Runoff and Soil Erosion Response to Clear Cutting Period of Acacia Plantation in A Headwater Mountain of Vietnam

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Abstract: This study evaluated the responses of runoff and soil erosion to a clear-cutting period of Acacia plantation in a headwater mountain. Two plots with 15m2 (3m width*5m length) were installed in a headwater mountain of Hoa Binh, Vietnam. Plot 1 remained untreated as the control plot, while plot 2 was clear-cutting in March 2019. Runoff and soil erosion was observed from April to September 2018 for the pre-cutting period with 55 storm events and from March to May 2019 for the post- cutting period with 15 storms-events. Observed data was examined the effects of the cutting period by using paired-plot analysis that compared the control plot and the treatment plot. The main results included: (1) Surface runoff after clear-cutting increased statistical significantly from 0.18 mm storm-1 (corresponding to 0.38 %) to 0.26 mm storm-1 (corresponding to 0.56 %). Paired- plot analysis showed the increase of surface flow is 81.14% after cutting; (2) Soil erosion increased statistically significant after clear-cutting from 228.44 g/storm to 309.27 g/storm on average, the amount of soil erosion due to treatment effect increased 33.1 %. The increase of runoff and soil erosion is quite high after the cutting period. This suggests that plantation management practices to control runoff and soil erosion in the headwater basin are necessary for Vietnam.

Keywords: Acacia plantation, Clear-cutting, Paired – plot analysis, Runoff, Soil erosion.

INTRODUCTION

Acacia plantations have emerged and developed as an important resource for supporting the livelihood of many thousands of rural families, especially in northern Vietnam (Namniar *et al.,* 2014). The area of Acacia plantation has increased from 66.000 ha in 1992 (corresponding to 7.2 % of all plantation) (Jong *et al.,* 2006) to 1 million ha (corresponding to 51 %) in 2013 (Kien *et al.,* 2014) and 1.5 million ha in 2019 (Ngoan & Bao, 2019). Most Acacia plantation was planted for commercial use in headwater

areas, which serve as source areas for groundwater recharge, runoff generation and maintaining water quality (Miyata *et al.,* 2007; Gomi *et al.,* 2010). Despite the importance of headwater areas, the rotation cycle of Acacia plantation is very short, with 5 to 8 years for high disturbance (Dung *et al.,* 2019). To start a new rotation, all trees were clear-cutting by heavy machinery and removed by humans. Left and grass were also cut and kept on the ground surface for about one week. They then were burned over to remove weeds, litters and make ground preparation before planting new trees (Dung *et al.,* 2019). A clear-cutting period can cause soil compaction and soil water repellency (Ziegler *et al.,* 2001), limiting soil infiltration capacity, resulting in increasing horton overland flow and soil erosion.

Previous attempts during the past few decades to evaluate how forest cutting affects runoff and soil erosion have been conducted. Almost previous findings for the catchment scale showed increases in annual water yield and sediment after forest harvesting (Dung *et al.,* 2012; Nam *et al.,* 2016). However, findings from these studies also varied due to many factors such as topography, soil characteristics, climate, forest types, harvesting methods, and scales. For instant, Bosch and Hewlett (1982) and Stednick (1996) found that climate conditions and vegetation affected on runoff responses to forest harvesting (Bosch & Hewlett, 1982; Rahmat *et al.,* 2018; Rahmat *et al.,* 2019). Specifically, increases in annual water yield tend to be greater in areas of high precipitation and in a wetter year. Otherwise, increases in annual water yield due to harvesting were greater in coniferous than in deciduous forests. Rates of canopy removal also appear to be related to increased water yield and sedimentation (Nam *et al.,* 2016; Dung *et al.,* 2011). For hillslope scale, overland flow and soil erosion tended to be increased after forest cutting (Nam *et al.,* 2016). For example, Ruprecht *et al.,* (1991) showed that 84% of thinning of Eucalyptus plantation in South Africa with an area of 0.8 km^2 hillslope increased by 20% amount of runoff after 3 years due to reduction of canopy interception and evaporation (Ruprecht *et al.,* 1991). However, increasing soil erosion and runoff after cutting trees depend on soil disturbance. If the soil surface is minimally disturbed by site preparation and cutting practice, it resulted in reducing overland flow and soil erosion (Dung *et al.,* 2015). On the other hand, harvesting has conducted by tract heavy machine associated with the system of road logging and skid trail during the rainy season, the soil surface is disturbance and compaction, resulting in a higher increase of runoff and soil erosion (Dung *et al.,* 2012).

Evaluating runoff and soil erosion responses to forest management in complex interactions at various treatment methods is very important (Dung *et al.,* 2015). However, most of the previous studies only focused on one aspect, such as runoff or soil erosion, while the two processes have a significant relationship with each other. Otherwise, the previous studies conducted to apply for only harvesting but have not yet assessed the impact of burning on both runoff and soil erosion, especially in headwater areas (Sayer, 2006). Therefore, understanding soil erosion and runoff response to a clear-cutting period of Acacia plantation in the headwater mountain of Vietnam is essential for building a sustainable plantation forest model, which can minimize negative impact from human interventions as protect soil loss and threaten to natural resources. This study was applied paired-plot (Brown *et al.,* 2005) approaches in a clear-cut experiment. Soil erosion and runoff are assessed responses to clear-cutting and then compared before and after a cutting treatment.

METHOD

Study site

This study was conducted in two small plots (control and treatment) covered by Acacia plantation located in Truong Son commune, Luong Son district (Fig. 1). The study area is deeply incised with dominant slope gradients ranging from 26° to 27° (mean gradient slope was 26° in the control plot and 27° in the treatment plot). The low mountainous terrain is approximately 200-400 m above sea level, formed by magma, limestone, and terrigenous sediments, with a dense network of rivers and streams. The soils are red-yellow ferralit with a thickness layer of A horizon and mud volume of about 6-7% with high soil moisture (Dung *et al.,* 2019). Luong Son climate is tropical monsoon, with cold winters - less rainfall; hot summer - heavy rain. The unevenly distribution mainly occurs in some months during the rainy season; it can generate a huge amount of runoff, causing flood and severe landslide and erosion. Mean annual precipitation and air temperature are approximately from 1500 mm to 2200 mm and 23^oC, respectively. Each year, at least two typhoons affect the area; the wind velocity is about 30 m/s. Households managed most Acacia plantation, so the stand densities vary by the year and aging with mean canopy cover about 89% during clear-cutting.
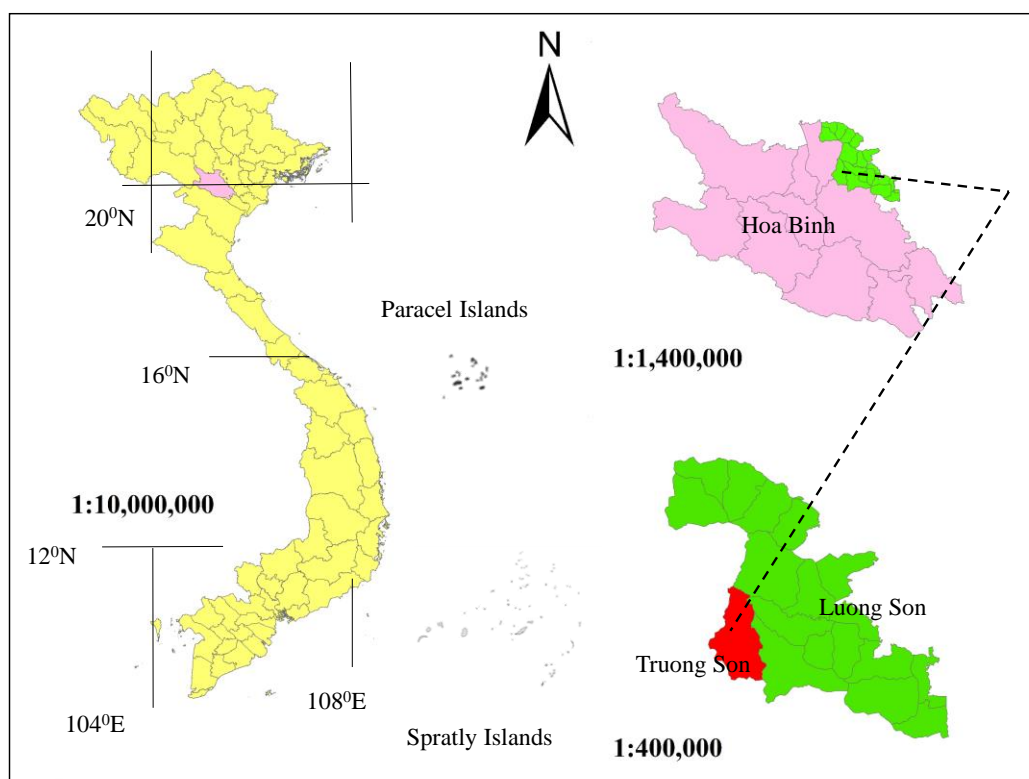

Figure 1. The location of study site

Methods

Installation of monitoring plots

Observed plots were established on a deep planar slope, in which plot 1 is the control plot installed at the mid-hill and plot 2 is the treatment plot set up in the mid-hill. The area of each plot is 15m^2 (3m x 5m) (Fig. 2a). The plot's border was built by aluminum

plates with 0.25m in height to prevent rain splash, held and reinforced to stand upright by steel wires and bamboo piles. The aluminum plates' feet were buried at least 10cm deep to withstand heavy winds and heavy rain. The plots were designed for collecting overland flow near the soil surface and sediments to the buckets, which were used to hold water and soil after each storm event. At the downslope ends of the plots, an aluminum trough was installed flashing between the soil surface and soil depth of 2 cm for collecting overland flow to a gutter which was connected with a container (volume of 180 L by a plastic tube) (Fig. 2a). Precipitation was measured by a tipping bucket rain gauge (Davis Instruments Co., Rain collector Metric Standard #7852M) located in an open area 50 m away from the study area (Fig. 2b) to avoid interception from the overlying canopy. Rainfall was monitored continuously in 70 storm events from April 2018 to September 2018 and from March 2019 to May 2019.
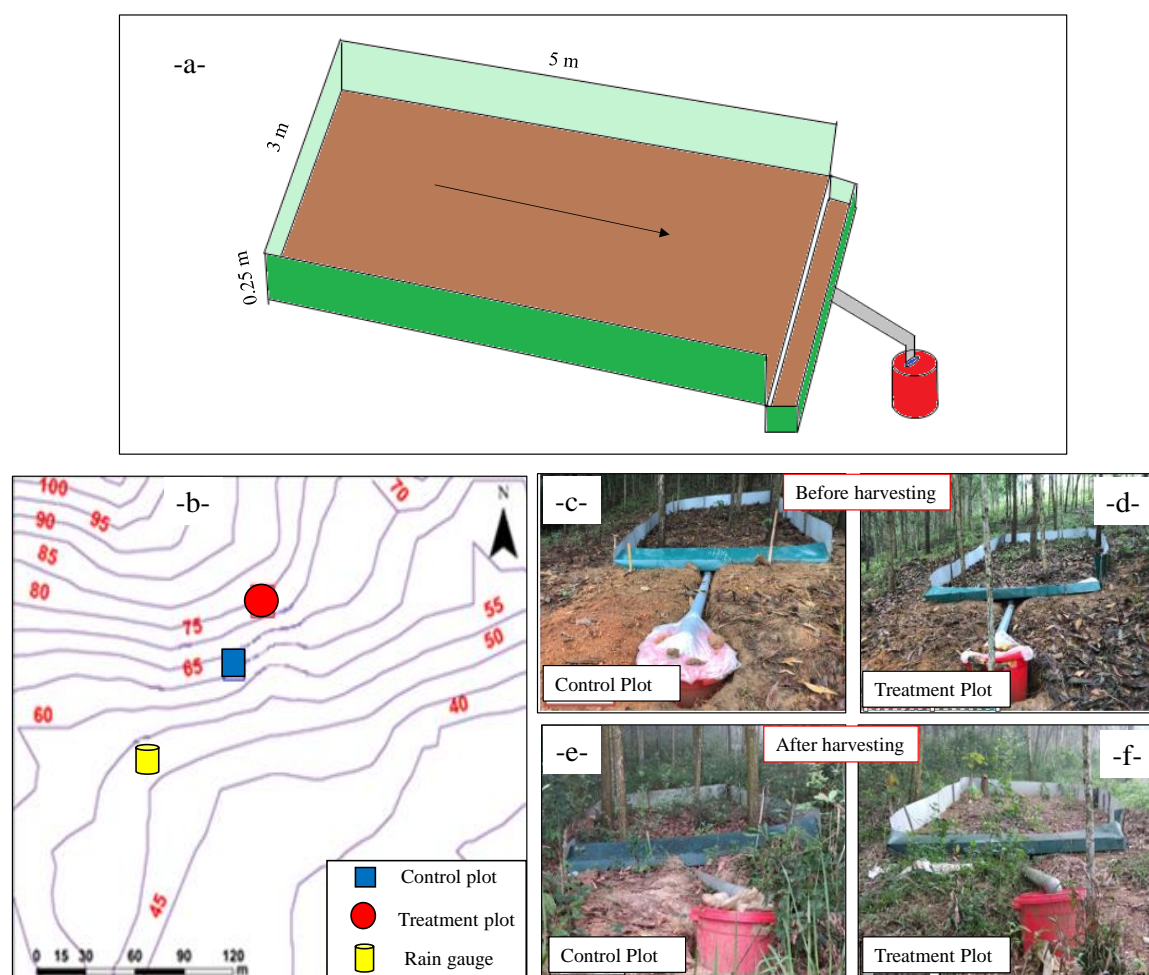
Figure 2. The location of two plots and design experiment for monitoring soil erosion and runoff: (a) Plot model; (b) Location of plot; (c, d, e, f) the status of two plot before and after clear cutting.

Table 1: The characteristic about natural condition of before and after clear-cutting

	Parameters	Before clear cutting		After clear-cutting	
		Control	**Treatment**	**Control**	**Treatment**
Plot characteristic	Slope (^{0}C)	26	27	26	27
	Elevation (m)	60	72	60	72
	Soil texture	Clay loam	Clay	Clay loam	Clay
	Porosity (%)	56	59	55	52
	Ground cover (%)	36.2	38.9	30.1	0
	Canopy cover (%)	85.9	86.9	89.7	0
	Number of trees	5	5	5	0
	Average of DBH (cm)	8.5	8	8.7	0
	Average of height (m)	6.2	6.1	6.3	0
Rainfall conditions	Number of storm events (mm)	55		15	
	Max storm event rainfall (mm)	117.5		62	
	Total rainfall (mm)	1887.4		627	
	Average storm rainfall (mm)	31.3		41.8	
	Average rainfall intensity (mm hr^{-1})	8.42		7.07	

Experimental design

Paired-plot experiment was used to examine the effects of plantation harvesting on soil erosion and overland flow. Control plot 1 remained untreated as a control plot, whereas experimental harvesting practices was conducted in treatment plot 2. Therefore, the observation period can be divided into pre-treatment (from 22nd April to 3rd September, 2018) and post-treatment period (from 21st February to 12 May, 2019) (Table 1). All twigs, branches, and timber of cutting were abandoned on the forest floor and then burning. All the clear cutting operation were conducted by household using heavy machinery. Thus, soil disturbance associated with cutting operations was effect on the treated hillslope. Forest cutting is generally conducted with vegetation on ground floor, the understory vegetation did not cover until the end of the monitoring period.

Surface runoff measurement

After the rainwater flows into the tank, the amount of water was measured to calculate the surface runoff by using graduated cylinder to directly measure. Initially, the flow can be measured directly, but if the water is turbid, it is necessary to filter and then measure. The unit of surface runoff is milliliters (ml), then which is converted into millimeters (mm) according to the plot area (m^2). Storm runoff coefficient was also calculated as the below equation 1:

$$\text{Runoff coefficient} = \text{storm runoff/storm precipitation} *100 \qquad [1]$$

Soil erosion measurement
Eroded soil also came with surface runoff to the plastic buckets, after each storm, soil is settled down to the bottom of the bucket. The soil was left in the bucket would be collected then bring to the laboratory as well as the soil from troughs and pipes in each plot. The soil was dried in laboratory and weighted to determine the amount of soil erosion. The amount of soil erosion was monitored in 70 storms with 55 storms before clear cutting and 15 storm after clear cutting of each plot.

Analysis runoff and soil erosion
The types of analysis was examined the treatment effects on runoff and soil erosion generation to control plot, was traditional paired-plot analysis (Brown *et al.,* 2005). Paired-plot was designed to show the changing correlation of precipitation, runoff, soil erosion between two plots before and after clear cutting to minimize the effects of climate and inter-catchment variability on experimental outcomes. Therefore, the response of clear cutting to soil erosion and runoff depends more on precipitation during a given storm event than on prior storm events (Gomi *et al.,* 2008). The paired-plot approach was applied based on an assumption that rainfall and soil erosion/runoff response between treatment and control plots remained consistent during the pre- and post-cutting period. Based on the pre-treatment data, calibration regression equation was developed between runoff in the control plot (plot 1) Q_{c1} and treatment plot (plot 2) Q_{t1} as equation [2] follow:

$$Q_{t1} = a\, Q_{c1} + b \qquad [2]$$

Whereas, *a* and *b* are the regression coefficients. By using parameters *a* and *b*, we calculated overland flow in the treated plot during post clear-cutting period Q_t^{est} as equation [3] follow:

$$Q_{t2}^{est} = a\, Q_{c2} + b \qquad [3]$$

Whereas, Q_{c2} is overland flow in the control plot during the post clear-cutting period. The residuals between the observed and estimated in post clear-cutting were calculated by equation [4] as below:

$$\Delta Q^1 = Q_{t2}^{obs} - Q_{t2}^{est} \qquad [4]$$

Change in coefficient of overland flow due to the treatment effect (ΔR^1) were determined using the following equation [5] as below;

$$\Delta R^1 = Q_{t2}^{obs}/P_{post} - Q_{t2}^{est}/P_{post} \qquad [5]$$

With soil erosion, all steps are similar to runoff analysis with the residual ΔQ^2 (mm $storm^{-1}$), change in soil erosion (%) due to the treatment effect (ΔR^2).

For paired-plot analysis, 55 observed storms was included of data for pre-cutting period and 15 observed storm events for the post clear-cutting period. The residuals and changes in the runoff coefficient and soil erosion were calculated either based on storm data. Although ground cover condition of plots differed in control and treatment plot

(Table 1), ground cover condition in plot 1 remained the same before and after clear cutting. Therefore, internal hydrological processes for runoff and soil erosion generation in plot 1 remained similar condition. Then, plot 2 was used as treatment plot for examining of runoff and soil erosion after clear cutting.

RESULTS AND DISCUSSION

Surface runoff response to clear-cutting period
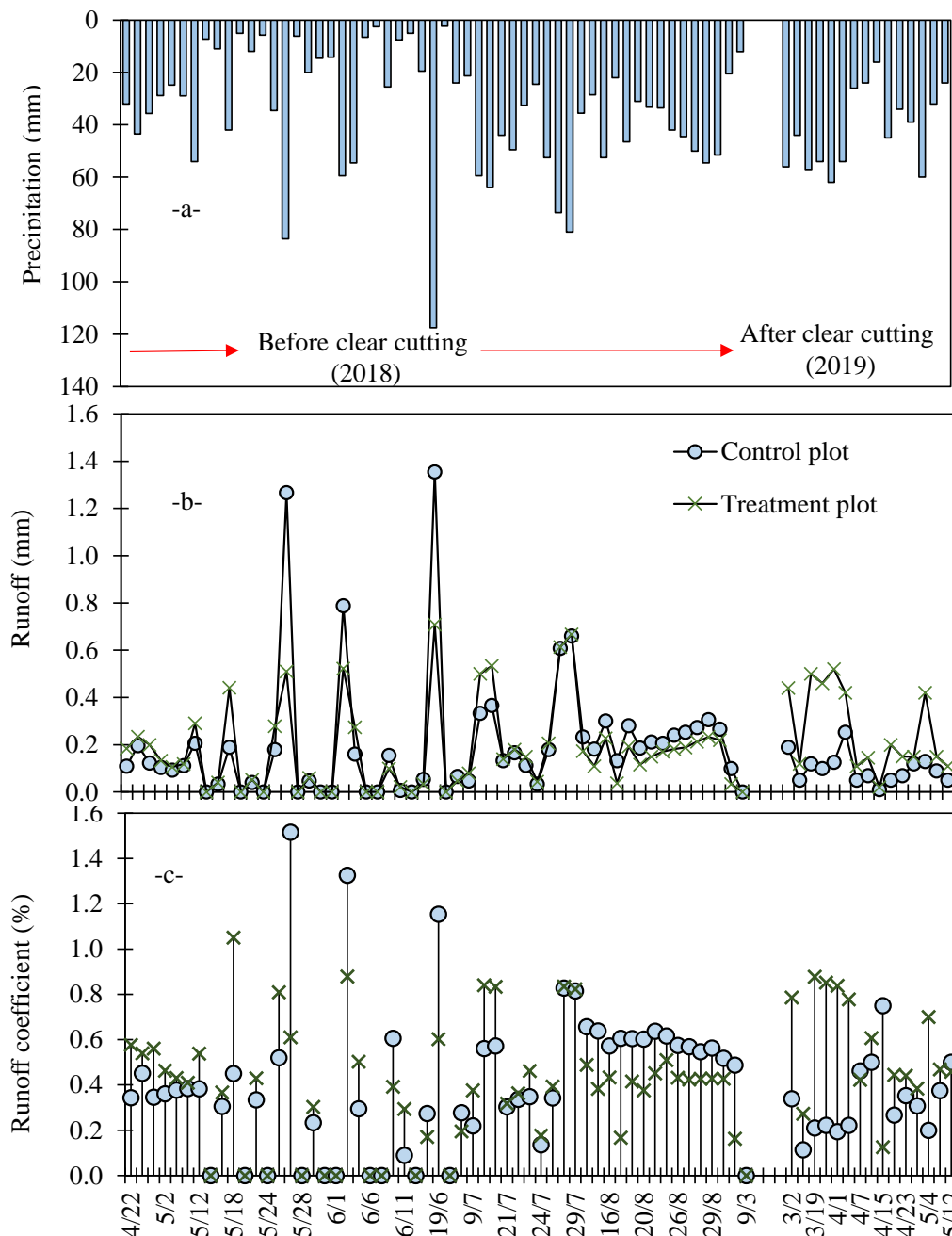
Figure 3. Rainfall and runoff characteristic: (a) Precipitation; (b) Surface runoff; (c) Runoff coefficient

Observed storm events were 55 in the pre-cutting and 15 in the post-cutting (Fig. 3 and Table 1). Average storm rainfall tended to be higher after cutting, which was 31.3 mm storm^{-1} in the pre-thinning and 41.8 mm storm^{-1} in the post-cutting. However, rainfall intensity (8.42 mm hr^{-1}) in pre-thinning is higher than one (7.07 mm hr^{-1}) in the post-thinning (Table 1).

Surface runoff response quickly to rainfall inputs during the pre- and post- cutting periods (Fig. 3). Higher rainfall also got higher runoff and runoff coefficient in both plots. However, the responses of surface runoff was different between pre- and post-cutting. Before cutting, runoff and runoff coefficient in the control plot 1 were 0.20 ±0.27 mm storm^{-1} and 0.41 ±0.33%, respectively, while they in the treatment plot 2 were 0.18 ±0.18 mm storm^{-1} and 0.38 ±0.27%, respectively (Fig. 3 and Table 2). However, after clear-cutting, surface runoff and coefficient of storm events in control plot 1 was noticeably lower than ones of treatment plot 2 (Fig. 4 and Tab 2).
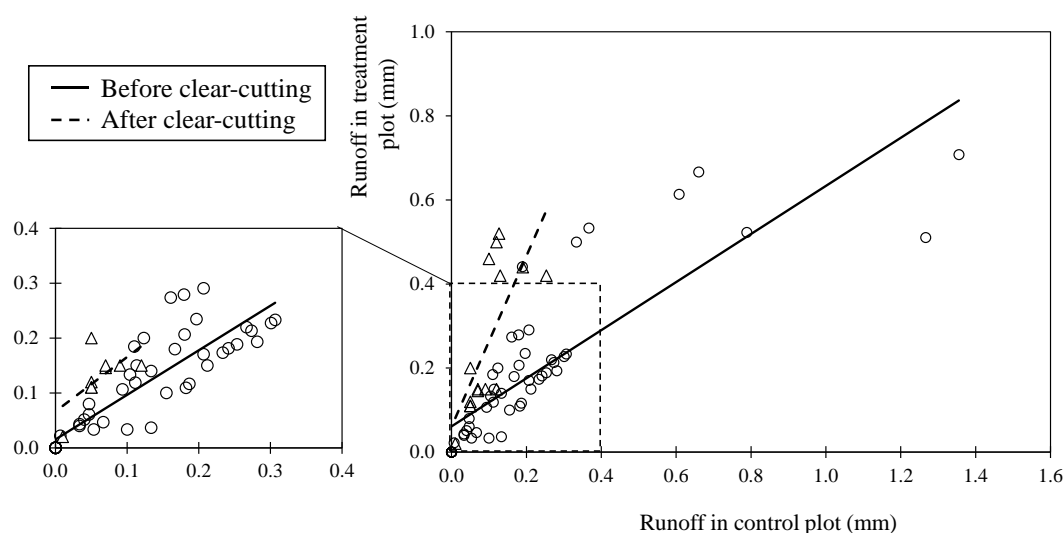
Figure 4. Correlation between runoff in control and treatment plots.

Runoff between control and treatment plot responses varied with clear-cutting. The amount of storm runoff from treatment plot increased significantly after clear-cutting (Fig. 4). In the pre-clear cutting, runoff from control and treatment plots did not have statistic significant difference (p-value>0.05), while runoff between control and treatment plots was statistic significant difference in the post- cutting (p < 0.05) (Table 2).

Table 2. Descriptive statistic and summary of residual analysis between observed and predicted surface runoff based on paired-plot analysis

Period	Parameter	Plot (m^2)	Min	Max	Mean	Sd	t	df	p-value
Before clear-cutting	**Surface runoff (mm)**	Control	0	1.36	0.20	0.27			
		Treatment	0	0.7	0.18	0.18	1.22	54	0.11
	Runoff coefficient (%)	Control	0	1.52	0.41	0.33			
		Treatment	0	1.05	0.38	0.27	0.94	54	0.17
After clear-cutting	**Surface runoff (mm)**	Control	0.01	0.25	0.1	0.06	-		
		Treatment	0.02	0.52	0.26	0.17	4.62	14	0
	Runoff	Control	0.06	0.47	0.23	0.1	-	14	0.01

	coefficient (%)	Treatment	0.13	0.88	0.56	0.23	2.54		
Treatment	ΔQ^1 **(mm)**		-0.05	0.39	0.14	0.2	-	-	-
effect	ΔR^1 **(%)**		-	-	81.14	-	-	-	-

Note: Sd: Standard deviation

The mean residual ± standard deviation (SD) between the observed and predicted runoff during the post-clear cutting period were 0.14±0.2 mm storm^{-1}. This mean that runoff increased 0.14 mm storm^{-1} after clear-cutting of Acacia plantation. On the other hand, sharly increasing in runoff coefficient (ΔR^1) after cutting was 81.14 % (Fig. 5a and Table 2).
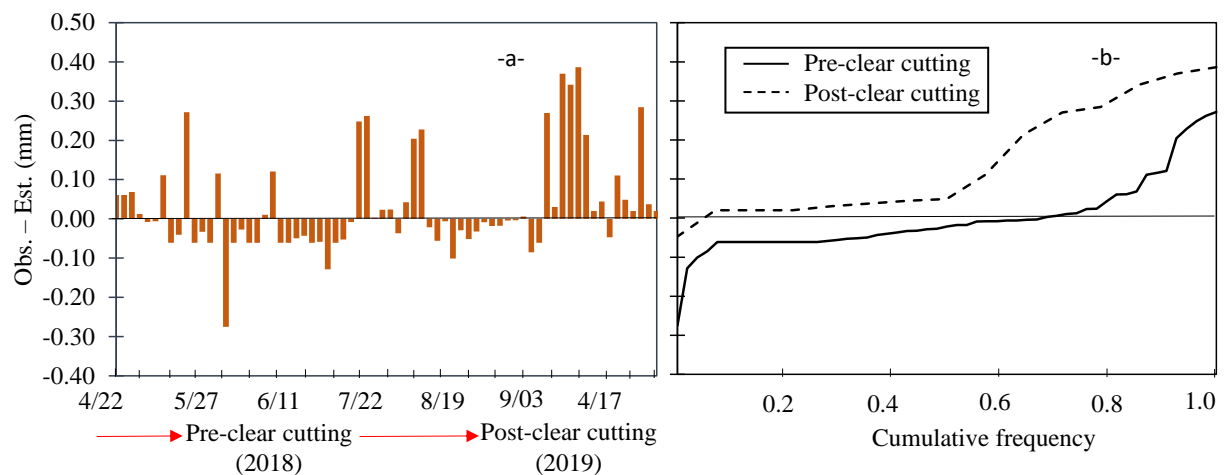

Figure 5. (a) Residual differences between observed and estimated runoff based on paired analysis; (b) Cumulative frequency distributions of pre- and post-clear cutting.

The amount of storm runoff (residual) from treatment plot increased significantly after clear-cutting (Fig. 5). Cumulative frequency distributions of treatment effect in the paired-plot analysis showed increase in runoff due to clear-cutting (Fig. 5b). These results illustrated a great treatment effect to runoff that the calibration equation was stable at predicting post-treatment runoff.

The paired- plot analysis indicated that surface runoff increased significantly to 0.14 mm storm^{-1} (corresponding to 81.14%) after clear-cutting of Acacia plantation. Potential reasons for the increased overland flow after clear-cutting are losing in canopy interception and soil compaction due to the cutting operation. Canopy removal due to clear-cutting likely decreased the amount of canopy interception, allowing a greater proportion of total precipitation to reach the forest floor (Dung et al.,2011; Gomi et al., 2008; Rahman et al., 2005; Komatsu et al., 2008). Another potential reason for increased overland flow is soil compaction due to forest operations. Clear-cutting involves removing all timber in the harvesting unit, generally using heavy machinery produced more soil disturbance and compaction, resulting higher soil bulk density and reduced infiltration capacity (Ziegler et al., 2001; Dung et al, 2012; Moore & Wondzell, 2005).

Soil erosion response to clear-cutting period

The amount of soil erosion from two plots in the pre-cutting was lower than ones in the post-cutting and witnessed quick response to the rainfall. When rainfall increased, the amount of soil erosion also increased and vice versa (Fig. 6). In pre-clear cutting, the soil erosion in control plot (from 0-572.37 ± 149.21, averaged 245.48 g storm^{-1}) was higher than that of treatment plot (from 0-790.9 ± 184.51, averaged 228.44 g storm^{-1}) (Fig 6b; Table 3). Soil erosion from the control plot (240.37 g storm^{-1} on average) was smaller than one of the treatment plot (309.27 g storm^{-1} on average) after clear- cutting (Fig. 7 and Table 3).
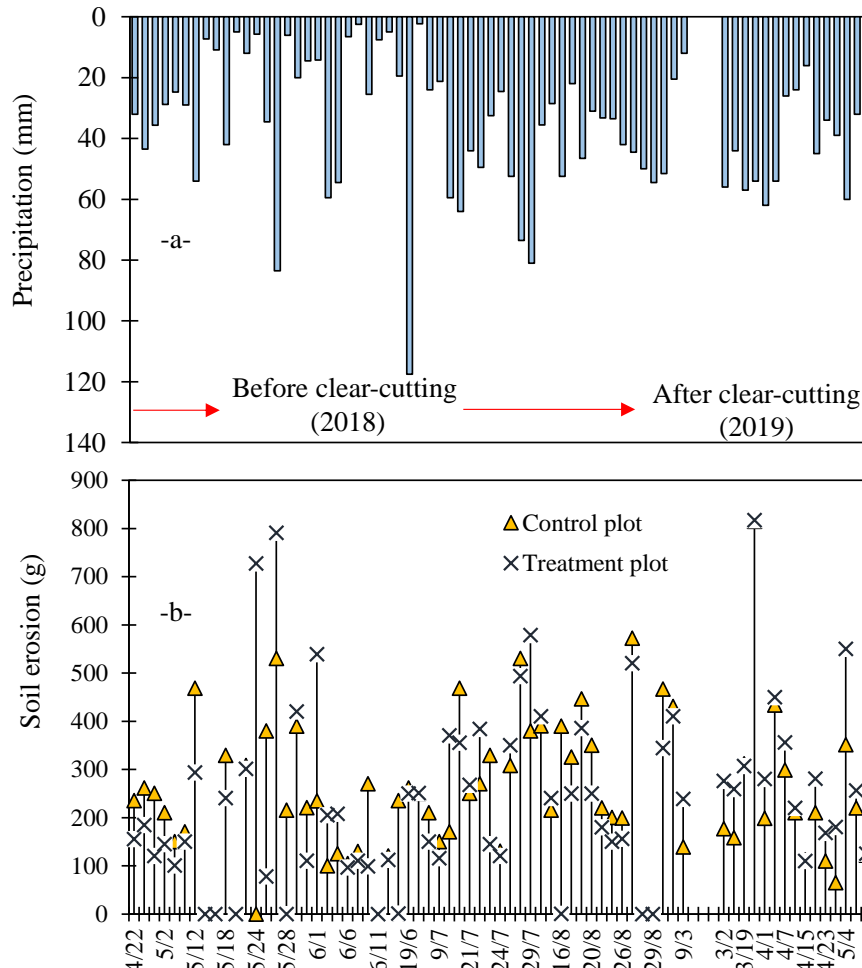
Figure 6. Soil erosion before and after clear-cutting: (a) precipitation; (b) soil erosion in control plot and treatment plot.
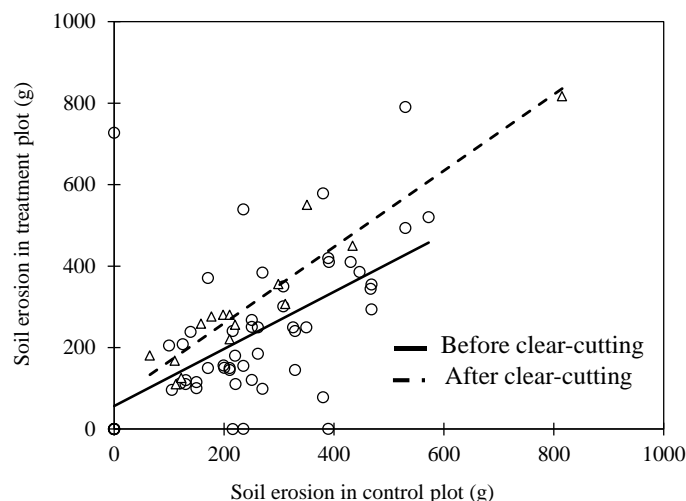
Figure 7. Correlation between soil erosion in control and treatment plots.

Table 3. Descriptive statistic and summary of residual analysis between observed and predicted soil erosion based on paired-plot analysis

Period	Plot (m^2)	Min (g)	Max (g)	Mean (g)	Std	t	df	p-value
Before	**Control**	0	572.37	245.48	149.21			
clear-cutting	**Treatment**	0	790.90	228.44	184.57	0.79	54	0.21
After	**Control**	65	625.50	240.37	146.21			
clear-cutting	**Treatment**	110.20	817.30	309.27	182.09	-4.12	14	0.01
Treatment	**ΔS (g)**	-24.98	248.34	75.7	71.0	-	-	-
effect	**ΔR^2 (%)**	-	-	33.1	-	-	-	-

Note: Std: Standard deviation

Soil erosion values from control plot 1 and treatment plot 2 were significant correlated when developing the calibration equations. Soil erosion increased significantly from the pre-cutting to post-cutting periods (Fig. 7 and Table 3). Mean and standard deviation of treatment effect for storm erosion were 75.7 and 71.0 g, respectively. The percentage of changes in soil erosion due to the treatment effect ΔR^2 was 33.1 % (Fig. 8 and Table 3). Thus, increases in soil erosion reflected the consistently positive treatment effects in the post-thinning period (Fig. 8a). Significant differences (95% confidence level) appeared in soil erosion between pre- and post- clear cutting (Table 3).
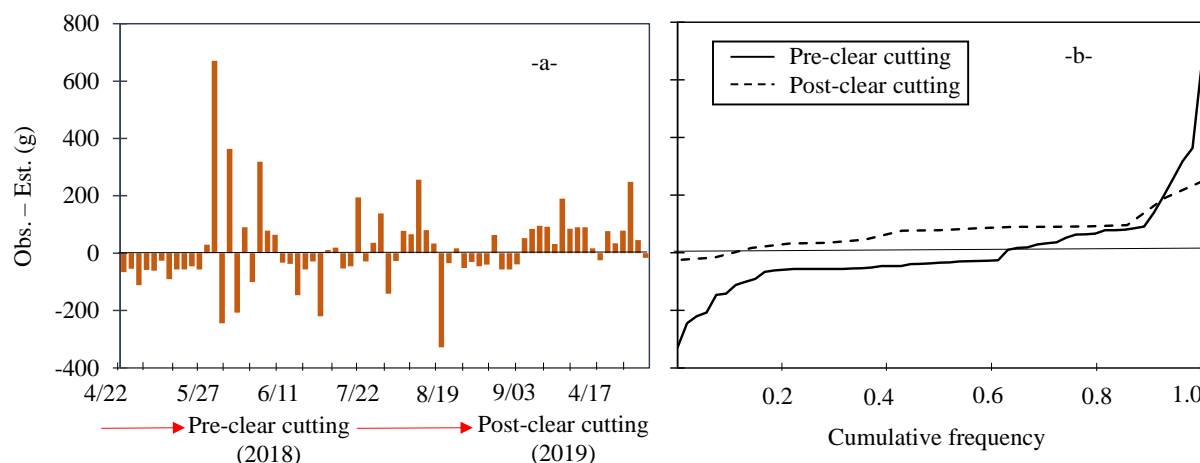
Figure 8. (a) Residual differences between observed and estimated soil erosion based on paired analysis; (b) Cumulative frequency distributions of pre- and post-clear cutting

Cumulative frequency distributions of treatment effect in the paired-plot analysis also showed increase in soil erosion due to clear-cutting (Fig. 8b). This results indicated that the treatment effect (observed minus estimated value) cause significant change in soil erosion in the post-clear cutting. The frequency curve of treatment effect suggest that observation higher than estimation during pre-clear cutting and post-clear cutting.

Potential reasons was found to analysis affecting of clear harvesting to soil erosion that lack of the canopy cover and vegetation cover in treatment plot. The probability of soil erosion increases if the soil has little or no vegetative cover (plants, grasses, crop residue or trees). Raindrops hitting leaves, stems and other plant parts get interrupted and redistributed, thereby reducing the velocity of direct soil impact (Bent, 2001). Additionally, plants have extensive root systems assist to keep soil and bound it together, reducing displacement. Therefore, vegetation that completely covers the soil is the most effective in controlling soil erosion. At our study site, forest operations were conducted by local people using heavy machinery, thus disturb soil structure. Burning process make understory vegetation loss, changing and increasing soil compaction resulted increasing of runoff and soil erosion.

CONCLUSION

We investigated the impact of clear-cutting period of Acacia plantation on overland flow and soil erosion using paired-plot analysis. Our main findings were (1) clear-cutting of Acacia plantation increased storm overland flow by 81.14% (corresponding to 0.14 mm storm^{-1}), as estimated by paired-plot analysis; (2) paired-plot analysis also showed that soil erosion increased 33.1% (corresponding to 75.7 g storm^{-1}) after clear-cutting period of Acacia plantation; and (3) increases in overland flow and soil erosion were associated with losing of canopy interception, increasing in throughfall and reducing infiltration capacity due to soil disturbance. This suggests that the effect of forest clear-cutting of Acacia plantation on overland flow and soil erosion is a big problem in headwater mountain. Thus necessary have to method to reduce negative impacts of clear-cutting periods.

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