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SOIL COMPACTION AND EROSION LEVEL DUE TO GAP PLANTING IN INDONESIAN DEGRADED TROPICAL RAINFOREST

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Abstract

Indonesia's natural forests consist of various land and stand qualities, both highly degraded. In the past few years, the forest area has continued to decline. Gap planting is one of the silviculture techniques which can increase the productivity of the low potential tropical natural forest, mainly by using fast-growing species with short cutting rotation. The objective of this research was to study the impacts of gap planting on soil compaction and erosion in the Indonesian lowland tropical rain forest. Soil compaction was measured using Humbolt-Digital Statis Cone Penetrometer, soil erosion was measured using erosion pins and gap area was measured using Hexadecagon Method. The result shows that using gap planting causes soil compaction in gaps with an area of less than or equal to 250 m^2 and 1250–1500 m^2. However, the compaction value is classified as very loose soil so that it can be ignored. Otherwise, gap planting, using planting strips and chop off strips, has a positive impact by lowering erosion at gap size less than or equal to 250 to 2000 m^2.

Key words: chop off strip, cone penetrometer, erosion pin, planting strip, silviculture system.

Introduction

Indonesia's natural forests consist of various land and stand qualities, both highly degraded (Kusmana 2011). In the past few years, the forest area has continued to decline (Hansen et al. 2009, Broich et al. 2011, KLHK 2015, KLHK 2016). According to KLHK (2017), the total state forest area of Indonesia was 125.96 million ha, and 32.70 million ha of which were degraded forest.

Gap planting is one of the silviculture techniques which can increase the productivity of low potential tropical natural forest, mainly by using fast-growing species with short cutting rotation. Gap planting can improve gradually the ecological stability of forests. On the other hand, the research results of Schwartz et al. (2017), Elias and Suwarna (2019) recommended applying gap planting technique in the tropical forest which was at risk of land-use changes. Kusmana (2011) stated that there were several ecological requirements in the application of silviculture systems. These requirements were (1) minimizing disturbances to the soil, (2) maintaining the availability of soil organic matter, (3) maintaining biodiversity and (4) limiting the size and shape of disturbed areas.

Tropical rainforest succession begins when the forest canopy is opened. This open area is called a gap (Halle et al. 1978, Perry et al. 2008, Fischer et al. 2016). Natural gaps can vary in size. Among others were 100–1000 m^2 (Botkin et al. 1972), 400 m^2 (Halle et al. 1978), and 32.3–1636 m^2 (Muin 2009).

Soil compaction and erosion are the ecological indicators in sustainable forest management. Kusmana (2011) explained that ecological factors needed to be considered in the selection of silviculture system. The compacted soil can disturb the growth of tree roots and seedlings (Kozlowski 1999, Matangaran 2002). The results of Matangaran et al. (2010) showed that seedling growth was inversely related to soil compaction. Furthermore, compacted soil increases runoff and erosion (Kozlowski 1999, Alaoui et al. 2017) and leads to soil fertility reduction due to topsoil loss (Kusmana 2011).

The research results of Cornelio and Rao (2011) in Oomsis Village, Morobe Province, Papua New Guinea showed erosion that occurred in the agricultural system, tropical natural forest, and grassland was ranging from 25–28 $t{\cdot}ha^{-1}$, 20–23 $t{\cdot}ha^{-1}$, and 8–10 $t{\cdot}ha^{-1}$, respectively. Elias and Suwarna (2019) also explained that erosion due to gap planting in different cover types (natural forest area, chop of strip area, planting area) was 17.05 $t{\cdot}ha^{-1}$, 16.83 $t{\cdot}ha^{-1}$, 5.56 $t{\cdot}ha^{-1}$, respectively. These results indicated that land use changes can affect soil erosion.

To address issue raised by Schwartz et al. (2017) and also Elias and Suwarna (2019), a study about the impact of gap planting on soil compaction and soil erosion is needed. However, this kind of study has not been so far carried out. Therefore, the objective of this research was to study the impacts of gap planting on soil compaction and erosion in Indonesian lowland tropical rainforest.

Materials and Methods

Research area

This research was carried out in lowland tropical rain forest at PT Intracawood Manufacturing (3°23'26" N, 116°55'19" E) which is in Betayau sub-district, Bulungan District, North Kalimantan, Indonesia. The forest condition was logged over forest. There were found 26 commercial tree species in this research area and 763 trees had a diameter at breast high (DBH) more than 20 cm. The soil type is red-yellow podzolic (ultisol). The topography of this area is 19.70 % flat to moderate slope, 23.70 % steep slope, and 60.50 % very steep slope. During the last 10 years, the average annual rainfall in the research area was 4091 $mm{\cdot}year^{-1}$; meanwhile, annual temperature and relative humidity were 27.6 °C and 85.29 % (BMKG 2018).

Tools and materials

The research tools were erosion pin, Humbolt-Digital Statis Cone Penetrometer, measuring tape, clinometer, compass, chainsaw, machete, hoe, sickle and GPS. The research materials were nitrogen, phosphorus, potassium (NPK) fertilizer 15-15-15, seedlings of red jabon (*Anthocephalus macrophyllus* (Roxb.) Havil) and white jabon (*Anthocephalus cadamba* (Roxb.) Bosser). Fertilizer was applied 100 g per planting hole. It applied inside the planting hole before seedlings were planted.

Research area design

To study how to improve degraded forest, a low potential lowland tropical forest has been chosen as a research location. The area was 10 ha. The research began with mapping the forest area mosaic. It was determined based on topographic classification, soil classification based on erosion vulnerability, tree density, and hydrological map. Topographic and tree density data were collected by the transect survey method. The transect size was 20×400 m and the plot size inside the transect was 20×20 m. Twelve transects were constructed in the research location.

Gap planting areas were planned on the forest area mosaic map (Fig. 1). The maximum of gap areas was 40 % of the total research area. The criteria for gap planting area were (1) the opened area or less productive forest that had volume of commercial species (DBH ≥ 40 cm) less than or equal to 20 $m^3 \cdot ha^{-1}$ and (2)

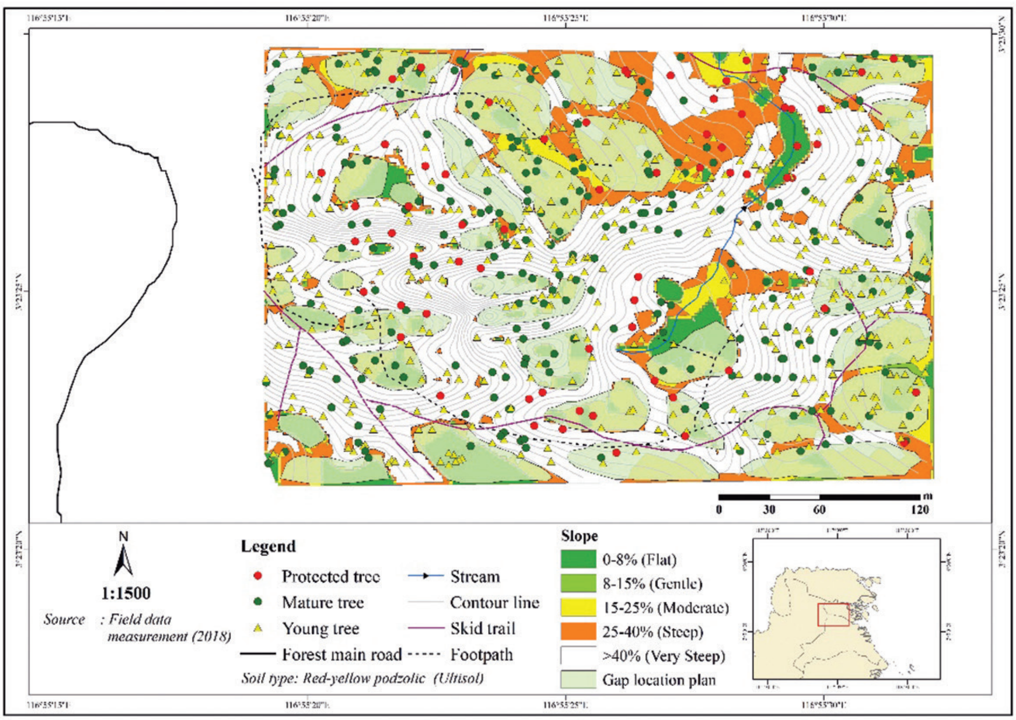


Fig. 1. Forest area mosaic map.

soil type not sensitive to erosion. Gap pattern and shape were constructed by adapting and following the field conditions. The gap was divided into 8 classes (class 1–8) with different areas: ≤ 250 m^2, 250–500 m^2, 500–750 m^2, 750–1000 m^2, 1000–1250 m^2, 1250–1500 m^2, 1500–1750 m^2, and 1750–2000 m^2.

Artificial gaps were constructed by cutting all trees inside the gap area boundary, except the commercial tree species with DBH ≥ 20 cm. Gap distance on average was 20 m. After its construction, planting strips and chop off strips were constructed inside the gap. The planting strip was the area for seedling planting. The chop off strip was the area located between 2 planting strips and its width was 3 m in which the understory was cleared as high as knee high. The planting strip width was 2 m in which the understorey was totally cleared. Planting strips and chop off strips were constructed in the east-west direction and the design was presented in Figure 2.

The gap area was measured with Hexadecagon Method (Green 1996, Zhu et al. 2009). Size of gap area was calculated by using the equation (1):

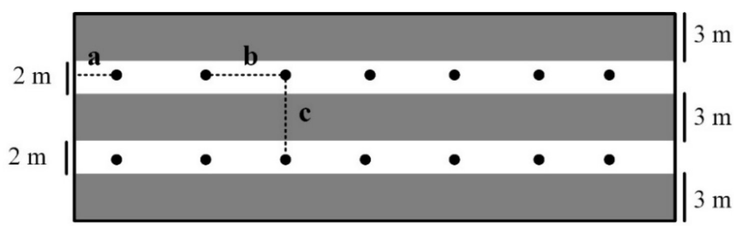
$$A_{sm} = 0.5\sum_{i=1}^{16} L_{i+1} \cdot L_i \cdot \sin(\frac{\pi}{8}) , \qquad (1)$$

where: A_{sm} is gap area (m^2); L_{i+1} is the distance from the center to the edge of the gap; i = 1, 2, …, 16; π is radians (180°).

Data collecting

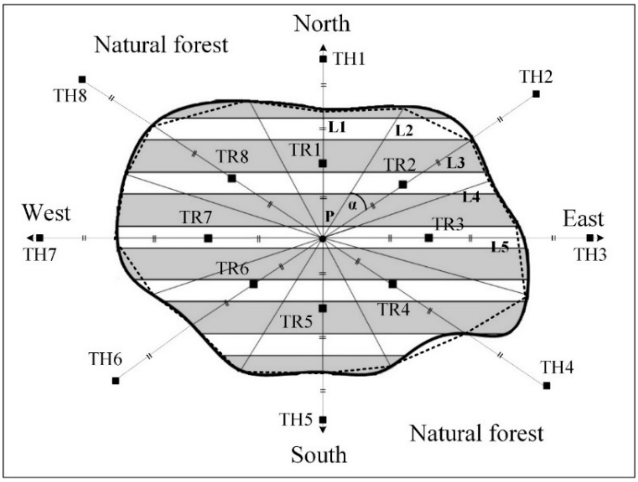
The research was conducted from January–April 2018. Soil compaction and soil erosion were measured after gap, planting strip, chop off strip, seedlings planting and gap area measurement. Soil compaction was measured in the center of the gap, planting strip, chop off strip, and outside the gap in the natural forest. Measurement was performed 3 times at each point using Humbolt-Digital Statis Cone Penetrometer after gap construction, gap planting, erosion pins installation were completed. The point of measurement location was nearby erosion pins (Fig. 3).

Erosion was measured using the field observation method (Elias 2012). Both soil erosion and soil deposition data were collected by erosion pin. The pins were pinned in the center of the gap (1 pin), planting strip (8 pins), chop off strip (8 pins), and outside the gap in the natural forest (8 pins). The first measurement of erosion was performed on 5th March and was used as the basis for the initial ground level benchmark. Erosion measurement was carried out 5 times a day after a rainy day in March which was 7th March, 9th March, 12th March, 19th March, and 22nd



■ – chop off strip; □ – planting strip, a = 2 m, b = 4 m, c = 5 m;
●= planting holes (40×40×40 cm).

Fig. 2. Planting and chop off strip design.



■ – chop off strip; □ – planting strip; ■ – points of measurement; TR1, TR2, …, TR8 – measurement points inside the gap; TH1, TH2, …, TH8 – measurement points outside the gap or in the natural forest; P – gap center; L1, L2, …, Ln – gap radius order; $\alpha = 22.5°$.

Fig. 3. Illustration of soil compaction and erosion measurement points.

March 2018. Rainfall variations at the research location before erosion measurement were 24.2 mm, 18.4 mm, 11.6 mm, 16.1 mm and 15.5 mm (BMKG 2018).

Data analysis

The examined parameters in this research were soil compaction, erosion height, soil erosion volume, and soil erosion weight on each cover type (planting strip, chop off strip, and natural forest). Soil compaction equation (2) is as follows:

$$EP_j = \frac{1}{n}\sum_{i=1}^{n} P_{ij} , \qquad (2)$$

where: EP_j is average of soil compaction at cover area type j (kgf·cm^{-2}), j is cover area type, n is number of repetitions, i is the point of measurement in each cover area type (1, 2, … 8), P_{ij} is soil compaction at point i and cover area type j (kgf·cm^{-2}).

Total soil erosion volume per hectare was calculated based on the area proportion of planting strip, chop off strip and natural forest. It was 15:25:60 %. This proportion implied in each hectare research area there were 1600 m^2 of planting strip, 2400 m^2 of chop off strip, and 6000 m^2 of natural forest. The soil erosion weight was calculated by using 0.59 g·cm^{-3} of natural forest soil bulk density and 0.67 g·cm^{-3} of planting and chop off strip soil bulk density (Handayani and Karmilasanti 2013). These soil bulk density values were used based on the same location of research. Erosion parameters were calculated by using the following equations (3–6):

$$EH_j = \frac{1}{n}\sum_{i=1}^{n} H_{ij} , \qquad (3)$$

$$EV_j = A_j \cdot EH_j , \qquad (4)$$

$$EW_j = BD_j \cdot EV_j \ , \quad (5)$$

$$TE = \sum_{j=1}^{3} EW_j \ , \quad (6)$$

where: EH_j is average of soil surface erosion height at cover area type j (m), j is cover area type, n is number of repetitions, i is the point of measurement in each cover area type (1, 2, … 8), H_{ij} is ground surface erosion height at point i and cover area type j (m), EV_j is average soil erosion volume at cover area type j ($m^3 \cdot ha^{-1}$), A_j is area of cover type j (m^2), EW_j is average of soil erosion weight at cover type j ($t \cdot ha^{-1}$), BD_j is soil bulk density cover area type j ($g \cdot cm^{-3}$), TE is total erosion in the research area ($t \cdot m^{-3}$).

Soil compaction and erosion level due to gap planting were analysed with ANOVA. The first factor was the type of cover areas: planting strip, chop off strip and natural forest area. The second factor was the gap size, which consisted of 8 class areas. They were analysed at a significant level of 5% (p = 0.05). Whenever the factors or their interactions were significant, Tukey test was carried out.

Results and Discussions

Soil compaction level

The average of soil compaction on planting strip was 3.38 $kgf \cdot cm^{-2}$ which ranged from 2.67 $kgf \cdot cm^{-2}$ (gap class 6) to 4.15 $kgf \cdot cm^{-2}$ (gap class 1) (Table 1). Soil compaction in planting strip in gap class 1 is 1.55 times larger than gap class 6. The average of soil compaction in chop off strip was 3.23 $kgf \cdot m^{-2}$ which ranged from 2.69 $kgf \cdot cm^{-2}$ (gap class 8) to 3.90 $kgf \cdot cm^{-2}$ (gap class 1) (Table 1). The lowest soil compaction in chop off strip almost has no difference compared to the lowest soil compaction in planting strip (0.02 $kgf \cdot cm^{-2}$). Otherwise, the highest soil compaction in both cover types has a difference of 0.25 $kgf \cdot cm^{-2}$. These results were relatively lower than other results by Elias and Suwarna (2019). They said that the average of soil compaction in planting strip and chop off strip were 3.90 $kgf \cdot cm^{-2}$ and 4.42 $kgf \cdot cm^{-2}$.

Soil compaction due to gap planting in this research was lower than soil compaction due to skidding in the industrial for-

Table 1. Soil compaction in each gap class and different forest cover types, and ANOVA test value.

Gap class	Soil compaction, $kgf \cdot cm^{-2}$			*p*-value*
	Planting strips	Chop off strip	Natural forest	
1	4.15	3.90	3.21	0.010**
2	3.83	3.88	3.38	0.285
3	3.13	2.79	2.53	0.113
4	3.71	3.31	2.95	0.099
5	3.56	3.46	2.95	0.238
6	2.67	2.88	2.05	0.011**
7	2.81	2.92	2.52	0.197
8	3.17	2.69	2.48	0.078
Average	3.38	3.23	2.76	

Note: *probability value, **significant.

est in South Sumatra (Matangaran 2012). The author also explained, with the same soil type, soil compaction on the skid trail that was not covered with wood harvesting waste was 8.50–10 kgf·cm^{-2}. On the other hand, soil compaction on the skid trail that was covered with wood harvesting waste before skidding was 5.70–9.00 kgf·cm^{-2}.

The average of soil compaction in natural forest was 2.76 kgf·cm^{-2} which ranged from 2.05 kgf·cm^{-2} (gap class 6) to 3.38 kgf·cm^{-2} (gap class 2) (Table 1). The difference between the highest and lowest soil compactions in natural forests was 1.33 kgf·m^{-2}. This result was lower than soil compaction in the undisturbed area of the industrial forest, with the same soil type, in South Sumatera of 4.49 kgf·cm^{-2} (Matangaran 2012) and the other gap planting construction of 3.04 kgf·cm^{-2} (Elias and Suwarna 2019).

The average of soil compaction in planting strip was the highest when compared to other cover types. In order, the average soil compaction in each forest cover type was planting strip (3.38 kgf·cm^{-2}), chop off strip (3.23 kgf·cm^{-2}), and natural forest (2.76 kgf·cm^{-2}) (Table 1). The highest soil compaction due to gaps construction was 0.25 times lower than soil density due to harvesting of the industrial forest using heavy equipment (12.96–13.98 kgf·cm^{-2}) (Matangaran and Suwarna 2012). The average soil compaction in all cover types after gap construction was classified as a very loose condition (Wesley 2010) and expectedly did not disturb root growth. Sinnett et al. (2008) explained that root growth was relatively undisturbed at soil compaction values ranging from 0–20.39 kgf·cm^{-2}. According to Wesley (2010), the value of cone penetrometer penetration was: very compacted soil more than 203.94 kgf·cm^{-2}, compacted soil 122.37–203.94 kgf·cm^{-2}, medium compacted soil 40.79–122.37 kgf·cm^{-2}, loose soil 16.32–40.79 kgf·cm^{-2}, and very loose soil less than 16.32 kgf·cm^{-2}.

ANOVA test with cover types and gap size revealed a significant result, cover type and gap size class 1 (p = 0.010) and gap class 6 (p = 0.011) for soil compaction (Tabel 1). Tukey test (Table 2) showed that the significant result in gap class 1 was in planting strip and natural forest (p = 0.010). Significant result in gap class

Table 2. Tukey test value.

Gap class	Cover type		*p*-value*
	Group 1	Group 2	
1	Planting strip	Chop off strip	0.663
	Planting strip	Natural forest	0.010**
	Chop off strip	Planting strip	0.663
	Chop off strip	Natural forest	0.064
	Natural forest	Planting strip	0.010**
	Natural forest	Chop off strip	0.064
6	Planting strip	Chop off strip	0.676
	Planting strip	Natural forest	0.061
	Chop off strip	Planting strip	0.676
	Chop off strip	Natural forest	0.011**
	Natural forest	Planting strip	0.061
	Natural forest	Chop off strip	0.011**

Note: *probability value, **significant.

6 was in chop off strip natural forest and (p = 0.011).

Erosion level

Erosion occurs due to interactions between climate, vegetation and topography parameters with humans (Suwarna et al. 2009, Lieskovský and Kenderessy 2012, Gabarrón-Galeote et al. 2013, Ochoa et al. 2016). Topography and vegetation (tree density and cover types) were parameters that were used in research area design. Topography variations and tree density in each gap class can be seen in Table 3.

Topography in each gap class area was determined by weighting the middle point of topography class with its area (Table 4). For instance, the topography of gap class 1 was found to be 33.62 % (or class 4 topography), which was calculated by formula (7).

$$\text{Gap topography}_a = \frac{\sum_{a=1,b=\text{flat}}^{n} \left(X_{ba} \cdot W_b\right)}{\sum_{a=1}^{n} X_a} \cdot 100\ \%, \quad (7)$$

where: Gap topography$_a$ is topography in gap class a; a is gap class 1, 2, …, 8; X_{ba} is area of topography b in gap class a; W_b is middle point of topography class b; b is topography class (flat 0–8 %, gentle slope 8–15 %, moderate15–25 %, steep 25–40 %, very steep class 40–83 %); X_a is area of gap class-a. For example, the calculation of gap class 1 topography:

[(26.52+0.13)·0.04+(10.14+1.62)·0.115+(24.12+2.57)·0.2+(159.61+212.58)·0.325+(28.99+33.33)·0.63)]·100%/(249.39+250.25) = 33.62 %

Gap topography variation in each gap class can be seen in Table 4.

Similarly, tree density was also determined by weighting the middle point of the tree density class with its area (Table 5). For example, the tree density of gap class 1 was 37 trees ha^{-1} (or class 1 tree density) which was calculated using formula 8.

$$\text{Tree density}_a = \frac{\sum_{a=1,b=\text{very low}}^{n} \left(X_{da} \cdot W_d\right)}{\sum_{a=1}^{n} X_a}\ \text{tree} \cdot \text{ha}^{-1}, \quad (8)$$

where: Tree density$_a$ is tree density in gap class a; a is gap class 1, 2, …, 8; X_{da} is area of tree density d in gap class a; W_d is middle point of tree density class d; d is tree density class (very low = 0–45 tree·ha^{-1}, low = 45–90 tree·ha^{-1}, moderate = 90–135 tree·ha^{-1}, high = 135–180 tree·ha^{-1}, very high = 180–225 tree·ha^{-1}); X_a is area of gap class a. For example, the calcula-

Table 3. Topography and tree density.

Gap class	Gap size interval, m^2	Topography class*	Tree density class**
1	≤ 250	4	1
2	250–500	5	1
3	500–750	4	2
4	750–1000	4	2
5	1000–1250	5	2
6	1250–1500	4	2
7	1500–1750	5	2
8	1750–2000	4	3

Note: *Slope of Topography class: 1 = 0–8 %, 2 = 8–15 %, 3 = 15–25 %, 4 = 25–40 %, 5 = 40–83 %. **Tree density class: 1 = 0–45 tree·ha^{-1}, 2 = 5–90 tree·ha^{-1}, 3 = 90–135 tree·ha^{-1}, 4 = 135–180 tree·ha^{-1}, 5 = 180–225 tree·ha^{-1}.

Table 4. Gap topography variation.

Gap class	Gap size interval, m^2	Gap code	Gap area, m^2	Gap topography*									
				Flat		Gentle slope		Moderate		Steep		Very steep	
				m^2	%	m^2	%	m^2	%	m^2	%	m^2	%
1	≤ 250	A	249.39	26.52	10.63	10.14	4.07	24.12	9.67	159.61	64.00	28.99	11.63
		L	250.25	0.13	0.05	1.64	0.66	2.57	1.03	212.58	84.95	33.33	13.32
2	250–500	B	372.19	151.54	40.72	5.01	1.35	17.78	4.78	14.86	3.99	183.00	49.17
		K	476.27	31.36	6.58	10.45	2.19	37.16	7.80	98.27	20.63	299.03	62.79
3	500–750	D	632.11	237.59	37.59	27.47	4.35	123.24	19.50	151.43	23.96	92.38	14.61
		G	538.13	9.31	1.73	16.30	3.03	72.81	13.53	120.96	22.48	318.75	59.23
4	750–1000	C	938.05	123.66	13.18	31.90	3.40	49.84	5.31	184.29	19.65	548.36	58.46
		N	983.19	121.38	12.35	34.28	3.49	188.10	19.13	591.46	60.16	47.97	4.88
5	1000–1250	M	1092.84	53.80	4.92	17.72	1.62	25.62	2.34	216.14	19.78	779.57	71.33
		F	1076.5	39.19	3.64	11.99	1.11	172.05	15.98	378.78	35.19	474.49	44.08
6	1250–1500	I	1250.33	207.39	16.59	34.06	2.72	53.22	4.26	255.95	20.47	699.71	55.96
		H	1489.48	545.15	36.60	57.64	3.87	181.46	12.18	220.30	14.79	484.93	32.56
7	1500–1750	P	1574.67	0.00	0.00	0.00	0.00	162.50	10.32	1318.89	83.76	93.28	5.92
		J	1622.88	8.45	0.52	19.53	1.20	125.64	7.74	527.71	32.52	941.55	58.02
8	1750–2000	O	1834.69	31.98	1.74	36.45	1.99	942.97	51.40	744.27	40.57	79.02	4.31
		E	1907.16	446.36	23.40	35.68	1.87	55.22	2.90	258.31	13.54	1111.59	58.29
Total			16 288.24	2033.82		350.26		2234.30		5453.80		6215.96	

Note: *Gap topography: Flat = 0–8 %, Gentle slope = 8–15 %, Moderate = 15–25 %, Steep = 25–40 %, Very steep class = 40–83 %.

Table 5. Tree density variation of gaps.

Class	Gap size interval, m^2	Gap code	Gap area, m^2	Tree density*									
				Very low		Low		Moderate		High		Very high	
				m^2	%	m^2	%	m^2	%	m^2	%	m^2	%
1	≤ 250	A	249.39	249.35	99.98	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00
		L	250.25	88.82	35.49	161.43	64.51	0.00	0.00	0.00	0.00	0.00	0.00
2	250–500	B	372.19	243.34	65.38	128.85	34.62	0.00	0.00	0.00	0.00	0.00	0.00
		K	476.27	329.94	69.28	146.33	30.72	0.00	0.00	0.00	0.00	0.00	0.00
3	500–750	D	632.11	85.26	13.49	188.89	29.88	357.96	56.63	0.00	0.00	0.00	0.00
		G	538.13	179.71	33.40	357.77	66.48	0.65	0.12	0.00	0.00	0.00	0.00
4	750–1000	C	938.05	14.44	1.54	671.49	71.58	252.11	26.88	0.00	0.00	0.00	0.00
		N	983.19	445.29	45.29	239.93	24.40	297.97	30.31	0.00	0.00	0.00	0.00
5	1000–1250	M	1092.84	520.03	47.59	162.39	14.86	3.27	0.30	294.11	26.91	113.04	10.34
		F	1076.5	913.89	84.89	162.61	15.11	0.00	0.00	0.00	0.00	0.00	0.00
6	1250–1500	I	1250.33	707.16	56.56	543.17	43.44	0.00	0.00	0.00	0.00	0.00	0.00
		H	1489.48	614.39	41.25	213.96	14.36	0.00	0.00	397.38	26.68	263.76	17.71
7	1500–1750	P	1574.67	5.09	0.32	1110.86	70.55	458.71	29.13	0.00	0.00	0.00	0.00
		J	1622.88	1266.21	78.02	244.39	15.06	49.96	3.08	62.33	3.84	0.00	0.00
8	1750–2000	O	1834.69	0.00	0.00	798.81	43.54	749.32	40.84	0.00	0.00	286.56	15.62
		E	1907.16	42.77	2.24	1286.57	67.46	577.81	30.30	0.00	0.00	0.00	0.00
Total			16 288.24	5705.70		6417.49		2747.76		753.82		663.36	

Note: *Tree density: Very low = 0–45 tree·ha^{-1}, Low = 45–90 tree·ha^{-1}, Moderate = 90–135 tree·ha^{-1}, High = 135–180 tree·ha^{-1}, Very high = 180–225 tree·ha^{-1}.

tion of gap class 1 tree density:

$$[(249.35+88.82)\cdot 22.5+(0.04+161.43)\cdot 67.5+(0+0)\cdot 112.5+(0+0)\cdot 157.5+(0+0)\cdot 202.5)]/(249.39+250.25) = 37\ \text{tree}\cdot\text{ha}^{-1}$$

Tree density variation in each gap class can be seen in Table 5. With the same technique, topography and tree density classes of other gap classes were determined.

The greatest soil erosion due to gap planting occurred in gap class 7 and the smallest occurred in gap class 8 (Table 6). Soil deposition occurred only in gap class 2. Soil erosion was considerably affected by the size of gaps, topography conditions, and tree density at each gap.

Gap class 8 had the highest tree density (class 3) compared to other gaps and had a relatively more sloping topography (class 4). Otherwise, gap class 7 had class 2 tree density and had the steepest topography (class 5). Sun et al. (2014) explained that denser vegetation provided more protection from erosion. The topography conditions in gap class 8 were relatively balanced between the flat to moderate (41.65 %) and the steep topographic class to very steep (58.35 %) (Table 4). Although gap class 5 had a mid-size area (1000–1250 m^2), it occupied the second-greatest erosion. Gap class 5 had the largest proportion of very steep topography (Table 4). Topographic variations in the gap affected erosion and the greater proportion of steep topography caused greater erosion. Tarigan and Mardiatno (2012), and Zhang et al. (2018) explained that soil erosion was directly related to slope gradient.

Chop off strip had the smallest erosion weight. The soil erosion weight ranged from 4.41 t·ha^{-1} to 15.39 t·ha^{-1} (Table 7). The high level of erosion in the natural forest was caused by topography conditions. Unlike gaps that were constructed on relatively flat areas, natural forests were outside the gaps with steep and very steep topography (Fig. 4). Topography, trees and gaps distribution can be seen in Figure 4.

In general, soil erosion weight decreased in the following order: natural forest > planting strip > chop off strip (Table 7). This result was different compared to other results. Cornelio and Rao (2011) said that the highest soil erosion occurred in the agricultural system and soil erosion decreased in the following order: agricul-

Table 6. Soil erosion weight.

Gap class	Cover type, t*			Total, t·ha^{-1}**
	Planting strip	Chop off strip	Natural forest	
1	0.70	8.34	9.68	18.72
2	-2.28	-1.13	-3.60	-7.00
3	3.97	-3.87	10.10	10.20
4	-0.25	-5.63	13.21	7.33
5	2.04	10.83	12.40	25.28
6	5.71	-0.55	6.89	12.05
7	7.72	0.90	20.47	29.09
8	-2.66	-0.43	4.70	1.61

Note: *The negative numbers represent soil deposition, while positive numbers represent soil erosion. **Cover type area proportion in 1 ha consists of planting strip 1600 m^2, chop off strip 2400 m^2 and natural forest 6000 m^2.

Table 7. Soil erosion weight.

Cover type	Soil surface erosion height, m	Soil erosion volumen, $m^3 \cdot ha^{-1}$	Soil erosion weight, $t \cdot ha^{-1}$
Planting strip	0.17	17.44	11.69
Chop off strip	0.07	6.58	4.41
Natural forest	0.26	26.08	15.39

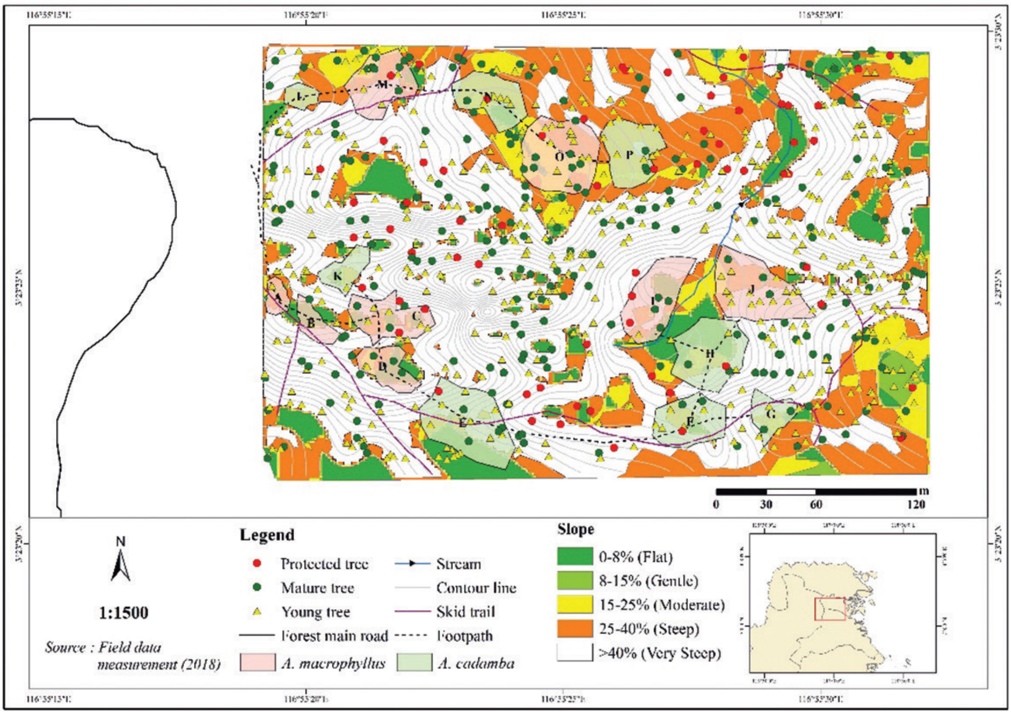


Fig. 4. Topography, trees and gaps distribution.

tural systems > forest systems > grasslands. It was 8–10 $t \cdot ha^{-1}$, 20–23 $t \cdot ha^{-1}$, 25–28 $t \cdot ha^{-1}$. Elias and Suwarna (2019) also explained that erosion due to gap planting in different cover types with the same soil decreased in the following order: forest area > chop of strip area > planting area. The soil erosion weight was 17.05 $t \cdot ha^{-1}$, 16.83 $t \cdot ha^{-1}$, 5.56 $t \cdot ha^{-1}$, respectively.

In addition to relatively flat topographic conditions, gap waste of logs, branches, twigs, leaves and grass in the gap also affect erosion. The waste from gap construction on chop off strip becomes litter and together with the grass slow down water flow, increase infiltration and reduce runoff. This result was in accordance with the results by Elias and Suwarna (2019) who explained that gap waste and grass in chop off strip reduced soil erosion. Research by Tang et al. (2014), in the upper Yangtze Watershed, China, proved that grass was more effective in reducing surface runoff and sediment than woody plants. Suwarna et al. (2009) also explained that the logged-over forest floor which was covered by grass or cover crop was more effective in reducing soil erosion.

The study results showed that soil erosion weight variations in each gap class were caused by topographical variations and tree densities. Greater erosion occurs at gaps with steeper topography. This result was also showed by Tarigan and Mardiatno (2012) and Zhang et al. (2018). It explained that steeper topography caused greater run off and soil loss. On the other side, the higher density of trees reduce erosion. Denser vegetation and the root systems of trees slowed overland water flow (Sun et al. 2014). Gap cover types also have a role to reduce the amount of soil erosion weight. Gap planting, using planting strip and chop off strip, has positive impact reducing the erosion. Grass and gap waste slowed down the water flow, increased infiltration and reduced runoff (Suwarna et al. 2009, Cornelio and Rao 2011, Tang et al. 2014, Elias and Suwarna 2019). However, ANOVA test results showed that the cover types and gap sizes were not significant for soil erosion weight.

Conclusion

The results of this study show that using gap planting technique to rehabilitate Indonesian lowland tropical rainforest caused soil compaction. Soil compaction due to gap planting occurs in gaps with an area of less than or equal to 250 m^2 and 1250–1500 m^2. However, the compaction value is classified as very loose soil so that it can be ignored. Otherwise, this technique can reduce soil erosion. Gap planting, using planting strips and chop off strips, has a positive impact lowering erosion at gap sizes less than or equal to 250 to 2000 m^2.

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