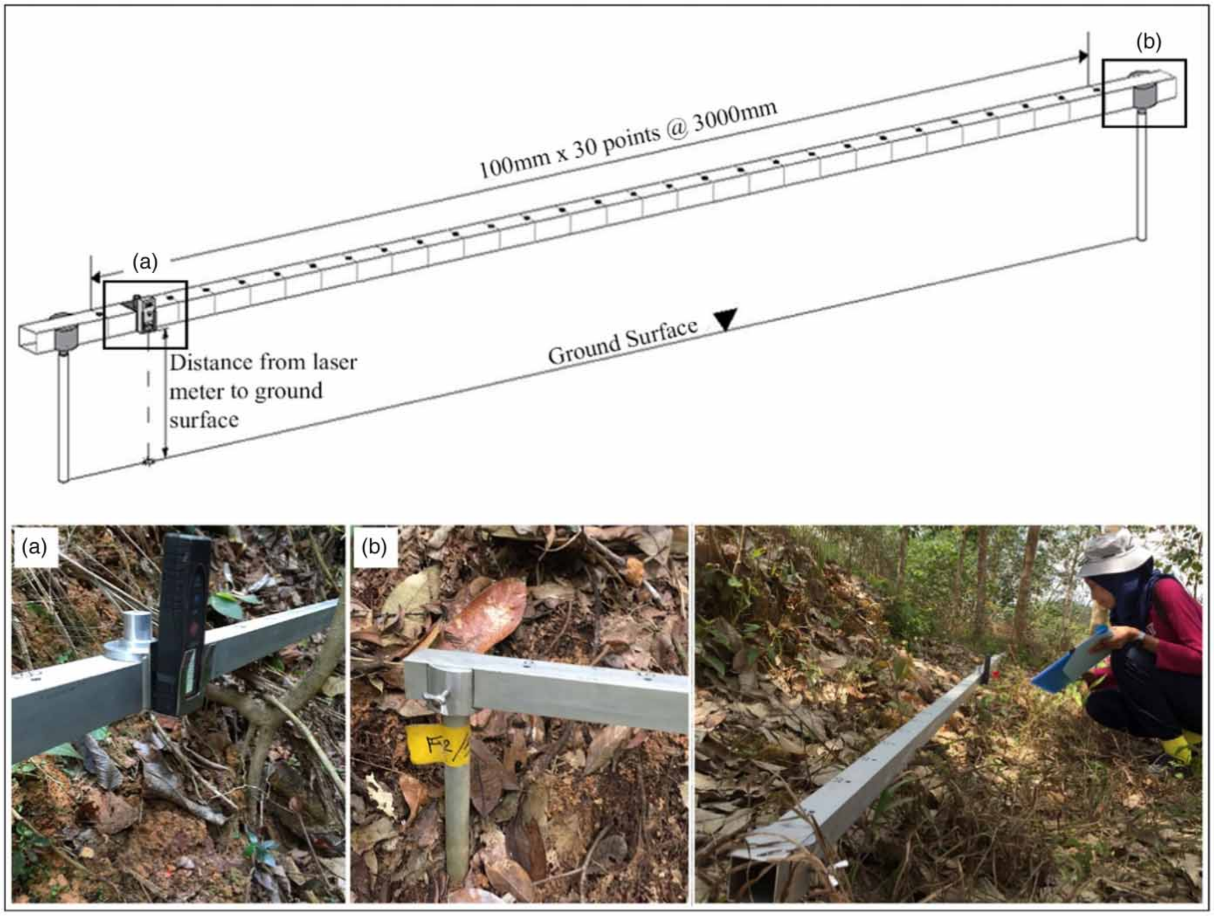


Figure 3 | Modified Laser Erosion Bridge (a) Laser meter with holder and (b) Connector (Mohamad *et al*. 2018).

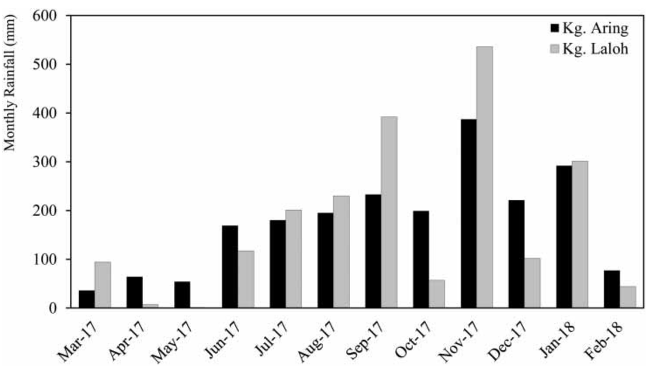


Figure 4 | Monthly rainfall over the monitored period in the Lebir catchment.

rain gauges as well as compared to central Kelantan may be due to localised convective and orographic rainfall that are commonly found in inland mountainous areas (Nainar *et al*. 2018).

Magnitude of the ground-lowering rate in different land uses

Changes in ground height, whether deposition or erosion is denoted by positive (+) and negative (–) signs, respectively. Figure 5 shows the ground-lowering rates between different land uses. HCVF recorded the highest count of erosion readings where only two extreme readings were found to record deposition. In LF, erosion readings were also more than that of deposition. MOP and MR, on the other hand, show almost equal records of erosion and deposition. The mean ground height change ranges from –1.23 to –21.30 mm for the HCVF, +15.66 to –19.87 mm for LF, +8.00 to –11.53 mm for MOP and +8.60 to –8.77 mm for MR.

The shape of boxplots (mean ground height change) in both MOP and MR is almost symmetrical, but HCVF and LF are skewed towards erosion. There were nine extreme

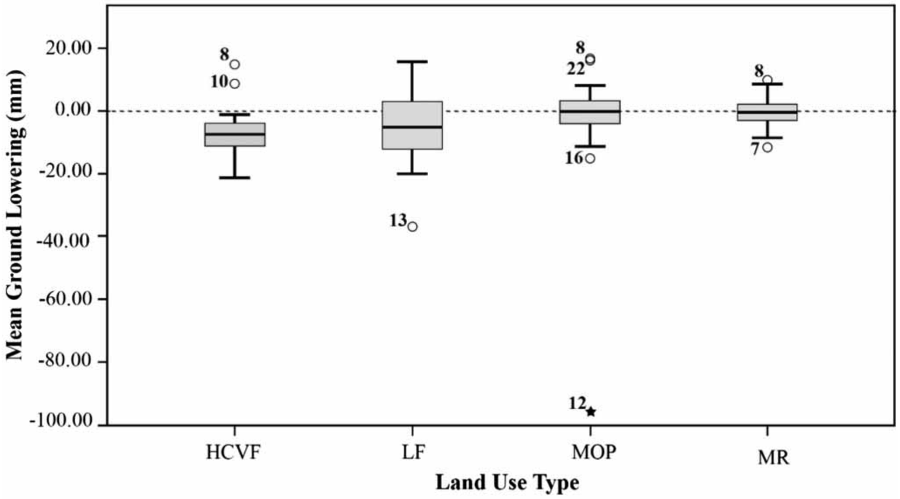


Figure 5 | Mean ground-lowering rate in different land uses.

values that were excluded at this stage for future detailed analyses over the pattern for long-term monitoring. Although not analysed statistically, these extreme values are briefly discussed. Extreme values may be caused either by severe ground surface changes or by unwanted disturbances such as being stumped by wild animals or impacted by falling trees or rocks (Giang *et al.* 2017). Changes in the soil profile for the extreme values are shown in Figures 6(a)–6(i).

HCVF transects (Figures 6(a) and 6(b)) indicate normal deposition and erosion pattern. Similar conditions occurred in the MOP transects (Figures 6(d)–6(f)). Transect 12 (Figure 6(g)) is an exception where excessive soil erosion (landslide) occurred due to the position of the transect that was very close to the vertical wall of the terrace. Conversely, erosion was observed in the LF transect (Figure 6(c)), which may have happened due to high exposure of the surface soil from logging. Extraordinary soil movements were recorded in the MR transect (Figures 6(h) and 6(i)), which may be due to the uneven ground surface caused by 'soil lumps' as shown in Figure 7. This phenomenon occurs when soils have different strengths due to disruption of the original soil condition during forest conversion to the plantation. Softer soils will be easily eroded as compared to locally compacted, stronger soils.

Effect of land use on soil erosion

The mean values of ground-lowering and erosion rates in different land uses are presented in Table 2. The highest mean annual erosion rate was found to be in HCVF at 87.63 t ha^{-1} yr^{-1}, while the lowest in MR at 5.90 t ha^{-1} yr^{-1}. The LF and MOP are positioned in the second and third place at 25.45 and 8.44 t ha^{-1} yr^{-1}, respectively. These results can be compared to that of Clarke & Walsh (2006), who computed annual erosions at 4.25 t ha^{-1} yr^{-1} within the primary forest area in East Malaysia. As a result, the primary forest has the lowest erosion rate when compared to other land-use types in this paper (primary forest < MR < MOP < LF < HCVF).

The mean annual soil erosion can be classified into six levels of severity based on Kisan *et al.* (2016). As mentioned by Kisan *et al.* (2016), India receives heavy rainfall with an annual average of 2,000 mm, which is similar to the annual rainfall in the current study site. The highest erosion rate in the HCVF (87.63 t ha^{-1} yr^{-1}) may reflect its steep topography. The second highest erosion rate in LF (25.45 t ha^{-1} yr^{-1}) may be linked to land-surface disturbances from logging, but this needs to be further investigated. The MOP and MR have moderate (8.44 t ha^{-1} yr^{-1}) and slight (5.90 t ha^{-1} yr^{-1}) erosion, respectively. Mitigation measures and further investigations should therefore be focussed on HCVF and LF.

Previous studies have found significant relationships between soil erosion and land uses (Sun *et al.* 2014). The test, which was corrected for tied ranks, was found to be significantly different $x^2(3, N = 98) = 22.64$, $p < 0.05$, with mean ranks of 18.04 for HCVF, 44.38 for LF, 56.67

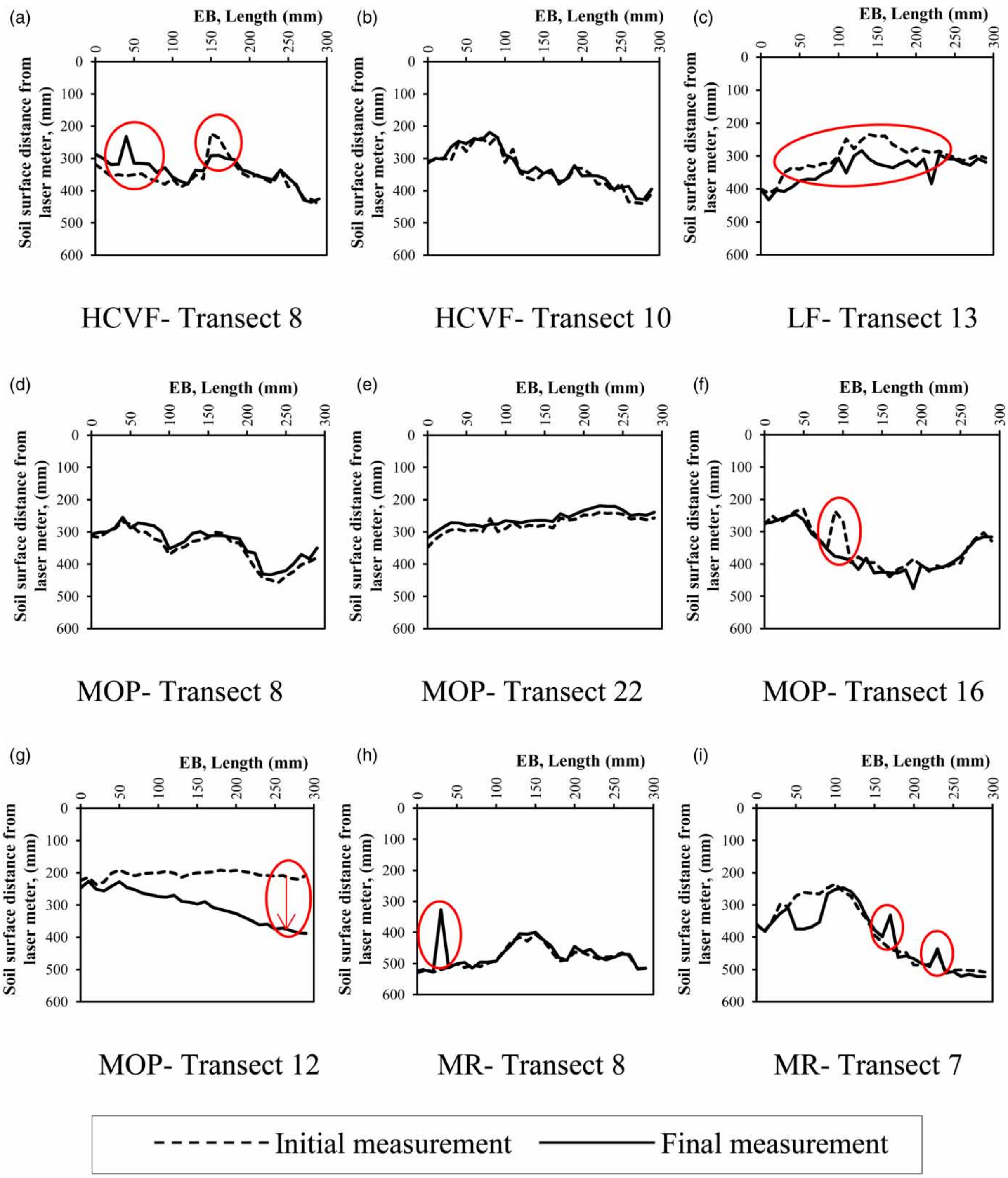


Figure 6 | Profile of ground-level changes (extreme values).

for MOP, and 57.44 for MR. The proportion of variability in the ranked dependent variable accounted for by the variable, land use, was 0.23, indicating a strong relationship between land use and the erosion rate. *Post hoc* tests were conducted to evaluate pairwise differences among the six groups, controlling for Type I error across tests by

Figure 7 | Soil lump.

Table 2 | Soil erosion rates in different land uses

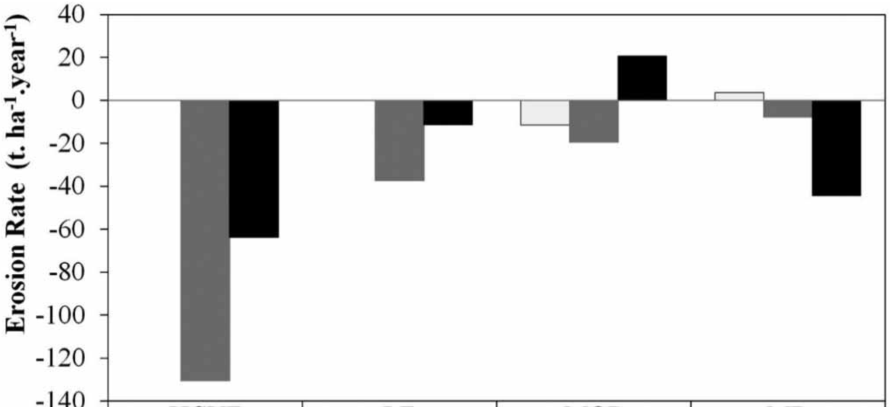
	Annual ground lowering			
Land use	**Mean (mm a^{-1})**	**SD**	**Annual erosion rate (t ha^{-1} yr^{-1})**	**Soil erosion class (Kisan *et al.* 2016)**
Primary forest	−0.36 (Clarke & Walsh 2006)	4.25	Nill	
MOP (Borneo)	−6.38 to 43.72 (Annammala *et al.* 2012)	Nill	Nill	
HCVF	−9.63	5.92	87.63	Very severe
LF	−3.03	10.16	25.45	Very high
MOP	−0.67	5.31	8.44	Moderate
MR	−0.5	3.76	5.9	Slight

using the Bonferroni approach. The results of these tests showed a significant difference ($p < 0.05$) between the pairs HCVF–LF, HCVF–MOP, and HCVF–MR.

The standard deviation (SD) in each site does not only show the uncertainty of the data but also indicates the variation in ground movement. Small SD values indicate that there are no extreme variations in soil movement among all transects in an observed site as found in HCVF, MOP, and MR. The high SD values at LF may convey that each transect responds differently to different factors and conditions. Logging activity has altered the original properties of natural topography. Substantial alteration of the topography may have changed the structure and stability of soils, as well as canopy cover. These factors enhance the erosion process (Giang *et al.* 2017).

Effects of slope on soil erosion

The slope gradient is one of the crucial topographical properties that should be considered when observing soil erosion on hillslopes. Soil erosion rates may be a lot higher on steeper slopes under the same rainfall conditions (Liu *et al.* 2001). Previous studies have found that erosion has a strong positive relationship with slope gradient (Sun *et al.* 2014; Bao *et al.* 2018). Results from Spearman's rho show a weak positive linear relationship, $r(61) = 0.34$, $p < 0.05$, two-tailed. Insufficient data points in relation to the large changes in soil level may have caused this weak correlation. Another possible reason is that although erosion and deposition may be high and frequent, the net soil movement remained low because of the similar magnitudes of erosion and deposition that cancel one another out. Besides this,



	HCVF	LF	MOP	MR
□<15°	Nill	Nill	-11.61	3.75
■15°-30°	-130.49	-37.36	-19.57	-7.83
■>30°	-63.77	-11.21	20.47	-44.32

Figure 8 | Mean erosion rate within three slope classes; <15°, 15°–30°, >30° in different land-use types.

soil movement is also affected by soil compaction, loosening and weathering (natural and biological).

Both HCVF and LF showed high erosion rates for slopes of 15° – 30°, while MOP showed an increase in soil loss in the <15° slope category, but with deposition at higher slope class, as shown in Figure 8. From field observation, it was noted that this site was located adjacent to a large tree with big buttress roots that acts as a retaining wall, thus retarding erosion. In the case of MR, the deposition was observed at the lowest slope class, but this gradually changed to erosion as slope class increased.

CONCLUSIONS

High rainfall intensity may trigger high soil erosion rates, but various *in situ* factors may also exert influence. Therefore, the assessment of soil erosion within tropical regions is necessary. Additionally, measuring soil erosion at the hillslope scale using the MLEB method and comparing these values between different land uses are an emerging research in the tropics that serves to fill the knowledge gap relating to erosion rates within large-scale agricultural plantation (rubber and oil palm plantation). Based on the annual soil erosion rates and according to a relatable soil erosion classification from India, the studied area can be classified as having severe erosion for HVCF (87.63 t ha^{-1} yr^{-}), very high for LF (25.45 t ha^{-1} yr^{-1}), moderate for MOP (8.44 t ha^{-1} yr^{-1}) and slight (5.90 t ha^{-1} yr^{-1}) for MR. HCVF and LF should be prioritised for erosion and sediment control plans. The relationship between the soil erosion rate and the slope gradient shows a weak positive relationship. Continuous long-term monitoring that includes other factors is needed to better understand the soil erosion rate in different land uses. Extreme values may contain messages of environmental processes that can only be understood through focussed, detailed analyses.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Rasmussen Foundation Funds, USA for providing the project grant entitled Transference from Crime Scene to Forensic Evidence: Linking Land-use, Erosion, Sediment and Quantitative Evaluation of Erosion in Kelantan River Basin, Malaysia and Universiti Teknologi Malaysia (Vote 4B243) as financial support for this project. They would also like to express their gratitude to the Forestry Department Peninsular Malaysia (JPSM) and Felda Global Ventures Plantations Sdn Bhd (FGV).

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First received 10 March 2019; accepted in revised form 20 August 2019. Available online 9 October 2019