Influence of soil and topography on success of post-mine rehabilitation in Indonesia

Research on a coal mine rehabilitation with trees at PT Adaro Indonesia on WDPS, South Kalimantan, Indonesia

Source: Joas Paatsch, Rehabilitation area of PT Adaro Indonesia (2019)

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Abstract

The rehabilitation forest on the Waste Dump Paringin South (WDPS) of PT Adaro Indonesia was established in 2015 and 2016. The area is on the Paringin mining site near Tanjung, South Kalimantan, Indonesia. Although trees were planted on the whole area and the starting conditions were similar, the area had strong variations in the tree density in 2019. Some parts of the area had dense forests with a closed canopy while other parts had almost no trees.

This research was carried out to investigate if the soil conditions or topography influenced the tree species distribution and abundance on the rehabilitation area. The objective was to contribute to a more successful post-mine rehabilitation on the mining area of PT Adaro Indonesia.

The forest of the rehabilitation area was stratified and divided into dense forest (≥67% canopy cover), sparse forest (20-67% canopy cover) and open area (≤20% canopy cover). Twenty sample plots and three transect lines were distributed over the 12,05 ha research area. The sample plots were set up as squares covering 0,05 ha each and data on the trees, soil and topography were taken. The transect lines were used to make profile diagrams of the vegetation and to analyze the forest structure. With T-tests and regression analysis, the data from the monitoring was analyzed.

Cassia siamea, Leucaena leucocephala, Acacia mangium, Sesbania grandiflora, Paraserianthes falcataria and *Enterolobium cyclocarpum* were the most abundant tree species and accounted for 84% of all trees on the rehabilitation area.

The dense forest areas were richer in tree species (10,6/plot), had more trees (6151/ha) and were growing on the steeper parts of the area (8,9°). The sparse forest areas were less rich in tree species (7,9/plot), had a moderate number of trees (3255/ha) and were growing on the less steep parts of the area (3,5°). The open areas were habitat to few species (2,4/plot), a low number of trees (180/ha) and were on flat parts of the rehabilitated area (0,6°). Significant differences were found between the areas.

The topography (and the soil-water balance) had a significant effect on the tree species distribution and abundance of the rehabilitation area.

No clear relation was found between the soil characteristics and the trees. The soil conditions varied throughout the area and on average they were slightly acidic to neutral (6,4-7 pH), had a very low electric conductivity (0,2-0,4 dS/m), a moderate carbon to nitrogen ratio (14,1-14,5), moderate total phosphorous (22,7-27,9 mg/100g), moderate cation exchange capacity (17,5-18,8 me/100g) and a moderate alkali saturation (50,9-57,5%).

The maximum height of trees in the sparse forest was 9,8 m and 13,9 m in the dense forest. About half of the trees were in the understory and subcanopy layer and the other half in the main canopy; no emergent layer was distinguished.

This research showed a strong variation of tree densities on the rehabilitation area.

The topography influenced tree species distribution and abundance.

The soil characteristics did not influence the tree species distribution and abundance.

With the findings of the research, the post-mine rehabilitation of PT Adaro Indonesia can be improved for a more sustainable and successful restoration in the future.

Keywords Coal mine rehabilitation; Rehabilitation success; Topography; Soil characteristics; Indonesia; Profile diagrams

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List of Abbreviations and Symbols

<	less than
>	more than
1-D	Simpson's Diversity Index
avg	average
C organic	organic carbon
C/N ratio	carbon to nitrogen ratio
Ca^{++}	calcium cation
CC	canopy cover
CCA	Coal Cooperation Agreement
CEC	cation exchange capacity [me/100g]
cm	centimeter
DBH	diameter breast height (measured at 1,3m)
E	equitability of Shannon Index
EC	electrical conductivity
Eh	reduction potential
GPS	Global Positioning System: electronic system that uses satellites to determine the position on the earth surface
H	Shannon Index
H_2O	formula of water
ha	hectare
H_{max}	maximum value that H can reach in a community with a given number of species
IBM SPSS Statistics	Statistic software developed by International Business Machines Corporation
K total	total potassium [mg/100 grams]
K^+	potassium cation
m	meter
me/100g	milliequivalents/100 grams
mg/100g	milligrams/100 grams
Mg^{++}	magnesium cation
mS/m	millisiemens per meter
Na^+	sodium cation
Nr/ha	number per hectare
ø	average
OB	overburden
P	P-value from statistical tests
P total	total phosphorus [mg/100 grams]
PAF	Potentially Acid Forming
pH	potential of Hydrogen: a measure of the acidity or alkalinity of a solution
R^2, r^2	coefficient of determination: a value showing the strength of a connection between data sets
RI	relative importance
S	total species of a community
trees/ha	trees per hectare
trees/plot	trees per plot
VDT	vegetation direct transfer
WDPS	Waste Dump Paringin South
Σ	capital sigma: the sum of

1. Introduction

1.1. Coal mining

The coal industry is of great importance all around the world. It is a major source of economic value, employment and energy (Statistics South Africa, 2015). In 2016, the coal production worldwide was about 17,61 billion tons and Indonesia had a production of about 463 million tons. The worldwide coal export in 2016 was about 1,36 billion tons with Indonesia alone contributing about 26,8% of the total (Internal Energy Agency, 2016). In 2017, Indonesia produced 461 million tons of coal and exported almost 79% (Indonesia Investments, 2018). When comparing coal export on the basis of dollar value worth of coal Indonesia was the second biggest coal exporter in 2017, after Australia (Workman, 2018).

PT Adaro Indonesia is the biggest mining company in South Kalimantan, Indonesia. 1982 Adaro Indonesia signed the Coal Cooperation Agreement (CCA) under the Spanish Government company Enadimsa. In August 1991, the official opening of the Paringin mine took place. From its outset, PT Adaro Indonesia decided to integrate local communities as much as possible. After a first shipload of 68,750 tons to Germany, the coal export of PT Adaro Indonesia experienced a steady increase and in 2018, 54 million tons were produced (PT Adaro Indonesia, 2019b, 2019a). In 2019, PT Adaro Indonesia operated three mining-pits: Paringin, Wara and Tutupan. The government permit of PT Adaro Indonesia included a concession area of 31.379,80 ha. About 4.800 ha were used for active mining and 9.800 ha for disposal. 4.300 ha from the disposal were already rehabilitated. The remaining concession area was used for buffer zones and supporting structures as seen in Figure 1 (Wahyudi, 2019).

Figure 1 Supporting structure: area for coal transshipment (PT Adaro Indonesia, 2019a)

Coal mining is carried out as surface/open-pit mining or as underground mining. Both ways cause interferences in the natural ecosystem but mining at the surface results in loss of habitat for the natural vegetation and wildlife. Once the extraction of all minerals is completed, the open-pit mine often remains with loosely adhered particles of boulders, stones, shale, cobbles and other debris (Gogoi, Pathak, Dowrah, & Deka Boruah, 2007). The resulting rock material is mostly nutrient poor and can contain increased concentrations of trace metals (Novianti, 2013; Pourret et al., 2016). In some cases, the surface material of new open-pit mines is spread over the nutrient-poor rock material to promote the growth of new vegetation. Also, further management practices like increasing soil fertility, recharging soil microbes and re-establishing nutrient cycles can help in reclamation of abandoned mines (Sheoran, Sheoran, & Poonia, 2010). Agriculture, pastures, forestry, tourist attractions and construction are common land uses of post-mining areas and sometimes the decision of which land use to apply is a complex process (Akbari, Osanloo, & Hamidian, 2006).

1.2. Post-mine rehabilitation

Many countries have government regulations to make sure post-mine reclamation or rehabilitation is carried out by the operators of the mine. In Indonesia, the Government Regulation GR 78/2010 dealt with reclamation and post-mining activities. Among other requirements, a five-year reclamation plan and a post-mining plan had to be written. Also, a reclamation guarantee and a post-mining guarantee, in form of a time deposit with a state-owned bank, were required from the mine operators (PwC Indonesia, 2018). The Ministry Regulation PerMen 7/2014 included the procedures for the preparation of the reclamation and post-mining activities report (PwC Indonesia, 2018).

PT Adaro Indonesia aimed at restoring the natural conditions of vegetation and creating a diverse and abundant habitat for wildlife (PT Adaro Indonesia, 2013). An interview with the rehabilitation department of PT Adaro Indonesia (2019) showed that the rehabilitation measures after mine pit closure were: land preparation, topsoil spreading, regulation of Potentially Acid Forming (PAF) material, erosion control, hydroseeding cover crops, planting fast- and slow-growing trees and maintenance.

The overburden (OB) of active pits was piled in the abandoned pit and the topography was shaped with terraces and slopes as shown in Figure 2 (Nugroho, Dewangga, Luthfiansiyah, & Habibie, 2019). Detailed information on the mine rehabilitation of PT Adaro Indonesia is given in Annex 1.

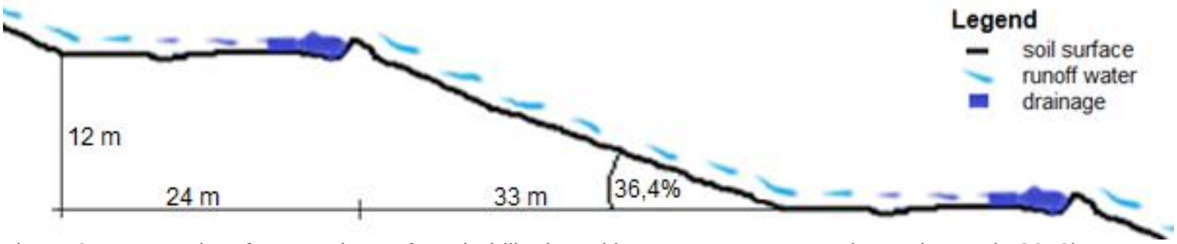

Figure 2 Topography of terraced area for rehabilitation with water management (Nugroho et al., 2019)

1.3. Problem analysis

One of the problems of surface coal mining is the loss of habitat for natural vegetation and wildlife due to deforestation (Pandit, Sodhi, Koh, Bhaskar, & Brook, 2007).

Borneo, as the third largest island in the world, is home to a very diverse nature (MacKinnon, Hatta, Halim, & Manglaik, 1996). As the oldest rainforest on earth, it is home to at least 15.000 plant species of which 6.000 are endemic and 3.000 are tree species. It is also habitat to 222 mammals, 420 bird species and many reptiles, amphibians and fish (The Borneo Project, 2019; WWF, 2019b). Although Borneo only covers about 1% of the world's land surface it holds approximately 6% of the global biodiversity (WWF, 2019a). The forests of Borneo are under threat due to human influence. From a forest cover of 96% at the turn of the 20th century it dropped to 55% in 2015. Especially, lowland and freshwater swamp forests are under pressure and will decline if development continues as it does now (Wulffraat et al., 2017).

In 2015, at least 11,9 million ha of forests were threatened by coal mining over the whole world and in Indonesia 850.000 ha (9% of national forest cover) were at risk (Olden & Neumann, 2015). Deforestation and the resulting loss of habitat is a major driver of biotic extinction; especially, endemic species or endangered species are endangered (Pandit et al., 2007). For example, the orangutans live only on Sumatra and Borneo and are rated as critically endangered on the red list (Nowak, Rianti, Wich, Meijaard, & Fredriksson, 2017).

To reduce the ecological footprint of open-pit coal mining a good restoration, rehabilitation and revegetation of the abandoned mines has to take place (Lechner, Kassulke, & Unger, 2016). In the tropical climate of Indonesia, the natural succession of vegetation can be very fast. Under favorable conditions, the colonization of shrubs and trees starts early and after sixty-four months they dominate the vegetation (Novianti, Marrs, Choesin, Iskandar, & Suprayogo, 2018). Although natural succession starts early and develops fast, schemes to improve rehabilitation are beneficial. For example, in the very early succession stage, soil erosion is a problem (Carroll & Tucker, 2000).

Measuring the success of restoration projects includes diversity, vegetation structure and ecological processes (Ruiz-Jaen & Aide, 2005). Most of the studies on restoration success have been carried out for plant species. Ruiz-Jaen and Aide (2005) found out that 38% of the articles on rehabilitation success have measured all three ecosystem attributes.

The problem of the post-mine rehabilitation from PT Adaro Indonesia was that the success of establishing a forest strongly varied. Figure 3 shows that some parts of the rehabilitation areas were mostly covered with grasses and herbs (front) while other parts had a closed tree canopy (background).

Figure 3 Variation in vegetation on the rehabilitation area of PT Adaro Indonesia (2019)

Trees/plants require five basic items for growth: temperature, light, water, air and nutrients (Webster, 2016). On the rehabilitation area of PT Adaro Indonesia, the factors of temperature, light, air and water (precipitation) were given due to the climate and there was little variation over the area. And, although planting and management of the areas were similar, the success of restoration varied. Aerial photographs and satellite images showed that the establishment of the forests on the rehabilitation areas was inhomogeneous.

Two abiotic factors that might influence the success of reforestation are the soil and the topography.

- The soil characteristics vary depending on the OB substrates and the topsoil that is spread over it. The quality of the topsoil depends on its origin and reduces over time if it is stored on stockpiles (Ghose, 2004).
- The topography is important because it influences the potential erosion and the soil-water balance. Infiltration and water runoff can lead to differences in the soil-water balance and the topographic position of an area can have a large effect on water regime (Daws, Mullins, Burslem, Paton, & Dalling, 2002).

Little is known about the importance of slope angle in vegetation development of rehabilitated coal mines.

González-Alday, Marrs and Martínez-Ruiz (2008) found out that south-facing slopes had less vegetation cover than north-facing slopes. They had not included the differences in slope angle in their analysis.

Another study showed that species composition of a rehabilitated area was affected by the aspect (Alday, Marrs, & Martínez-Ruiz, 2012). Alday et al. (2012) also found that age since restoration was the key driver in soil development. A correlation of vegetation and organic matter, total nitrogen and sand content was also found.

Sjoerdsma (2016) had analyzed the success of mine rehabilitation under consideration of the soil properties. A significant influence on the performance of trees had been found in age of rehabilitation, EC of the soil and C/N ratio.

Research on the rehabilitation area of PT Adaro Indonesia is necessary to improve the success of reforestation. More insight into the effect of soil and topography on the success of post-mine rehabilitation will help in improving the current practices. Through improvement of the rehabilitation methods, more sustainable land management can be achieved.

1.4. Objective

The objective of this thesis is to contribute to a more successful post-mine rehabilitation on the mining area of PT Adaro Indonesia.

To achieve this objective the research question answered by this thesis is:

Do soil characteristics or topography influence the success of post-mine rehabilitation?

The sub-questions leading to the answer of the research question are the following:

- What is the current state of vegetation (forest and tree species) on the rehabilitation area?
- Is the tree species distribution and abundance related to the soil conditions of the area?
- Is the tree species distribution and abundance related to the topography of the area?

➢ For the investigation into the research question four hypotheses were constructed:

1. Different soil conditions affect tree species distribution on the rehabilitation area.
2. Different soil conditions affect abundance of the trees on the rehabilitation area.
3. Variation in topography affects tree species distribution on the rehabilitation area.
4. Variation in topography affects abundance of the trees on the rehabilitation area.

2. Methodology

2.1. Study site

The field research took place on the Paringin mining site near Tanjung, South Kalimantan, Indonesia. The area for data collection was on the Waste Dump Paringin South (WDPS). The trees were planted in 2015 (6,51 ha) and in 2016 (5,54 ha). A map with the location of the planting years is attached in Annex 3. The climate in Tanjung is classified as tropical (Af) and the average temperature is 26,9°C. Throughout the year the variation in temperature is 1,3°C. The average annual precipitation is 2480 mm with August being the driest month (76 mm) and December the wettest (374 mm) (climate-data.org, 2019).

As the area for sampling had a large variation in tree density, stratification of the area was done. Figure 4 shows the final stratification with open area (2,12 ha), sparse forest (5,97 ha) and dense forest (3,96 ha).

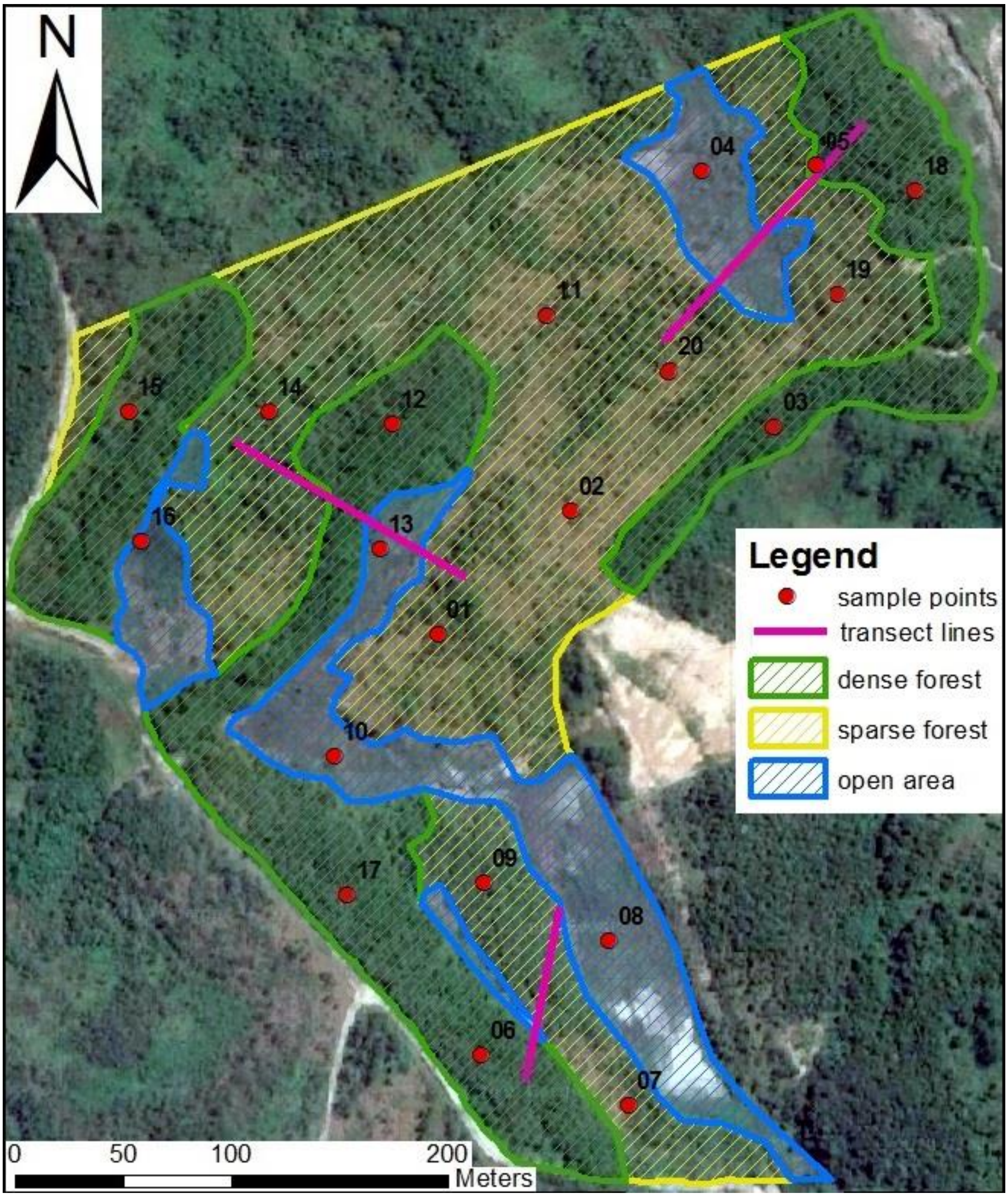

Figure 4 Map of the survey area with forest types, sample plots and transect lines (Google, 2018)

The stratification was based on the canopy cover (CC) of the trees estimated with the pictures of a surface map (Google, 2018).

The sample plots were randomly placed on representative places within the different forest types. GPS coordinates (UTM 50 M) were selected based on the map. In the field, plots were set up close to the selected coordinates but in such a way that the plots only covered one tree density. The starting points for the transect lines were selected randomly and the compass direction was chosen so that it covered all forest types.

The list of coordinates is attached in Annex 4.

2.2. Data collection

Sample plots

The monitoring was carried out as an inventory with twenty sample plots between the 13th of March and the 15th of April 2019. Five plots were in open area, eight in sparse forest and seven in dense forest. In each planting year, ten of the plots were established. The plots were set up as square plots covering 0,05 ha each and Figure 5 shows the plot setup.

a) For all trees taller than 30 cm the species was determined. The diameter breast height (DBH) was measured on all trees higher than 1,3 m. The trees below 1,3 m (seedlings) were only counted.
   When species were unknown, pictures were taken to tell them apart and to compare the unknown species from the different sample plots. Later, these pictures were used to identify the unknown species.
b) The topography (slope in percent) was measured for each sample plot with a clinometer. This included the minimal and maximal slope, the average slope over the sample plot and the compass direction of the slope. Another factor that was examined together with the slope was the soil-water balance. The soil-water balance was estimated based on the existing vegetation, the water condition of the soil and flooded parts on the area. The classification was based on nine levels with five main levels (very dry, dry, moist, wet, very wet) and four mixed levels between the main levels.

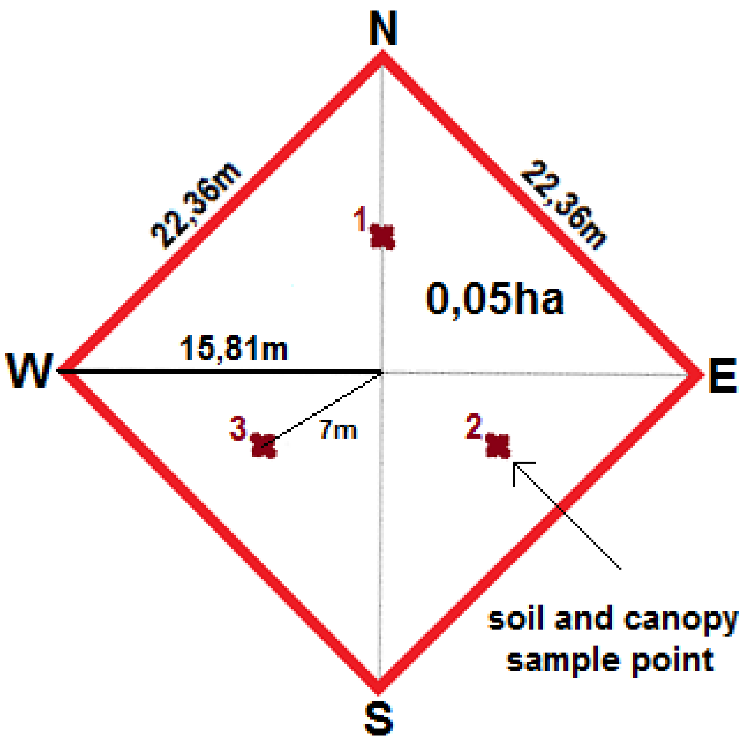

Figure 5 Inventory plot setup

c) Soil samples were taken as composite samples from three sample points within each plot. Two depths were sampled by drilling a hole into the soil with an auger. The first depth was 0 to 30 cm for the topsoil and the second depth was 30 to 60 cm for the subsoil. The three samples of one depth from one plot were mixed and a sample of the earth material was taken for analysis in the laboratory.
The composite soil samples were air-dried, crushed, and sieved (2 mm). Soil analysis in the laboratory of PT Adaro Indonesia included pH in H_2O, reduction potential (Eh), electrical conductivity (EC), soil moisture content (SMC), amount of organic carbon (C organic) and soil organic matter, total nitrogen (N total), carbon to nitrogen ratio (C/N ratio), total potassium (K total) and total phosphorus (P total), exchangeable sodium (Na^+), potassium (K^+), calcium (Ca^{++}) and magnesium (Mg^{++}), cation exchange capacity (CEC) and alkali saturation.
As methods for soil analysis the Technical Guidelines for Research Centers by Eviati and Sulaeman (2009) were used.
d) At the soil sample points, the canopy cover was also analyzed with the CanopyCapture app on an Android smartphone.

Transect lines

Along the three transects lines the profile diagrams were drawn, consisting of:

- tree species
- crown height
- crown width and size above the transect.

The CanopyCapture app was used for photographic analysis of the canopy cover every 10m of the transect line. Annex 4 includes a list of the coordinates and direction of the transect lines and in Figure 4 they are drawn on the map.

Additional information on the data collection is attached in Annex 5.1.

2.3. Data analysis

For the data analysis, Microsoft Excel was used with its statistical tests. Independent-sample t-tests were used to compare tree species distribution, tree species abundance, topography and soil conditions of the different forest types. Two-sample f-tests were conducted prior to the t-tests to show if equal or unequal variances should be assumed for the t-tests.

Regression was used to analyze if topography or soil properties had an influence on the tree species distribution and abundance.

Vegetation

The tree species known as Sengon (*Paraserianthes falcataria* [Fabaceae]) and Sengon buto (*Enterolobium cyclocarpum* [Fabaceae]) could not be distinguished by the survey team as they look similar. Therefore, they were handled as one species (“Sengon”) in the statistical analysis of the species distribution and abundance.

The relative importance of trees or tree species was calculated as percentage of the whole area. For this, the percentage of trees or tree species from the forest types was multiplied with the percentage of the total area that was covered with sparse forest (49,5%), dense forest (32,9%) and open area (17,6%).

The biodiversity of the forest was calculated for each forest type with different measures. The α-diversity describes the diversity within the forest types and the β-diversity describes the diversity between the forest types (Stilma, 2018b). The calculations for the diversity are presented in Annex 5.2.

For the α-diversity three indexes were used:

- species richness with the total species of a community (S)
- Shannon Index (H)
- Simpson's Diversity Index (1-D).

For the β-diversity, Sørensen's similarity index was used to compare the species distribution between the forest types.

From the transect lines two and three the DBH and measured crown height of the trees were compared with an independent-sample t-test to analyze the differences in the forest types. With regression analysis, the DBH and measured crown height were compared.

For the comparison of forest structure, the trees were grouped into:

- understory (lower third of height)
- subcanopy layer (middle third)
- main canopy (top third).

The emergent layer was not very pronounced, and therefore not included in the analysis (Rainforest Journal, n.d.). An example of forest layers is given in Figure 6 and for additional information see Annex 5.2.

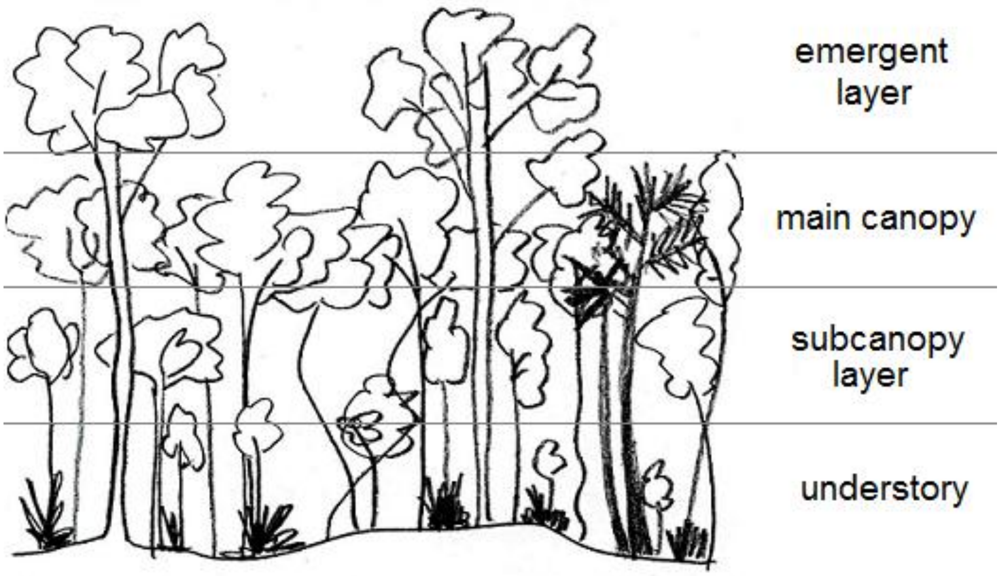

Figure 6 Example of forest layers (Paatsch, 2019)

Soil

The differences in soil characteristics were analyzed among forest types, planting year and soil depth.

IBM SPSS Statistics was used for a multiple stepwise regression analysis to investigate if the soil properties had an influence on the number of trees or tree species distribution.

Topography and soil-water balance

For analysis of topography, the average slopes of the sample plots in the different forest types were compared.

The analysis of the soil-water balance was done by ranking the nine levels from one (very dry) to nine (very wet). With this ranking, an independent-samples t-test was carried out and the average was classified according to the soil-water balance levels.

3. Results

3.1. Vegetation

Forest types and Canopy cover

For the final stratification no forest was present on the open area with a canopy cover (CC) below 1%, the sparse forest had a CC between 24% and 67% and the dense forest had a CC of more than 67%.

The monitoring of the CC from sample plots and transect lines gave similar results for the forest types. Table 1 shows the average CC from the composite samples in the sample plots and the average CC from the transect lines. Based on this classification of the forest types the results of this research are presented.

Table 1 Mean canopy cover from sample plots and transect lines of the forest types

forest type	canopy cover from plots			average canopy cover from transects
	max	min	average	
dense forest	84,7%	68,7%	81,0%	82,9%
sparse forest	65,3%	24,7%	44,6%	49,9%
open area	0,7%	0,0%	0,4%	0,3%

Ten of the plots had a dense to very dense grass cover over the ground (75-100%). These ten plots included all five of the plots in the open area and most of the plots in the sparse forest planted in 2016. None of the dense forest plots had a dense grass cover.

Tree species richness, diversity and distribution

With a maximum of 13 tree species in one plot, the dense forest had the highest number of species followed by the sparse forest. Table 2 shows that there was a variation in the number of tree species per plot. T-tests comparing the forest types showed a significant difference in the number of tree species per plot. The dense forest had the highest species richness and the open area had the lowest species richness.

Table 2 Tree species distribution with average showing the significant difference between the forest types

forest type	Nr of plots	Nr of species in one plot		
		max	min	average
dense forest	7	13	7	$10{,}6^{s*,\ o***}$
sparse forest	8	10	5	$7{,}9^{d*,\ o***}$
open area	5	4	0	$2{,}4^{s***,\ d***}$

*=significant (p<0,05), **=highly significant (p<0,01), ***=very highly significant (p<0,001) with d=dense, s=sparse, o=open

The tree species diversity of the forest types is presented in Table 3. The Shannon Index (H) and the Simpson's Diversity Index (1-D) were highest in the sparse forest although the number of species (S) and the number of trees/ha was higher in the dense forest.

Table 3 Diversities of tree species in the forest types

forest type	trees/ha	S	H	H_{max}	E	1-D
dense forest	6151	18	1,837	2,89	63,6%	0,733
sparse forest	3255	17	1,901	2,833	67,1%	0,819
open area	180	7	1,467	1,946	75,4%	0,701

S=total number of species, H=Shannon Index, H_{max}=maximum value of H
E= equitability of H, 1-D=Simpson's Diversity Index

The results of the Shannon Index showed:

- The dense forest had the highest maximum value (H_{max}) but due to the unevenness in abundance of tree species the equitability (E) was low.
- The open area had the highest E value but due to the low H_{max} the Shannon Index was also low.
- The sparse forest had the highest Shannon Index and the E value was between the values of the other forest types.

The Simpson's Diversity Index showed that the evenness of the species in the sparse forest was higher than in the dense forest and the open area.

When comparing the dense and the sparse forest Sørensen's similarity index (β) was 0,69. This value of β indicates that there was diversity within the tree species composition of the different forest densities and 43,5% of the tree species were only found in one of the forest types.

The open area only had tree species that also grew in the other forest types; therefore, it had a low β-diversity.

A total of 23 different tree species were found on the whole research area. From these species, 14 could be determined in the field and 9 species were unknown. The unknown species were mostly small trees and seedlings and three of them could be identified from the pictures. The three species were *Homalanthus populneus* (Euphorbiaceae), *Melia azedarach* (Meliaceae) and *Leea indica* (Vitaceae). All of them are native to Indonesia.

The distribution of the tree species varied between the forest types. Six species (including "Sengon") were present in all of the forest types. Six species were only found in the dense forest and another four species only occurred in the sparse forest. In the open area, 16 of the tree species were absent.

Cassia siamea and *Leucaena leucocephala* were the most common tree species on the research area. They were present in all plots of the dense and sparse forest. Table 4 shows the distribution of the seven most common species in the sample plots of the different forest types and as relative importance on the whole area. A table with all trees found on the area is included in Annex 6.

Table 4 Relative importance of the seven most common species on the whole research area

family name	scientific name	local name	Nr of plots			relative importance
			dense forest (7)	sparse forest (8)	open area (5)	
Fabaceae	*Cassia siamea*	Johar	7	8	3	93,0%
Fabaceae	*Leucaena leucocephala*	Lamtoro	7	8	1	85,9%
		"Sengon"	7	8	1	85,9%
Fabaceae	*Sesbania grandiflora*	Turi	6	7	2	78,6%
Lamiaceae	*Vitex pubescens*	Alaban	7	3	3	62,0%
Fabaceae	*Acacia mangium*	Akasia	5	6	0	60,6%
Fabaceae	*Calliandra calothyrsus*	Kalliandra	6	4	0	52,9%

Between the number of species and the number of trees a significant and strong connection was found in the regression analysis. 86,4% of the variation in the number of tree species per plot could be explained by the abundance of trees per plot.

Tree species abundance and diameter distribution

On average the dense forest had 6151 trees/ha, the sparse forest had 3255 trees/ha and the open area had 180 trees/ha. Figure 7 presents the abundance of all trees/ha in relation to the diameter distribution.

In all forest types, more than 50% of the trees had a DBH lower than 3 cm.

The average DBH of the sample plots did not differ significantly in the forest types.

The research gave a significant difference in the number of trees for the forest types. These results showed that the dense forest areas had more trees than the other areas.

A t-test showed that the plots with high grass cover had a significantly lower number of trees than the plots with less grass cover. This was true for all trees and for the trees with a DBH below 2 cm.

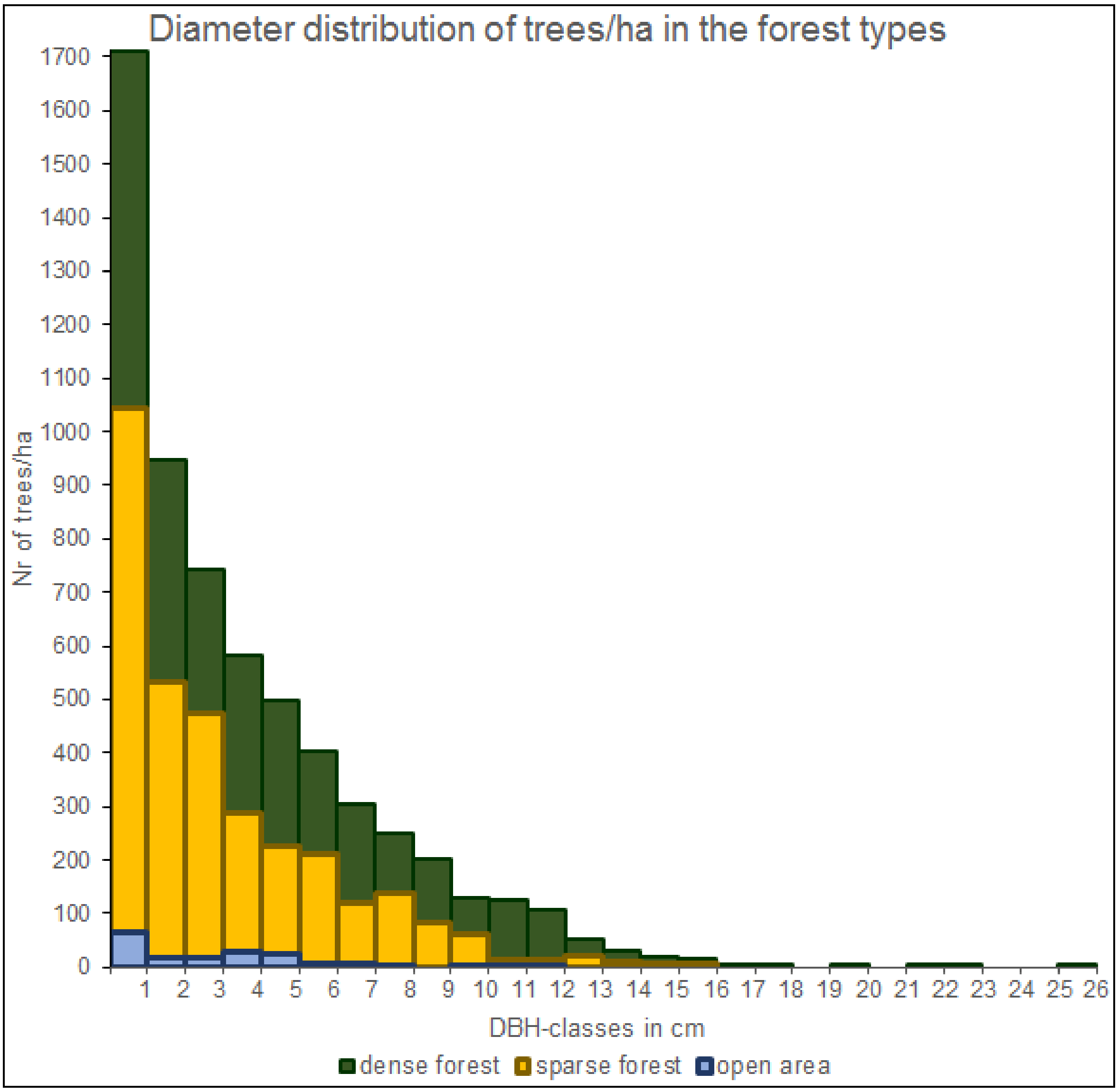

Figure 7 Diameter distribution (DBH) of trees per ha in the forest types

Not only the abundance of trees in the forest types differed but the abundance of the tree species varied strongly as well. For four of the species mentioned in the previous chapter the population characteristics are summarized in Table 5. In Figure 8 the diameter distribution of the species is illustrated.

- *C. siamea* was the most abundant tree species on the research area. Most of the trees were found in the dense forest, where they made up almost half of the trees. The highest number of trees was measured between 1 cm and 2 cm DBH.
- The second most important species was *L. leucocephala.* Most of the trees grew in the sparse forest, where it was the most abundant tree. *L. leucocephala* had the highest number of small seedling (197 trees/ha smaller than 1,3 m) and with an increase of the DBH the number of trees constantly decreased.
- Most of the *A. mangium* trees were found in the sparse forest and there it was the second most abundant tree. *A. mangium* had a low number of small seedlings (16) in relation to the higher DBH-classes.
- *S. grandiflora* was the most important species in the open area but most of the trees occurred in the sparse forest. It had the highest average DBH of all tree species. The diameter distribution of *S. grandiflora* in Figure 8 shows that there were only 5 trees/ha with a DBH below 1 cm (no seedlings below 1,3 m height existed). The maximum number of trees had a DBH between 7 cm and 8 cm.
  Many of the *S. grandiflora* trees throughout the whole area did not look healthy. Often the crown had few leaves and, especially, in the open areas many dead *S. grandiflora* trees were standing or lying on the ground.
- *C. calothyrsus* grew mainly in the dense forest and had mostly small trees; similar to *L. leucocephala.*
- *V. pubescens* was the second most abundant tree species in the open area. 77,3% of the trees were smaller than 1,3 m.
- Species that had not been known to the team during the monitoring had germinated naturally (106 trees/ha). 92% were in the dense forest and 8% in the sparse forest. And 93% of these trees were shorter than 1,3 m.

Annex 7 shows the abundance of all tree species in the forest types.

Table 5 Population characteristics of Cassia siamea, Leucaena leucocephala, Acacia mangium, Sesbania grandiflora *and all species*

scientific name	average trees/ha	% of total avg trees/ha	DBH max [cm]	DBH avg [cm]	forest type	trees/ha	importance in forest type
C. siamea	1248	34%	16,6	3,6	dense	2926	48%
					sparse	568	17%
					open	28	16%
L. leucocephala	753	21%	11,5	1,8	dense	914	15%
					sparse	910	28%
					open	12	7%
A. mangium	440	12%	14,9	3,9	dense	343	6%
					sparse	660	20%
					open	0	0%
S. grandiflora	264	7%	17,5	7,3	dense	194	3%
					sparse	375	12%
					open	84	47%
all species	3667	100%	25,5	3,2	dense	6151	100%
					sparse	3255	100%
					open	180	100%

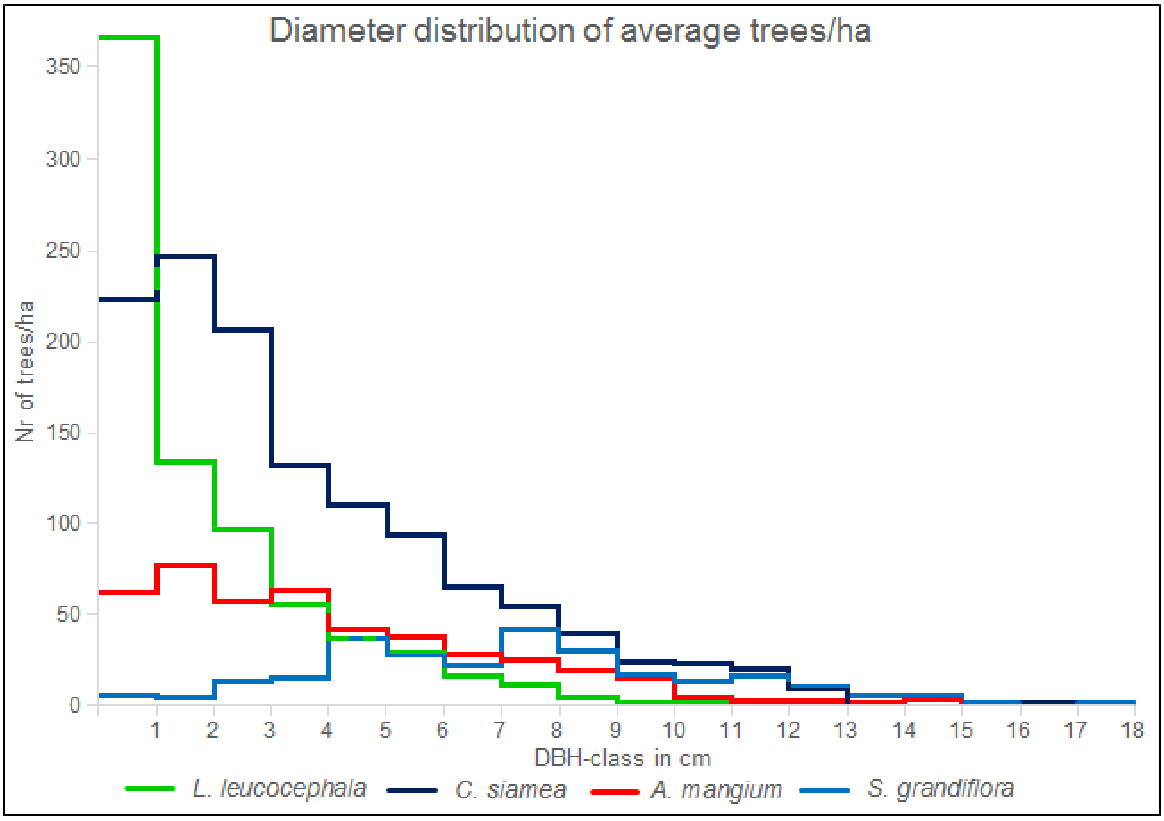

Figure 8 Diameter distribution (DBH) of Leucaena leucocephala, Cassia siamea, Acacia mangium *and* Sesbania grandiflora *as average trees/ha of the research area*

Forest structure

The monitoring of the second and third transect lines included 50,5 m of dense forest, 135,5 m of sparse forest and 34 m of open area.

138,6 trees/100 m were measured in the dense forest and 67,9 trees/100 m in the sparse forest. No trees were found in the open area.

The dense and sparse forest did not have a significant difference when comparing the number of trees per species.

Table 6 shows the relative importance of the tree species found on the transect lines and the variation in forest canopy structure for the dense and sparse forest.

- *C. siamea* was the most abundant tree species in the dense forest and *L. leucocephala* was most abundant in the sparse forest.
- A slight variation was measured in maximal canopy height.
- No significant difference was found in abundance of trees in the forest types.

Table 6 Relative importance of tree species found in the second and third transect line and the forest structure with the percentage of trees in the canopy layers

forest type	*C. siamea*	"Sengon"	*A. mangium*	*L. leuco-cephala*	*S. grandiflora*	*C. calothyrsus*	*A. scholaris*
dense	64,3%	17,1%	0,0%	8,6%	7,1%	2,9%	0,0%
sparse	19,6%	17,4%	6,5%	28,3%	27,2%	0,0%	1,1%

forest type	average DBH	maximal height	main canopy	subcanopy	understory
dense	6,4 cm	13,9 m	44,3%	27,1%	28,6%
sparse	5,0 cm	10,4 m	45,7%	30,4%	23,9%

The height of the trees above the transect line in the dense forest was significantly higher than in the sparse forest.

The DBH of the dense forest was significantly higher than in the sparse forest.

Between the height and DBH of trees a strong and significant connection existed in both forest types. This relation showed that the trees with higher DBH grew taller.

One section of the forest structure is presented in Figure 9 and the total profile diagrams are included in Annex 8.

The profile diagrams showed that *S. grandiflora* and "Sengon" were mainly present in the main canopy while *A. scholaris* and *C. calothyrsus* were species in the understory. *C. siamea, A. mangium* and *L. leucocephala* had trees in the understory, subcanopy and main canopy.

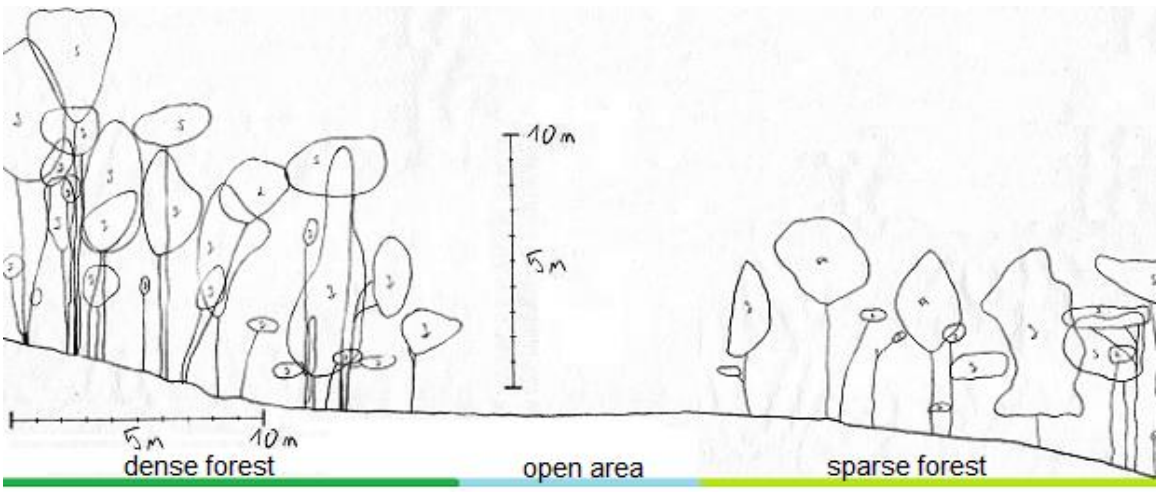

*Figure 9 Profile diagram showing a section of the second transect line (J=*Cassia javanica*, S="Sengon", A=*Acacia mangium*, L=*Leucaena leucocephala*, T=*Sesbania grandiflora*)*

3.2. Abiotic factors

Year of planting

The averages of the number of trees per plot, number of species per plot, average DBH per plot and average slope per plot were slightly higher in the sample plots planted in 2015.

T-tests comparing the different characteristics showed that there was no significant difference between the years of planting.

The transect lines showed a significant difference in the height of trees and tree DBH between the years of planting. The dense forest had been planted in 2015 and the sparse forest in 2016. Both, height and DBH of the trees was higher in the dense forest.

Soil characteristics

No significant connection was found between the soil characteristics and the total number of trees or tree species distribution in the multiple stepwise regression analysis.

The soils of the sample area had a high variation in their characteristics and a list of all results from the laboratory analysis is presented in Annex 9.

Table 7 shows the average values of the soil characteristics for the topsoil per forest type and the subsoil.

Table 7 Average values of soil characteristics for topsoil (0-30 cm) in forest types and subsoil (30-60 cm) of all plots

	forest type	pH in H_2O	EC [dS/m]	C organic	N total	C/N ratio	P total [mg/100g]	K total [mg/100g]
topsoil	dense	6,1	0,17	1,3%^{o**}	0,12%	11,0^{o*}	20,5	30,8
	sparse	6,4	0,16	1,7%	0,11%	14,9	21,6	34,2
	open	6,8	0,25	2,0%^{d**}	0,12%	17,0^{d*}	27,6	35,0
	total	6,4	0,19	1,6%	0,12%	14,1	22,7	33,2$^{15/16***}$
subsoil	total	7,0	0,42^{t***}	1,7%	0,13%	14,5^{td*}	27,9^{t**}	51,9^{t***}

	forest type	exch. Na^+ [me/100g]	exch. K^+ [me/100g]	exch. Ca^{++} [me/100g]	exch. Mg^{++} [me/100g]	CEC [me/100g]	Alkali saturation
topsoil	dense	4,39	0,57	1,15	1,84	15,9	52,2%
	sparse	5,31	0,80	1,41	2,07	18,0	56,3%
	open	3,31	0,63	1,10	2,62	18,8	40,5%
	total	4,49	0,68$^{15/16**}$	1,24	2,13	17,5	50,9%
subsoil	total	5,55^{t*}	1,15^{t**}	1,41^{t15*}	2,51^{t*,t15*}	18,8^{td*,t15*}	57,5%

electrical conductivity (EC), amount of organic carbon (C organic), total nitrogen (N total), carbon to nitrogen ratio (C/N ratio), total potassium (K total), total phosphorus (P total), exchangeable sodium (exch. Na+), exchangeable potassium (exch. K+), exchangeable calcium (exch. Ca++), exchangeable magnesium (exch. Mg++), cation exchange capacity (CEC)

*=significant ($p<0,05$), **=highly significant ($p<0,01$), ***=very highly significant ($p<0,001$) with d=dense, o=open, t=topsoil, td=topsoil in dense forest, t15= topsoil in area planted 2015, 15/16=between planting years

On average the soils of the rehabilitation area had:

- a slightly acidic to neutral pH
- very low EC and exchangeable calcium
- low organic carbon and total nitrogen
- moderate C/N ratio, total potassium, total phosphorous, CEC and alkali saturation
- high exchangeable magnesium and exchangeable potassium
- very high exchangeable sodium.

Detailed descriptions of the soil characteristics on the rehabilitation area are attached in Annex 10.

Significant differences in the soil characteristics were measured between:

- dense forest and open area in organic carbon and C/N ratio of the topsoil
- planting years in total potassium and exchangeable potassium of the topsoil
- topsoil and subsoil in C/N ratio and CEC of the dense forest
- topsoil and subsoil in exchangeable calcium, exchangeable magnesium and CEC of the area planted in 2015
- topsoil and subsoil in EC, total phosphorous, total potassium, exchangeable sodium, exchangeable potassium and exchangeable magnesium of all plots.

For the abundance of individual tree species, a relation to the soil characteristics of the topsoil was measured.

- *A. mangium* had significantly more trees in plots with lower pH levels, lower P total, higher exchangeable Na^+ and higher alkali saturation.
- *S. grandiflora* had significantly more trees in plots with a higher C organic level, higher C/N ratio, higher P total and higher CEC.
- *C. siamea* had significantly more trees in plots that had a lower CEC.

Topography and soil-water balance

The topography of the research area varied strongly.
Table 8 shows the average slopes in the plots of the forest types. The average slope did not exceed 23% and the maximum slope measured on the area was 45% in one plot of the dense forest. In Annex 11 a list of all slopes that were measured in the sample plots is attached.
T-tests gave significant differences in the average slope per plot for the forest types. The dense forest had the steepest slopes and the open area had the flattest surface.

Table 8 Average slope in the plots of the different forest types

forest type	average slope in one plot		
	max	min	average
dense forest	23%	4%	15,7% s**, o***
sparse forest	10%	1%	6,1% d**, o**
open area	3%	0%	1% s**, d***

*=significant (p<0,05), **=highly significant (p<0,01), ***=very highly significant (p<0,001) with d=dense, s=sparse, o=open

Regression analysis gave significant results when comparing topography to tree species distribution and tree abundance. Figure 10 compares trees per plot to the slope of the plots.

- 65,2% of the number of trees/plot could be described with the angle of the slope. More trees were growing in plots with a steeper slope.
- The number of the trees/plot showed a stronger linear connection to the slope and had a higher coefficient of determination than the species/plot.

Regression analysis showed that the relation between the slope and soil-water balance was strong (r^2=0,75) and significant. On the research area the steep slopes had dryer soils while the flat areas were very wet.

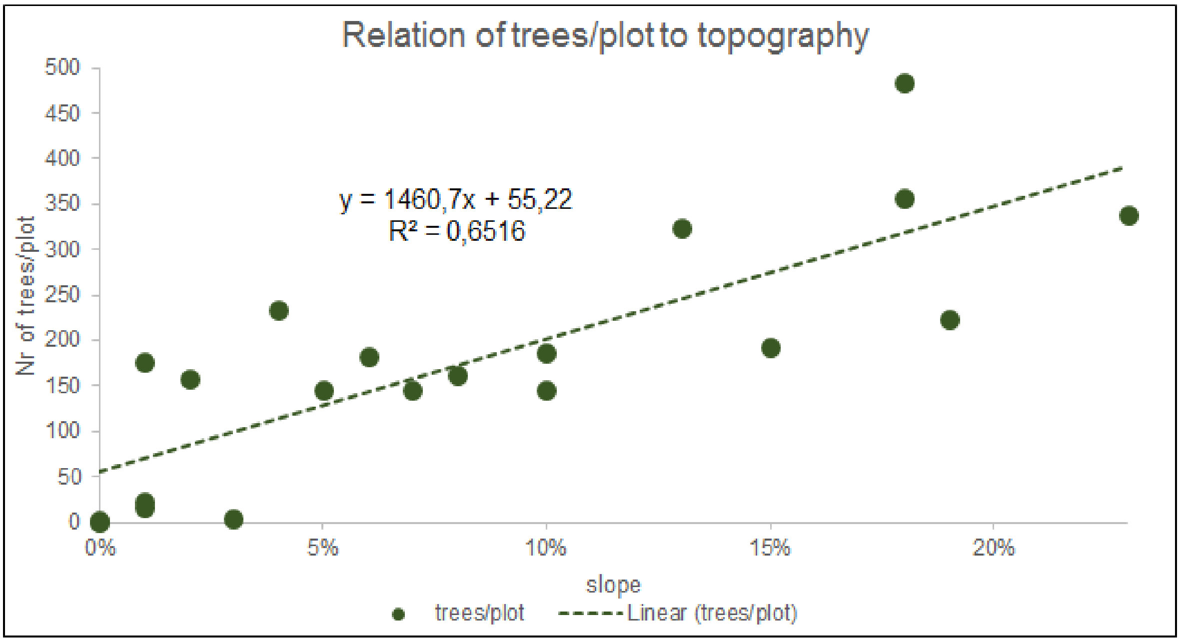

Figure 10 Relation of number of trees per plot to topography

T-tests showed a significant difference in soil-water balance of the forest types.

- The open area had an average of “wet to very wet” soil-water balance. Some of the sample plots had waterlogging with up to 15 cm deep water.
- The sparse forest had an average of “moist” soil-water balance.
- The dense forest had an average of “dry” soil-water balance.

Annex 11 shows the soil-water balance of all sample plots.

The soil-water balance had a strong and significant connection to the number of trees in the sample plots. 83,6% of the tree abundance could be described by the soil-water balance. The plots with “very dry” soil-water balance had the highest number of trees. A similar trend was found in the species per plot.

4. Discussion

4.1. Vegetation

Tree species richness

The distribution of the tree species on the research area gave a current snapshot of the rehabilitation success. With 23 different tree species on 1 ha the species diversity was similar to other mine rehabilitation areas in Indonesia.

- On the Satui mine project in South Kalimantan, Indonesia, 14 tree species grew on OB substrate as natural regeneration after seven to sixty-four months (Novianti, Choesin, Iskandar, & Suprayogo, 2017).
- On the mining site of PT Adaro Indonesia, a research in 2013 resulted in 11 tree species being present on a fifteen-month-old reclamation area and 20 tree species on a twenty-two-month-old reclamation area (Soendjoto, Mahrudin, Riefani, & Triwibowo, 2014).
- In another research on the mining area of PT Adaro Indonesia Sjoerdsma (2016) had found 12 tree species four to six years after rehabilitation.

As the potential diversity is highly dependent on the location due to climatic conditions and soils it would be interesting to compare the current forest to the forest that had existed before the mining process. Unfortunately, no information was available to the reference vegetation before the mining started. Whitmore (1995) states that 100 to 150 different tree species (≥10 cm DBH) in 1 ha are typical for southeast Asian lowland rainforests. Compared to this the current richness of tree species is far from a diverse natural forest. But the fact that tree species were found in the monitoring that had not been planted shows that natural succession takes place, and therefore the species diversity will increase over time.

Tree species diversity

For ecological studies, typical values of the Shannon Index lie between 1,5 and 3,5 (Kerkhoff, 2010). Compared to this the α-diversity of the rehabilitated area was low. This was not surprising due to the limited number of trees that had been planted (Annex 1) and the dominance of *C. siamea* and *L. leucocephala* on the area.

The slightly higher α-diversities in the sparse forest showed that not only the total number of species but also the evenness of species are important for diversity.

The findings of this research are in line with the development of species diversity found by Novianti et al. (2018).

The β-diversity is expected to grow over time. Natural germination of native trees and enrichment planting with shade-tolerant seedlings will increase the diversity of the area. The survival of species in the different areas will create a variation in the species composition of the forest types (Ghazoul & Sheil, 2010).

Tree species distribution

The significant differences in the species per plot showed that there was a difference in the distribution of tree species. This indicated that the species found on the area were better adapted to the conditions of the dense forest and sparse forest than to the conditions of the open area.

Key characteristics that influence the distribution and diversity in tree species are the individual shade tolerance of juveniles, height of adult plants, leaf-longevity and drought tolerance (Ghazoul & Sheil, 2010).

Tree species abundance

The relation between the tree species distribution, abundance of the species and the forest types was clearly seen in the results of the analysis.

The abundance of trees on the rehabilitation area was the result of the success of planting, maintenance and natural regeneration (Nugroho et al., 2019). The results of earlier studies for PT Adaro Indonesia gave comparable results to this research:

- Sjoerdsma (2016) found that *E. cyclocarpum, C. siamea, Acacia auriculiformis* and *L. leucocephala* were the most abundant tree species on rehabilitation areas from 2010, 2011 and 2012.
- Soendjoto et al. (2014) had measured that *S. grandiflora, C. siamea, L. leucocephala* and *P. flacataria* were the most abundant tree species on rehabilitation areas from 2012.

The differences in DBH distribution of the tree species gave insight into the state of the individual populations.

- The high number of small trees of *L. leucocephala* showed that these species rejuvenate readily. The same was found for *C. calothyrsus* and *V. pubescens.*
  A reverse J-shape in the diameter distribution is typical for trees that have a high reproduction (van der Meer, 2017).
- *C. siamea* and *A. mangium* only showed a low rejuvenation and *S. grandiflora* did not rejuvenate well.
  As the state of the existing *S. grandiflora* trees was not good this species is likely to disappear from the area in the future.

Seeds from *C. siamea*, *P. falcataria*, S*. grandiflora* and *C. calothyrsus* had been included in the hydroseeding (Nugroho et al., 2019). Through dormancy of some of the seeds, the natural regeneration of the species might look higher than it actually was.

Forest succession

The distribution of the species on the area will change because most of the current trees are fast-growing pioneer species and slow-growing climax species will take over as succession continues (Guariguata & Ostertag, 2001).

The germination of local trees is very positive and the *V. pubescens* trees are a good sign of natural succession. *V. pubescens* is a slow-growing tree that can reach a diameter of about 70 cm (Orwa, Mutua, Kindt, Jamnadass, & Anthony, 2009). The small seeds of *V. pubescens* are dispersed by birds, but the seeds need light to germinate (National Parks Board, 2013). As *V. pubescens* had only been planted in 2015 the results from the monitoring proved that this local species regenerated readily. And it was probable that the abundant bird species carry the seeds from mature *V. pubescens* trees in the nearby forest to the rehabilitated area.

Also, the presence of the unknown tree species shows that natural succession is adding new species to the rehabilitated forest.

A. mangium had not been planted, and therefore it was surprising that from a total of 437 trees/ha only 0,04% were seedlings below 1,3 m. *A. mangium* rejuvenates very well and can be highly invasive (Koutika & Richardson, 2019). Although *A. mangium* is able to fix atmospheric nitrogen to the soil (Haruni Krisnawati, Maarit Kallio, & Markku Kanninen, 2015) its leaves have allelopathic effects that can reduce germination, growth and reproduction of the surrounding vegetation (Ismail & Metali, 2014). The origin of the *A. mangium* trees on the rehabilitation area was unknown (Wahyudi, 2019). The seeds are known to be bird-dispersed (Gibson et al., 2011) and 24 months after planting the trees have viable seeds (National Research Council, 1983). As the number of seedlings in 2019 was very low the first seeds might have come to the area as seedbank in the topsoil. During the monitoring, seeds were noticed on some of the trees. Therefore, the number of *A. mangium* trees/ha is likely to increase if no measures are taken to prevent it.

Grass cover

On the one hand, the results of the grass cover analysis led to the assumption that grass grew better/denser in areas with fewer trees. And on the other hand, it indicated that the establishment of seedlings was reduced if the ground was covered with a dense grass layer.

A negative effect of grass competition on the growth of tree seedlings was measured by Bhadouria et al. (2018).

In addition to the reduced growth, a very dense grass cover can prevent seeds distributed by birds from reaching the ground and germinating.

Although the grass can slow down the natural succession of the area, it is beneficial to the reduction of soil erosion (Durán Zuazo & Rodríguez Pleguezuelo, 2008; Mukhopadhyay, Maiti, & Masto, 2014).

Forest structure

The profile diagrams showed the variation of canopy height and the relation of tree species to each other.

For both forest types, almost half of the trees were part of the main canopy. This represents the homogeneous character of an even-aged plantation as the trees have the same age (Stilma, 2018a).

The development of understory and subcanopy layer through natural regeneration and enrichment planting is good for the forest. Each layer in the forest supports unique interactions between plants and animals (Butler, 2012; Rainforest Journal, n.d.).

The profile diagrams also highlight the importance of species in the different forest layers.

Not all species were present throughout the total height of the forest. For example, *C. calothyrsus* was only found as small trees while “Sengon” trees were developing into the emergent layer.

Comparing the profile diagrams of the research area to old-growth rainforests is not very meaningful because of the young age. The profile diagrams of Pitopang (2012) showed that primary rainforests in Central Sulawesi, Indonesia were more than thirty meters higher and very diverse in their structure and species composition (twenty-nine species in 50 m).

Even though the research showed that the trees with higher DBH grew taller no predictions for growth of the trees could be made. The transect data could not be used for this because the distance of the crowns above the transect line did not always match the total height of the trees.

4.2. Abiotic factors

Year of planting

On the one hand, the results from the sample plots did not show a significant difference in the vegetation characteristics between the area planted in 2015 and 2016. On the other hand, the results from the transect lines did.

These inconsistent results might be caused by the variation throughout the forest types in sample plots of different years. Comparing the individual forest types of different years was not possible because of the low sample size.

Sjoerdsma (2016) found that the planting year had no significant effect on the average tree height after 4 to 6 years. The results from the transect lines were contradictory to this. The contrary results might be caused by the fast early growth of the pioneer trees (Ruge, 2016) and the natural regeneration of the forest.

Soil characteristics

The results from the analysis of the soil characteristics did not support the first and the second hypothesis.

The first hypothesis had to be rejected because the multiple stepwise regression analysis had not found a significant connection of soil characteristics to tree species distribution.

➢ The soil conditions of the research area did not affect the tree species distribution.

The abundance of tree species per plot showed different connections to the soil properties. *A. scholaris* had the highest number of significant relations. The only strong relation was found between *A. mangium* and the exchangeable sodium.
The connection of most of the species to the soil characteristics was very weak or weak, not significant and showed different trends.

Because of this, the second hypothesis had to be rejected.

➢ The soil conditions of the research area did not affect the overall abundance of the tree species.

The variation of the values from the soil characteristics were more between the sampling depths than between the forest types or year of planting. These differences can be related to the OB and topsoil material (Nugroho et al., 2019), to soil development (Alday et al., 2012) or, most likely, to both.

When comparing the results of the soil analysis to the researches that had been conducted for PT Adaro Indonesia on a 1 to 2-year-old rehabilitation area by Soendjoto et al. (2014) and on a 4 to 6-year-old rehabilitation area by Sjoerdsma (2016) similarities and differences are seen.

- The soils of this research were less acidic.
- The average C organic was similar to 2016 but higher than in 2014.
- The average N total values were similar to the other rehabilitation soils.
- The average EC higher than that of the research in 2016.
- The average CEC was higher than the average from the research in 2014.

Topography and soil-water balance

The research area had a topography similar to that explained in the introduction (Figure 2). Slopes and terraces were visible on the area but the slope gradient differed from the planning. On average all slopes were significantly less steep than the planned 36,4%; only one sample plot had a maximum slope that was steeper.

Signs of erosion were visible and on parts of the steeper slopes OB material was visible as the topsoil had been washed away.

The research of Daws et al. (2002) in Panama revealed that slope sites had a better soil-water balance than plateau sites because they were supplied by water from upslope. Especially, in drought periods the forests on slopes can benefit from the additional water from higher grounds while flat areas dry out (Daws et al., 2002).

During the monitoring of the sample plots, large parts of the flat area were flooded. The rainfall during the time of sampling was not heavy, and therefore the infiltration of the soil was presumed to be low.

The low infiltration might be caused by the compaction of the soil from heavy machines when spreading the OB and topsoil and by the high silt and clay content of the soil (Nugroho et al., 2019; Soendjoto et al., 2014).

The significant differences in the slope of the forest types revealed that the dense forest was growing on the steeper parts of the area while the open areas were mostly flat. Since the dense forest had the highest number of species and the highest abundance of trees per plot a connection between topography and trees was predictable.

In this research, the flat and wet areas had significantly less trees and tree species than the dryer slopes.

With this results, the third and fourth hypotheses were proven to be true.

Variation in topography affected both:

- the tree species distribution and
- the abundance of the tree species on the rehabilitated area.

The link between tree species distribution/abundance and the topography was the soil-water balance.

This indicated that the precipitation was not the limiting factor but most of the tree species had problems with the flooding of the flat areas.

- Tree species from the dry lowland rainforest of Borneo are not adapted to flooding while tree species found in the wet swamp lowland rainforest (mangrove, freshwater swamp and peat swamp forest) are adapted (MacKinnon et al., 1996).
- On the rehabilitated area *Melaleuca leucadendra* was the only species that was found in the flooded part of a sample plot. *M. leucadendra* is known to be flood-tolerant and grows well in swamp areas (Franklin, Brocklehurst, Lynch, & Bowman, 2007; Heyne, 1981).

The connection between soil-water balance and trees show how important the selection of suitable tree species is for the success of rehabilitation measures.

Generalizing the effect of topography (and soil-water balance) on tree species distribution and abundance found in this research is not possible. The results of this research might not hold true for natural forests because they exist of species that are well adapted to their environment (MacKinnon et al., 1996).

4.3. Limitations

In field studies, the number of variables that can influence the outcome of a research should be held as small as possible (Kraaijvanger, 2018). Because of this, it was not ideal that the year of planting differed on the research area. Nevertheless, the results of the research are clear.

The influence of the planting year on the species distribution and abundance is unknown and expected to be low. But the time difference certainly influenced DBH growth and height of the trees (Ruge, 2016).

Data on tree species that were planted was available only for larger areas. The research area included only 27,2% (2015) and 25,8% (2016) of those bigger areas.

Although lists of planted tree species with the number of seedlings were available it was not possible to compare these lists to the results from the monitoring. Information on where the species had exactly been planted and how they had been mixed was not available because it had not been documented (Nugroho et al., 2019).

For example, 1723 *Moringa oleifera* (Moringaceae) trees had been planted in 2015, but none of them were found in the sample plots. Instead of drawing the conclusion that this species was not suitable for the mine rehabilitation, because none of the seedlings were found, it is possible that they were planted on another part of the area rehabilitated in 2015.

With the information that only 10 to 15 cm of topsoil had been spread over the OB (Nugroho et al., 2019) the depth of the soil samples could have been changed. Sampling depths of 0 to 5 cm and 5 to 20 cm (Novianti et al., 2018) or 0 to 15 cm and 15 to 30 cm (Sjoerdsma, 2016) would have been more representative for the topsoil.

However, the deep subsoil samples show the differences in soil characteristics for the deeper dept.

Although this research included measurements of diversity, vegetation structure and ecological processes (Ruiz-Jaen & Aide, 2005) to assess the rehabilitation success the informative value is limited. The overall success of the rehabilitation could not be analyzed because the focus of this research was on trees.

4.4. Sustainability

The findings of this research can help in making post-mine rehabilitation more sustainable. For this to become possible, PT Adaro Indonesia is responsible of using the new insight into rehabilitation success for an improved restoration method in the future.

The recommendations in Chapter 6 and the draft action planning in Annex 12 are intended to help PT Adaro Indonesia with ideas for more sustainable post-mine rehabilitation.

Especially, the importance of selecting suitable species became clear. If the success of rehabilitation is improved with the selection of adapted species the whole rehabilitation becomes more sustainable. A faster forest recovery improves the habitat for many birds and animals and can deliver more ecosystem services to the local communities (McDonald, Gann, Jonson, & Dixon, 2016).

5. Conclusion

The conclusion of this research is that the topography on the rehabilitated area influenced the tree species distribution and abundance, and the soil characteristics did not.

The three forest types (dense forest, sparse forest and open area) showed a significant connection to the topography.

- The dense forest areas were richer in tree species, had more trees and were growing on the steeper parts of the area.
- The open areas were habitat to few tree species, a low amount of trees and were on flat parts of the rehabilitated area.
- The sparse forest had values between those of the dense forest and the open area.

The topography also affected the soil-water balance. Therefore, the soil-water balance had similar effects on the trees of the rehabilitation area.

*Cassia siamea, Leucaena leucocephala, Acacia mangium, "*Sengon" and *Sesbania grandiflora* were the most abundant tree species and accounted for 84% of all trees on the rehabilitation area.

Most of the species growing on the research area belonged to the species that were planted as seedlings or as seeds with hydroseeding. The most important exceptions were the invasive *A. mangium* and the native *Vitex pubescens*. Further native species from natural regeneration were found but they only made up 2,9% of the total trees.

The analysis of the DBH distribution of the individual species revealed major differences.

- On the one hand, species like *S. grandiflora* had a very low number of small trees.
- On the other hand, species like *L. leucocephala* had very many small trees.

These differences showed that species with a high number of small trees had a good reproduction. Without rejuvenation, the species are likely to disappear from the area.

6. Recommendations

The management practices on the areas should be well documented and homogeneous for best possible results of future monitoring. a clear map showing the species that are planted and spacing of the trees are important for meaningful research.

Permanent sample plots that are demarcated in the field are recommended for an analysis of the vegetation and soil development. Yearly monitoring of trees and soils will lead to a thorough understanding of rehabilitation success and soil development. Further aspects of flora and fauna should be included in the monitoring for more information on the ecological value of the rehabilitated areas.

Planting suitable tree species on the flat areas is highly recommended. New tree species are needed because most of the trees on the rehabilitation area did not withstand the conditions of the flat and wet areas. Research on the variation of soil-water balance throughout the year can be helpful for the selection of adjusted tree species. Possible tree species are mentioned in Annex 12.

Effective management strategies against the invasive *Acacia mangium* and the dense grass cover are recommended to improve and enhance the natural forest succession.

Further improvements for the rehabilitation from the results and conclusion of this research are described in the draft action planning in Annex 12.

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9. Annexes

Annex 1 – Mine rehabilitation of PT Adaro Indonesia

- For erosion control, the water was drained from the area with drop structures to reduce the velocity of the water.
- After the overburden was leveled topsoil was spread over it to support the establishment of vegetation (1 m in 2014 and before, 10 to 15 cm from 2015 to 2018, 20 cm in 2019). Topsoil was removed before mining and stored in topsoil banks that were planted with cover crops to reduce erosion. In 2019, the oldest topsoil bank was from 2015.
- Cover crop was planted with hydroseeding through a pressure canon from a vehicle. The hydroseeding liquid included seeds for legumes and grass, water, organic fertilizer, sawdust for water storage and glue to prevent the seeds from being washed away by rain. Before 2019, also seeds from fast-growing trees were included in the first seeding.
  The aim was to have at least 85% of the area covered by the cover crop after 6 months. If this was not the case, re-hydroseeding was done on areas that had not developed properly.
- Pioneer trees (mainly fast-growing species) were planted on the rehabilitation area after hydroseeding.
  - Before 2019, trees were planted from the nursery of PT Adaro Indonesia. The species mixture, planted each year, varied due to the seedlings that were available. The plan was to plant trees on the whole area with a spacing of 3 m by 3 m. But the planting team had not always planted as planned and no documentation of where the different species were planted took place.
    Table A1 shows the trees planted on the areas that include the research area.
  - Since 2019, contractors were responsible for planting and maintenance. The spacing was changed to 4 m by 4 m of fast-growing tree species with rows of slow-growing tree species alternating in the middle. Eleven species were selected for future planting. Planting setup and tree species are presented in Annex 2.
- Replanting and enrichment planting were carried out by contractors for the existing rehabilitation areas with slow-growing tree species (climax trees) and other local tree species.

Table A1 List of trees planted on WDPS in 2015 (23,93 ha) and 2016 (21,49 ha)

local name	planted 2015	planted 2016
Alaban	122	0
Angkuda	55	0
Angsana	92	0
Asam jawa	0	113
Belangiran	0	31
Eucalyptus	1460	51
Flambomyan	987	113
Gamal	2943	3726
Gamalina	88	0
Gempol	212	0
Gumbisi	74	0
Jabon	37	0
Jambu Biji	346	0
Jengkol	554	11
Johar	3376	1462
Kaliandra	4556	0
Kapuk randu	92	0
Kayu putih	1199	0
Kelor	1723	272
Kesambi	0	134
Ketapang	231	0
Ketapi	7	215
Kopi	21	8
Kupang	199	0
Lamtoro	2078	1110
Mahoni	171	725
Mangga	5	6
Nangka	1	0
Nyamplung	5	181
Pinus	53	0
Pitaruk	1624	113
Pongemea	23	208
Pulai	143	7260
Rambutan	99	0
Rotan	21	0
Salam	203	0
Sengon	5150	1374
Sengon buto	198	549
Sepatudea	0	12
Sungkai	156	5
Trembesi	1507	613
Turi	950	0
Waru	50	4

Annex 2 – Planting setup and tree species planted by contractors since 2019

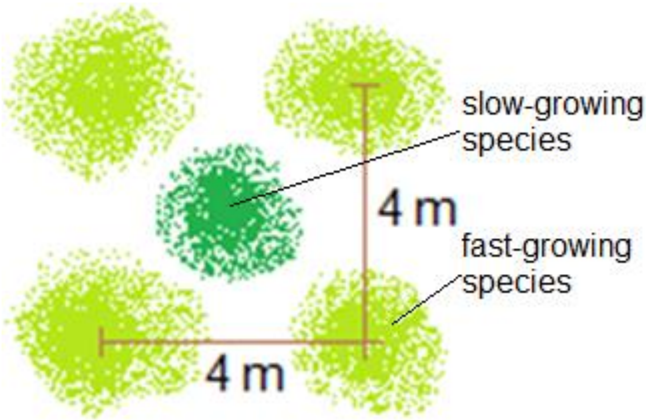
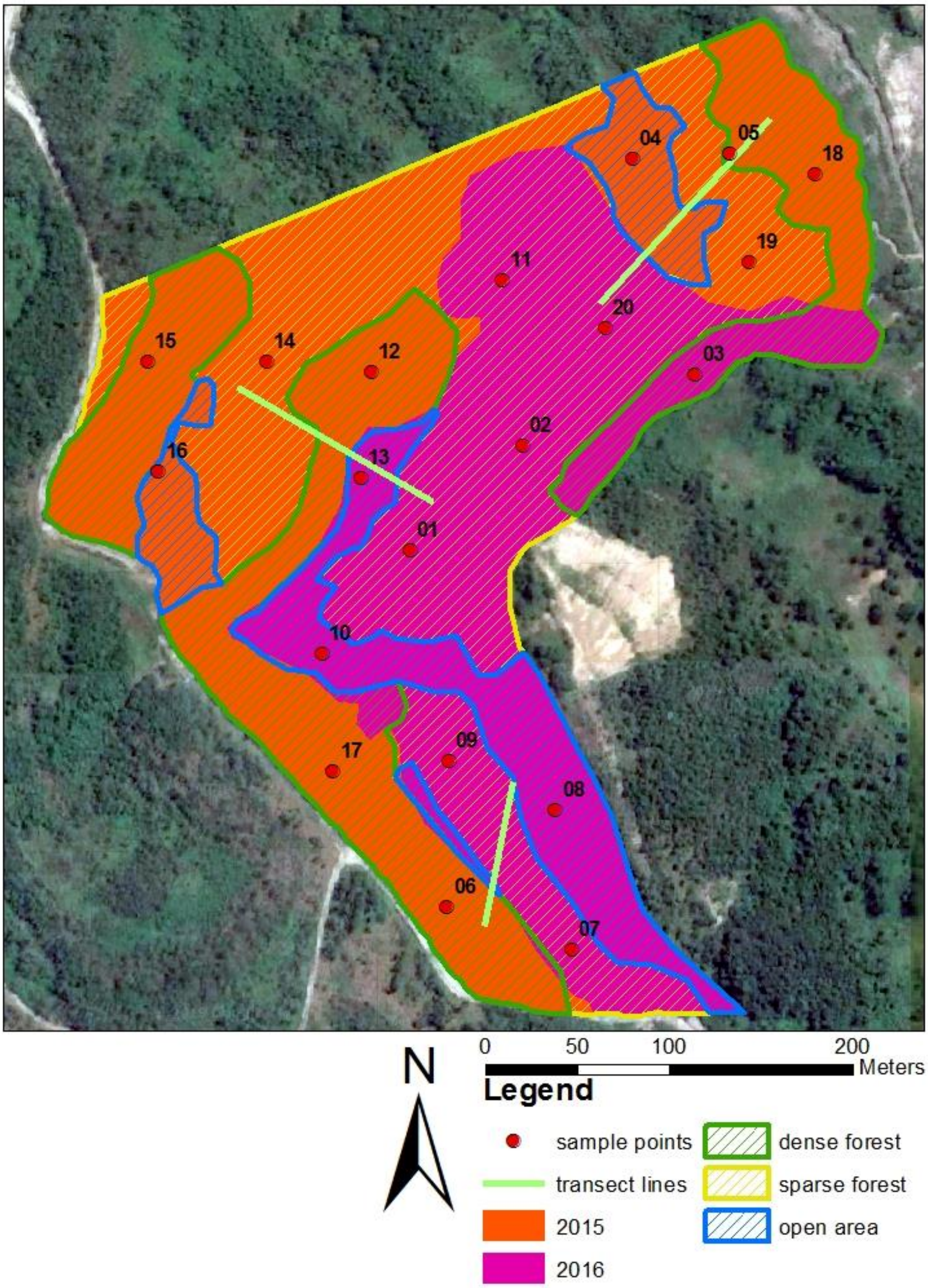


Figure A2 Planting setup of trees on rehabilitation area

fast-growing tree species		
family name	scientific name	local name
Combretaceae	*Terminalia catappa*	Ketapang
Fabaceae	*Cassia siamea*	Johar
Fabaceae	*Enterolobium cyclocarpum*	Sengon buto
Fabaceae	*Paraserianthes falcataria*	Sengon
Fabaceae	*Pterocarpus indicus*	Angsana
Fabaceae	*Samanea saman*	Trembesi
slow-growing tree species		
family name	scientific name	local name
Apocynaceae	*Alstonia scholaris*	Pulai
Meliaceae	*Swietenia macrophylla*	Mahoni
Lauraceae	*Eusideroxylon zwageri*	Ulin
Lamiaceae	*Peronema canescens*	Sungkai
Lamiaceae	*Vitex pubescense*	Alaban

Annex 3 – Map of the research area with planting years, forest types, sample plots and transect lines



Map of planting year and forest types on the survey area from PT Adaro Indonesia in WDPS, South Kalimantan, Indonesia
Source: Google Maps
Date: 23.05.2019

Annex 4 – List of sample point and transect coordinates with stratification of the forest types and year of planting

plot Nr	X-coordinates	Y-coordinates	forest type	planting year
01	0331610	9745589	sparse forest	2016
02	0331671	9745646	sparse forest	2016
03	0331765	9745685	dense forest	2016
04	0331731	9745802	open area	2015
05	0331784	9745805	dense forest	2015
06	0331630	9745395	dense forest	2015
07	0331698	9745372	sparse forest	2016
08	0331689	9745448	open area	2016
09	0331631	9745475	sparse forest	2016
10	0331562	9745533	open area	2016
11	0331660	9745736	sparse forest	2016
12	0331589	9745686	dense forest	2015
13	0331583	9745629	open area	2016
14	0331532	9745692	sparse forest	2015
15	0331467	9745692	dense forest	2015
16	0331473	9745632	open area	2015
17	0331568	9745469	dense forest	2015
18	0331830	9745794	dense forest	2015
19	0331794	9745746	sparse forest	2015
20	0331716	9745710	sparse forest	2016
transect Nr	start X-coordinates	start Y-coordinates	direction	length
T01	0331713	9745726	45°	140 m
T02	0331516	9745680	120°	140 m
T03	0331650	9745388	15°	80 m

Annex 5.1 – Additional information on methodology - Data collection

Plot setup

- Plot Nr. 16 was set up as a circular plot (0,05 ha) but with the same plot setup because of the limited size of swampy area.
- The plots were set up from the center point and the corners were marked at 15,81 m with a measuring tape and compass to the North, East, South and West. If the plot was located on a slope, the measuring tape was held in a horizontal line so that the area of all plots was the same.
- To ensure that only trees within the sample plot were measured a rope was stretched along the borders. Further ropes were laid through the plots to reduce the chance of forgetting trees or measuring them twice.

Tree sampling

- For all trees within the plots, the diameter breast height (DBH) was measured at 1,3 m above the ground. Smaller trees were just counted with information about their high (50 cm or 1 m). As the caliper used for measuring the trees was not able to measure big trees accurately the circumference of the trees with a DBH bigger than 10 cm was taken with a measuring tape. If a tree had more than one stem only the biggest stem was measured to prevent multiple data from the same tree.
- Additional to the tree data, pictures of the sample areas were taken to compare the vegetation of the plots.

Topography measurement

- Small sketches were drawn to display the variation of the slope on the sample plots.

Soil sampling

- The locations for the soil sample points were at 7 m to the North, 7 m to 120° and 7 m to 240° from the center point.
- Some samples for subsoil were only 45-50 cm deep because of rocks in the soil. If this was the case a remark was made but the analysis of the samples was the same as for the others.

Canopy cover measurement

- At a height of 1,5 m above the ground three pictures were taken at every sample point. The pictures from the canopy were taken with different compass directions and the average was noted. If the result from the app was not correct due to the measurement of sky/clouds as canopy an objective correction was done. This was especially important if the canopy cover was low, as shown in Figure A5.

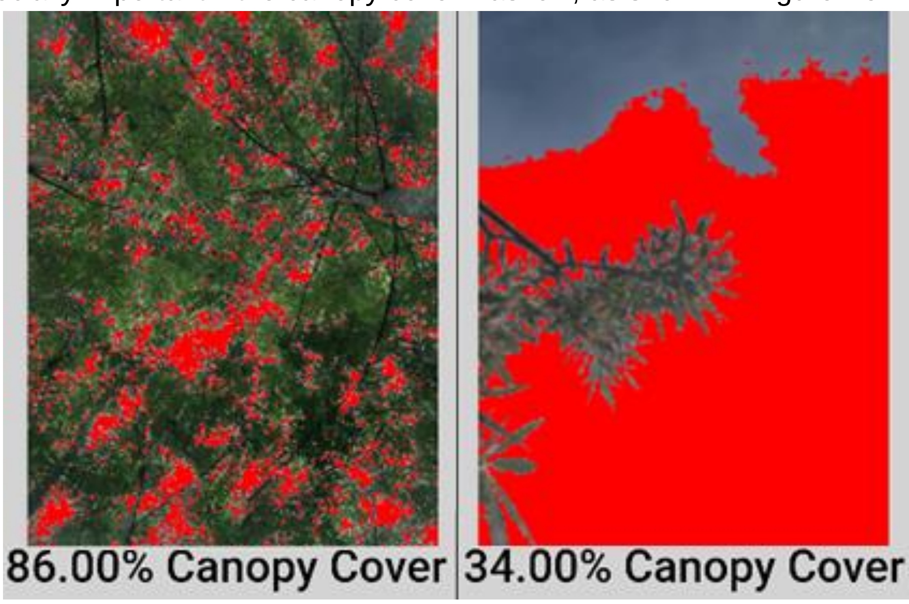


Figure A5 Canopy cover with CanopyCapture app

Annex 5.1 – Continued

Transect line

- The first and second transect line were 140 m long and the third transect line was 80 m long.
- The height was measured with a 6 m pole that had markings every 50 cm and with a clinometer for the taller trees.
- Only trees with a diameter of more than 5 cm were considered in the first transect line due to limited time. In the second and third transect line all trees were measured.

Annex 5.2 – Additional information on methodology - Data analysis

α-diversity

- The first index was the species richness. The species richness describes the number of species present in the habitat without looking at the individual abundance (Countrysideinfo, 2009).
- The second index was the Shannon Index (H). With the formula $H = -\sum_{i=1}^{S} p_i * \ln(p_i)$ the Shannon Index combines the number of species and the number of individuals per species (Spellerberg & Fedor, 2003). Within the total species of a community (S), p_i is the relative frequency of the species i. $H_{max} = \ln S$ gives the maximum value that H can reach in a community with a given number of species. This is the case if all species have the same abundance. The equitability ($E = H/H_{max}$) is the relative deviation of the Shannon Index from its maximum (Magurran, 1988). For ecological studies typical values of H lie between 1,5 and 3,5. The Shannon Index increases with an increase in species richness and with an increase in the evenness of individuals per species. Therefore, the Shannon Index gives a good summary but comparing communities that differ greatly in richness is difficult (Kerkhoff, 2010).
- The third measure was the Simpson's Diversity Index (1-D). The Simpson's Index (D) calculates the evenness or dominance of a community with the formula $D = \sum_{i=1}^{S} p_i^2$. The value of D lies between 0 and 1 and as D increases the diversity (in sense of evenness) decreases (D=1 for a monoculture). The Simpson's Diversity Index also ranges between 0 and 1 but 1-D shows a higher diversity as it approaches 1. The probability that two random individuals from a sample are from different species is represented by the Simpson's Diversity Index (Countrysideinfo, 2009; Kerkhoff, 2010; Magurran, 1988).

β-diversity

- The formula for the β-diversity is: $\beta = 2c/(S1 + S2)$
- In this formula, $S1$ and $S2$ are the total numbers of species in two areas and c is the number of species the two areas have in common.
- If the species in the two areas are exactly the same β is 1 and if there are no species in common β is 0 (Greig-Smith, 1983).

Transect line

- The structural analysis gave additional information on the development of the tree species and the relations between the species. Furthermore, the diversity in tree species was monitored on a structural level.
- For the analysis of the transect lines only the second and third transect were used because the first transect only included DBH ≥5 cm.
- For the dense forest, the boundary was 4 m for understory to subcanopy layer and 8 m for subcanopy layer to main canopy. The sparse forest had the boundary of 3 m for understory to subcanopy layer and 6 m for subcanopy layer to main canopy.

Annex 6– Distribution of tree species in forest types and relative importance (RI) of the different species on the total area

scientific name	local name	dense forest			sparse Forest			open area			sum of relative importance
		Nr of plots	%	RI	Nr of plots	%	RI	Nr of plots	%	RI	
Cassia siamea	Johar	7	100%	32,9%	8	100%	49,5%	3	60%	10,6%	92,96%
Leucaena leucocephala	Lamtoro	7	100%	32,9%	8	100%	49,5%	1	20%	3,5%	85,93%
	"Sengon"	7	100%	32,9%	8	100%	49,5%	1	20%	3,5%	85,93%
Sesbania grandiflora	Turi	6	86%	28,2%	7	88%	43,3%	2	40%	7,0%	78,56%
Vitex pubescens	Alaban	7	100%	32,9%	3	38%	18,6%	3	60%	10,6%	62,01%
Acacia mangium	Akasia	5	71%	23,5%	6	75%	37,1%	0	0%	0,0%	60,63%
Calliandra calothyrsus	Kalliandra	6	86%	28,2%	4	50%	24,8%	0	0%	0,0%	52,95%
Samanea saman	Trembesi	6	86%	28,2%	2	25%	12,4%	1	20%	3,5%	44,09%
	AB	6	86%	28,2%	2	25%	12,4%	0	0%	0,0%	40,57%
	AC	5	71%	23,5%	1	13%	6,2%	0	0%	0,0%	29,68%
Gliricidia sepium	Gamal	1	14%	4,7%	4	50%	24,8%	0	0%	0,0%	29,46%
Alstonia scholaris	Pulai	1	14%	4,7%	4	50%	24,8%	0	0%	0,0%	29,46%
	AF	3	43%	14,1%	0	0%	0,0%	0	0%	0,0%	14,09%
Hibiscus tiliaceus	Waru	3	43%	14,1%	0	0%	0,0%	0	0%	0,0%	14,09%
Acacia auriculiformis	Akasia	0	0%	0,0%	2	25%	12,4%	0	0%	0,0%	12,38%
Melaleuca leucadendra	Kayu putih	0	0%	0,0%	1	13%	6,2%	1	20%	3,5%	9,71%
	AE	0	0%	0,0%	1	13%	6,2%	0	0%	0,0%	6,19%
Leea indica	AG	0	0%	0,0%	1	13%	6,2%	0	0%	0,0%	6,19%
Pongamia pinnata	Pongamia	0	0%	0,0%	1	13%	6,2%	0	0%	0,0%	6,19%
Melia azedarach	AA	1	14%	4,7%	0	0%	0,0%	0	0%	0,0%	4,70%
Swietenia macrophylla	Mahoni	1	14%	4,7%	0	0%	0,0%	0	0%	0,0%	4,70%
Homalanthus populneus	AD	1	14%	4,7%	0	0%	0,0%	0	0%	0,0%	4,70%
	AH	1	14%	4,7%	0	0%	0,0%	0	0%	0,0%	4,70%

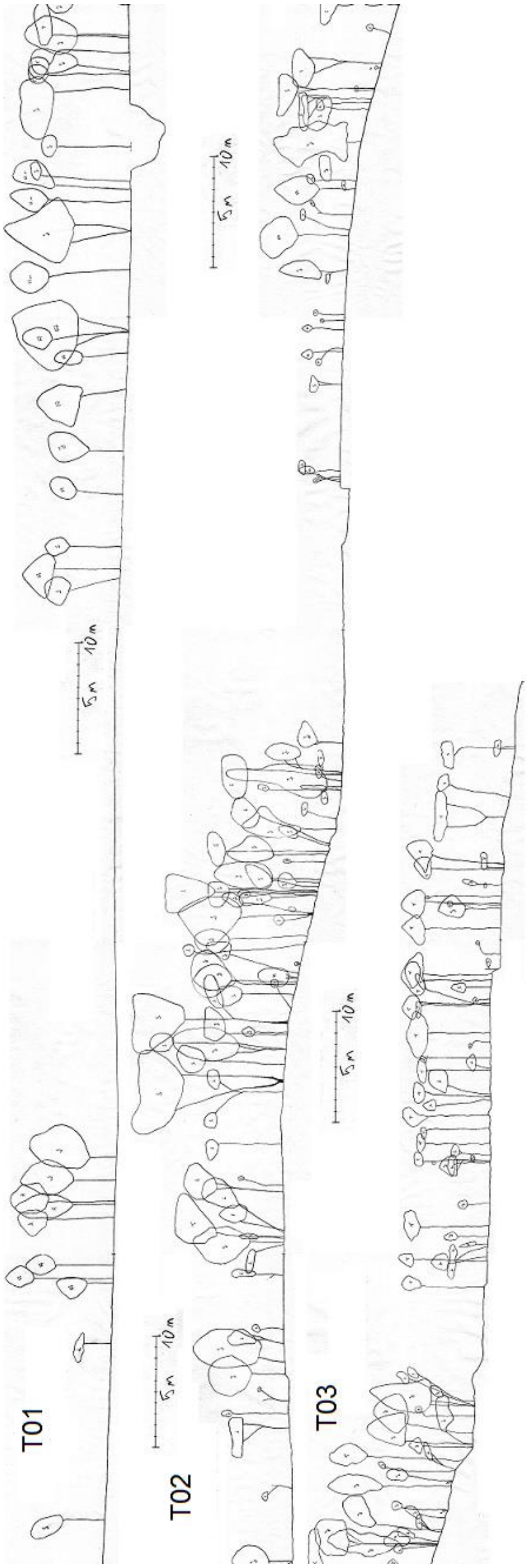
AA-AH: coded unknown species

Annex 7 – Number of trees monitored in the plots, calculated as trees/ha for the forest types, as relative (RI) trees/ha in relation to the area of the forest types and with average per ha on the total area

scientific name	local name	dense forest		sparse forest		open area		
		Nr/ha	RI per ha	Nr/ha	RI per ha	Nr/ha	RI per ha	average per ha
Cassia siamea	Johar	2925,7	962,1	567,5	281,0	28,0	4,9	1248
Leucaena leucocephala	Lamtoro	914,3	300,7	910,0	450,7	12,0	2,1	753
Acacia mangium	Akasia	342,9	112,7	660,0	326,8	0,0	0,0	440
	"Sengon"	522,9	171,9	410,0	203,0	4,0	0,7	376
Sesbania grandiflora	Turi	194,3	63,9	375,0	185,7	84,0	14,8	264
Calliandra calothyrsus	Kalliandra	397,1	130,6	52,5	26,0	0	0	157
Samanea saman	Trembesi	222,9	73,3	5,0	2,5	8,0	1,4	77
Vitex pubescens	Alaban	160,0	52,6	27,5	13,6	40,0	7,0	73
Alstonia scholaris	Pulai	85,7	28,2	102,5	50,8	0	0	79
	AC	194,3	63,9	5,0	2,5	0	0	66
Gliricidia sepium	Gamal	34,3	11,3	112,5	55,7	0	0	67
	AB	62,9	20,7	5,0	2,5	0	0	23
Hibiscus tiliaceus	Waru	48,6	16,0	0,0	0,0	0	0	16
	AF	22,9	7,5	0,0	0,0	0	0	8
Acacia auriculiformis	Akasia	0	0	10,0	5,0	0	0	5
Swietenia macrophylla	Mahoni	8,6	2,8	0	0	0	0	3
Homalanthus populneus	AD	8,6	2,8	0	0	0	0	3
Melaleuca leucadendra	Kayu putih	0	0	2,5	1,2	4,0	0,7	2
Leea indica	AG	0	0	5,0	2,5	0	0	2
Pongamia pinnata	Pongamia	0	0	2,5	1,2	0	0	1
Melia azedarach	AA	2,9	0,9	0	0	0	0	1
	AH	2,9	0,9	0	0	0	0	1
	AE	0	0	2,5	1,2	0	0	1
Sum		6151		3255		180		3667

AA-AH: coded unknown species

Annex 8 – Profile diagrams



Profile diagrams of transect line one (T01), two (T02) and three (T03).

Forest types:
- T01 0-39m sparse, -75m open, -105,5m sparse, -140 dense
- T02 0-42m sparse, -75m dense, -97m open, -140 sparse
- T03 0-17,5m dense, -24,5m open, -75m sparse, -80m open

Tree species: J=*Cassia javanica*, S="Sengon", A=*Acacia mangium*, L=*Leucaena leucocephala*, T=*Sesbania grandiflora*, K=*Calliandra calothyrsus*, P=*Alstonia scholaris*

Annex 9 – Results from the soil analysis

ID	pH H2O	Eh [dS/m]	EC [dS/m]	SMC	C organic	N total	C/N	P total [mg/100g]	K total [mg/100g]
P01 < 30 cm	5,45	95,00	0,28	4,85%	1,87%	0,12%	15,67	24,28	36,34
P01 > 30 cm	6,86	11,50	0,73	3,18%	2,02%	0,12%	17,24	30,17	52,11
P02 < 30 cm	5,23	108,90	0,06	2,26%	0,58%	0,07%	8,43	11,00	22,96
P02 > 30 cm	7,53	-27,85	0,25	2,67%	1,05%	0,09%	11,04	40,03	35,42
P03 < 30 cm	6,59	28,45	0,07	1,91%	0,76%	0,09%	8,04	18,58	47,87
P03 > 30 cm	8,59	-91,60	0,12	1,52%	1,27%	0,12%	10,67	22,37	59,61
P04 < 30 cm	7,38	-20,60	0,16	3,42%	2,16%	0,10%	20,72	32,56	23,05
P04 > 30 cm	7,76	-42,65	0,37	2,77%	1,62%	0,13%	12,10	24,22	55,35
P05 < 30 cm	4,21	169,55	0,13	2,09%	0,74%	0,08%	9,04	9,89	21,69
P05 > 30 cm	5,52	91,05	0,21	3,45%	0,89%	0,09%	9,69	23,93	41,27
P06 < 30 cm	7,89	-51,15	0,18	1,51%	1,37%	0,09%	15,31	28,81	24,43
P06 > 30 cm	8,09	-62,65	0,38	1,61%	1,43%	0,09%	15,96	31,33	30,69
P07 < 30 cm	7,09	-3,10	0,17	3,22%	2,50%	0,13%	18,60	26,83	40,24
P07 > 30 cm	5,41	97,70	0,67	3,57%	2,05%	0,13%	15,78	13,35	54,18
P08 < 30 cm	7,16	-7,45	0,23	5,95%	1,78%	0,15%	12,18	26,00	39,69
P08 > 30 cm	7,24	-13,45	0,23	3,43%	3,69%	0,15%	25,34	27,24	44,28
P09 < 30 cm	7,32	-4,00	0,16	4,51%	3,76%	0,15%	24,35	32,79	41,28
P09 > 30 cm	7,13	-6,90	0,35	3,82%	3,11%	0,13%	23,56	29,87	51,07
P10 < 30 cm	5,26	106,75	0,44	3,37%	2,26%	0,10%	22,63	31,62	46,91
P10 > 30 cm	6,20	50,95	0,86	2,51%	1,88%	0,09%	19,88	33,06	50,44
P11 < 30 cm	8,26	-73,80	0,18	2,17%	1,25%	0,07%	18,22	23,46	40,07
P11 > 30 cm	7,87	-51,10	0,18	2,17%	1,09%	0,10%	10,59	26,26	42,33
P12 < 30 cm	6,42	34,65	0,20	1,68%	0,98%	0,09%	10,46	19,93	29,70
P12 > 30 cm	7,13	-7,40	0,25	3,45%	2,04%	0,15%	13,81	28,17	99,12
P13 < 30 cm	7,79	-46,25	0,23	2,40%	2,64%	0,14%	18,61	29,33	39,64
P13 > 30 cm	7,10	-5,50	0,58	2,79%	2,91%	0,15%	19,82	18,31	55,42
P14 < 30 cm	5,55	87,40	0,23	3,49%	1,37%	0,11%	12,57	19,56	34,18
P14 > 30 cm	7,51	-30,05	0,53	2,66%	1,38%	0,10%	13,40	30,78	59,29
P15 < 30 cm	5,51	89,35	0,14	4,53%	1,39%	0,13%	10,54	17,45	33,71
P15 > 30 cm	5,01	119,50	0,44	4,66%	1,33%	0,11%	11,62	26,01	41,92
P16 < 30 cm	6,18	49,85	0,20	4,49%	1,07%	0,10%	11,07	18,43	25,71
P16 > 30 cm	7,14	-7,00	0,40	3,54%	1,31%	0,09%	14,37	31,36	32,75
P17 < 30 cm	6,47	32,95	0,16	2,01%	1,26%	0,10%	12,76	18,88	28,99
P17 > 30 cm	6,83	10,45	0,59	4,30%	2,26%	0,13%	17,77	28,83	42,22
P18 < 30 cm	5,72	76,95	0,28	4,28%	1,41%	0,13%	11,11	29,66	29,31
P18 > 30 cm	4,23	165,65	0,54	5,30%	1,57%	0,12%	13,17	33,41	36,98
P19 < 30 cm	5,35	99,05	0,09	2,89%	0,47%	0,07%	6,81	5,10	20,82
P19 > 30 cm	8,18	-69,80	0,43	3,27%	0,65%	0,11%	5,81	18,84	99,55
P20 < 30 cm	7,20	-11,10	0,14	1,65%	1,47%	0,10%	14,34	30,00	37,66
P20 > 30 cm	8,45	-85,40	0,19	1,89%	0,80%	0,09%	8,54	40,02	54,20

Annex 9 – Continued

ID	exchangeable Na [me/100g]	exchangeable K [me/100g]	exchangeable Ca [me/100g]	exchangeable Mg [me/100g]	CEC [me/100g]	Alkali saturation
P01 < 30 cm	8,94	0,58	2,15	2,73	22,27	64,62%
P01 > 30 cm	9,18	1,30	1,80	3,30	21,48	72,54%
P02 < 30 cm	8,83	0,38	2,25	1,17	13,91	90,85%
P02 > 30 cm	8,96	0,62	1,06	2,25	16,43	78,45%
P03 < 30 cm	8,59	1,12	0,60	2,08	16,31	76,00%
P03 > 30 cm	8,84	1,40	2,84	2,49	18,28	85,23%
P04 < 30 cm	2,41	0,35	0,75	2,64	19,05	32,31%
P04 > 30 cm	5,36	2,45	1,10	2,55	18,10	63,33%
P05 < 30 cm	8,39	0,25	0,79	0,73	14,30	71,03%
P05 > 30 cm	9,08	0,80	0,72	1,62	17,40	70,24%
P06 < 30 cm	5,57	0,35	0,89	1,99	11,77	74,67%
P06 > 30 cm	3,24	0,49	1,38	1,91	13,41	52,28%
P07 < 30 cm	1,06	0,81	0,92	2,96	20,24	28,41%
P07 > 30 cm	5,29	1,44	0,64	2,62	16,97	58,87%
P08 < 30 cm	3,50	0,99	1,05	4,04	22,15	43,21%
P08 > 30 cm	2,53	0,84	0,89	3,11	24,12	30,54%
P09 < 30 cm	3,07	0,87	1,68	3,20	25,76	34,29%
P09 > 30 cm	5,16	1,15	1,90	2,67	19,52	55,70%
P10 < 30 cm	3,92	0,58	0,49	2,09	17,38	40,76%
P10 > 30 cm	5,13	1,09	0,94	2,39	15,18	62,94%
P11 < 30 cm	7,14	1,15	0,84	1,88	14,31	76,93%
P11 > 30 cm	3,15	0,86	1,02	2,18	15,12	47,64%
P12 < 30 cm	1,73	0,50	1,43	1,59	13,83	37,98%
P12 > 30 cm	7,49	1,68	1,82	3,46	21,95	65,84%
P13 < 30 cm	3,96	0,84	1,85	2,63	20,49	45,28%
P13 > 30 cm	5,53	1,21	1,65	3,37	23,86	49,30%
P14 < 30 cm	2,86	0,71	1,12	1,75	17,82	36,18%
P14 > 30 cm	5,33	1,49	1,35	2,89	18,90	58,48%
P15 < 30 cm	2,40	0,74	1,36	2,04	17,59	37,16%
P15 > 30 cm	3,70	0,84	1,62	2,26	19,29	43,63%
P16 < 30 cm	2,75	0,40	1,35	1,70	15,07	41,10%
P16 > 30 cm	5,88	0,66	1,75	1,86	19,48	52,08%
P17 < 30 cm	2,73	0,62	1,39	1,93	15,92	41,91%
P17 > 30 cm	2,62	0,83	1,87	2,86	15,04	54,43%
P18 < 30 cm	1,31	0,38	1,57	2,52	21,72	26,63%
P18 > 30 cm	0,89	0,40	1,00	2,22	24,50	18,39%
P19 < 30 cm	5,74	0,46	0,39	1,02	13,18	57,67%
P19 > 30 cm	7,85	2,09	1,32	2,20	20,26	66,44%
P20 < 30 cm	4,80	1,43	1,95	1,84	16,27	61,62%
P20 > 30 cm	5,74	1,45	1,62	2,07	17,12	63,52%

Annex 10 – Description of soil characteristics

- The pH in H_2O of the sample plots ranged from highly acidic to slightly alkaline and the average of the soils in the forest types was neutral with no significant differences.
- The electrical conductivity (EC) had very low values for both soil depths in every sample plot. In the topsoil, the EC was significantly lower than in the subsoil.
- The average organic carbon (C organic) was highest in the open area and it was significantly higher than in the samples of the dense forest. The variance in C organic was highest in the sparse forest and ranged from very low to high.
- The average carbon to nitrogen ratio (C/N ratio) was highest in the open area and it was significantly higher than the average of the dense forest. The average C/N ratios were mostly moderate. The extremes were a high and low C/N ratio in plots of sparse forest.
- The amount of total phosphorus (P total) ranged from very low to moderate. In most samples, P total was higher in the subsoil than in the topsoil. In the dense forest, the difference was significant. Also, in the area planted in 2015, the topsoil had significantly lower P total than the subsoil. The average amount of P total was moderate for all forest types.
- The total potassium (K total) did not differ significantly between the forest types but it had significant differences between the sample depths and between the years of planting. In all sample plots, the K total of the subsoil samples was higher than in the topsoil. The plots in the area planted in 2016 had higher values than those of 2015. The average total potassium was moderate in the topsoil and high in the subsoil.
- The exchangeable cations or base cations calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}) and potassium (K^{+}) showed similar trends.
    - The exchangeable sodium had very high values in most of the sample plots and also the average was very high. A significant difference was found between the topsoil and the subsoil.
    - The exchangeable potassium had the same significant results as the total potassium. The average exchangeable potassium was moderate in topsoil and high in subsoil.
    - Both, the exchangeable calcium and the exchangeable magnesium had a significantly higher value in the subsoil of the area planted in 2015.
    - For the exchangeable calcium, the maximum was low. The average and minimum were very low.
    - The exchangeable magnesium showed a significant difference between the topsoil and subsoil. It had a high level as maximum and a moderate level as average. The minimum level was low to moderate.
- The cation exchange capacity (CEC) had moderate to high levels. Most of the subsoil samples had higher CEC values than the samples from the topsoil. In the dense forest and the area planted in 2015 the difference was significant.
- Both topsoil and subsoil had a very high maximum, a low minimum and a moderate average alkali saturation.

Annex 11 – List of slopes and soil-water balance measured in the sample plots

plot Nr	minimum slope	maximum slope	average slope	slope direction	soil-water balance	forest type
01	7%	20%	10%	NE	dry to moist	sparse forest
02	4%	7%	6%	N	moist	sparse forest
03	13%	23%	19%	SE	dry	dense forest
04	0%	1%	1%	-	wet	open area
05	3%	5%	4%	NE	moist	dense forest
06	5%	31%	18%	NE	very dry	dense forest
07	4%	15%	5%	NE	moist	sparse forest
08	0%	0%	0%	-	very wet (water up to 15 cm)	open area
09	0%	4%	2%	E	moist (small puddle)	sparse forest
10	0%	13%	3%	N	moist to wet	open area
11	3%	11%	7%	E	moist to dry	sparse forest
12	4%	16%	13%	SW	dry	dense forest
13	0%	2%	1%	SW	wet to very wet (water up to 10 cm)	open area
14	1%	2%	1%	W-E	moist	sparse forest
15	7%	45%	23%	SE	very dry	dense forest
16	0%	0%	0%	-	very wet (water up to 10 cm)	open area
17	3%	22%	18%	NE	very dry	dense forest
18	1%	30%	15%	E	moist	dense forest
19	6%	10%	8%	SE	moist	sparse forest
20	4%	12%	10%	E	dry to moist	sparse forest

Annex 12 – Draft action planning for future rehabilitation

Topography of rehabilitation areas

The topography in combination with the low infiltration of the soils and the bad drainage of the area caused the differences in soil-water balance.

The variation in the soil-water balance enables tree species with different traits to grow on a small area.

In case of the research area, most of the tree species did not stand waterlogging, and therefore no forest could develop on the flat areas.

A decision has to be made for the future if the planted species are adjusted to the topography and soil-water balance or if the topography of the rehabilitation area is changed. The tree species are discussed in the following chapter.

Improving the infiltration is the most difficult task.

- The soil material is given with the OB and topsoil.
- The addition of polyacrylamide could improve the infiltration of the soil (Vacher, Loch, & Raine, 2003) and reduce soil erosion and nutrient loss (Chen, Chen, Li, Pu, & Sun, 2016). But it would create additional costs.
- As soil compaction with heavy machines reduces the infiltration rate (Sheoran et al., 2010; Startsev & McNabb, 2000) a change of the topography construction and topsoil spreading could help increase the infiltration of the rehabilitation areas.
  A promising alternative of spreading the topsoil on the area is the loose-heaped-ground method (Wei, Hu, & Bai, 2001). Instead of spreading the topsoil evenly on the area with a caterpillar or grader, loose heaps of topsoil are dumped on the area. This method not only reduces the compaction and bulk density but also reduced the water runoff volume compared to leveled areas (Zhang, Wang, Bai, & Lv, 2015).
- The positive effects of vegetation on the infiltration (Dunne, Zhang, & Aubry, 1991; Meeuwig, 1970; Thompson, Harman, Heine, & Katul, 2010; Zhang et al., 2015) shows the importance of the cover crops and trees for the rehabilitated areas. In particular, the deep roots of trees are important for the redistribution of water between the soil layers and for recharging soil water (Burgess, Adams, Turner, & Ong, 1998; Burgess, Adams, Turner, White, & Ong, 2001).

Improved drainage or a change of the topography can have the same effect. They prevent flooding of areas by allowing excess water to flow away.

- Drainage needs maintenance to function properly over a long time. Therefore, a general change in the topography of future rehabilitation areas is recommended.
- The changes to the current system do not have to be big. The aim is to eliminate flat areas. Instead of leveling the plateaus and making them flat, a slight slope (2-3°) should be made. An example is shown in Figure A12.

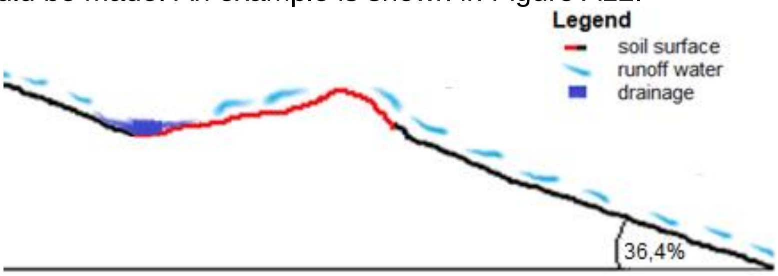


Figure A12 Topography of rehabilitation area without flat areas

Annex 12 – Continued

Planting tree species

The selection of suitable species is very important, especially for planting trees on the rehabilitation areas that have already been formed and for enrichment planting.

This research shows that most of the trees did not grow on the flat areas because of the soil-water balance. The tree species that were used for the rehabilitation worked well on well-drained slopes but did not endure waterlogging.

Instead of randomly planting various species on the areas, it is recommended to plant selected species according to soil-water balance and slope.

The research of Banjarbaru Forestry Research Unit, FORDA and Graham (2014) on silviculture of tropical peat swamp forests in Central Kalimantan presents some interesting facts and details to twenty-two species.

The research analyzed the response to light intensity, flooding, drought, nutrients and microbial availability of swamp forest tree species.

On the basis of the findings from that research, field experiments could be carried out by PT Adaro Indonesia to find out how the species grow on post-mine rehabilitation areas. Species like *Aglaia rubignosa* (Kajalaki), *Alstonia spatulata* (Pulai rawa), *Calophyllum sclerophyllum* (Kapurnaga), *Licania splendens* (Bintan), *Lophopetalum javanicum* (Perupuk), *Melaleuca leucadendra* (Galam) and more, could prove as species adapted to the wet soil-water balance of the flat areas.

A successful establishment of swamp forest tree species on the rehabilitation area would increase the α- and β-diversity. Furthermore, it would create a new habitat for animals, insects and plants that are adapted to wet swamp lowland forests of Borneo.

The reaction of tree species to drought and flooding differ (Banjarbaru Forestry Research Unit et al., 2014). For an optimal selection of the species to be planted on the flat areas information on the variation of flooding throughout the year is important.

A research monitoring the weekly or monthly precipitation and soil-water balance of the flat areas is recommended.

More detailed documentation of planting and maintenance is necessary. This will lead to better results from the monitoring of the performance of species.

- The information on the trees that were planted on the area of this research could not be used to draw valid conclusions.
- With information on the exact species composition, planting distance, planting time and planted area the survival, growth and reproduction of the different tree species can be monitored.

The best case would be a documentation of the planting methods on all rehabilitation areas, whereas sample plots would be sufficient for research.

Annex 12 – Continued

Topsoil management

Many lowland areas in Kalimantan have low soil fertility due to leaching and complete weathering of soils (MacKinnon et al., 1996). To prevent further loss of fertility the management of topsoil is important for mine rehabilitation.

A research in India showed that the soil quality of stockpiled topsoil deteriorated drastically in the first year and became biologically unproductive after six years (Ghose, 2004). Results from a research in Western Australia showed that the use of fresh topsoil was beneficial over topsoil that had been stockpiled for several years (van Etten, Mccullough, & Lund, 2012). Boyer, Wratten, Pizey, & Weber (2011) analyzed how earthworm communities were impacted by soil stockpiling and mine rehabilitation in New Zealand.

- They found out that earthworms did not survive at and below 1 m depth due to anaerobic conditions, and therefore stockpiling of topsoil was not recommended.
- Instead of stockpiling topsoil a vegetation direct transfer (VDT) is recommended by them.
- VDT includes the transfer of vegetation and soil units. Therefore, reasonably intact ecological communities or ecosystems are transferred.

If VDT is not applicable, the stockpiles should be kept low (best below 1 m) and loose. For example, by end-tipping to prevent soil compaction and anaerobic conditions (Boyer et al., 2011; Tanner & Swart, 2007).

Further schemes that could improve the rehabilitation are the application of biosolids (digested sewage sludge), biochar or coal ash.

- Biosolids can enrich the soils with organic carbon and improve physical conditions and soil chemical fertility (Rate, Lee, & French, 2004).
- Biochar application can create more favorable conditions for vegetation by increasing soil pH, soil EC, C content and C/N ratio (Reverchon et al., 2015; Smider & Singh, 2014).
- Coal ash application to the topsoil can reduce the risk of soil erosion; therefore, it can prevent the topsoil from being washed away (Matsumoto et al., 2016).

The costs, risks and benefits of these methods have to be analyzed in more detail before a recommendation can be made.

Management of planted areas

Once trees are planted on the rehabilitation area the management of these trees is very important. This management includes weeding and cutting climbers. Also, a strategy against the dense grass cover on areas planted in the past is necessary.

With the rapid growth of vegetation in moist tropical climate (Novianti et al., 2018) the overall success of tree planting depends on the quality and quantity of weed control. If the competing vegetation grows vigorously (year-round rainfall) up to eight weedings per year are recommended in the first year after planting (Stilma, 2018a).

During fieldwork for this research parts of the sparse forest had dense climbers growing over the trees. In worst cases, trees were covered by climbers and pressed to the ground by the extra weight.

Weeding is a time-consuming task but it is essential for the establishment of a dense forest cover. If money is saved by not doing proper weeding additional costs for replanting are created.

As mentioned in the discussion, the dense grass cover on most of the open area and sparse forest area may lead to a reduction in natural regeneration of trees.

- The grass cover in the sparse forest was partially 40 to 50 cm thick and had a green top layer, dry and brown middle layer and a black layer of rotten grass above the ground.
- To enhance natural regeneration the dense ground cover has to be opened. Through this, seeds in bird droppings can reach the ground and germinate.

Because manual labor is expensive a cheap alternative is beneficial. It is recommended to consider the use of cows.

- If the local communities were allowed to graze their cattle on the rehabilitated area the cows would eat the grass and trample through the grass that covers the ground.
- Additionally, the herdsman could be instructed to cut the climbers on the trees as exchange for the free pasture.
- This new management is only applicable if the majority of trees is high enough so that the cows can not destroy them when grazing between them.

Although the rehabilitation of PT Adaro Indonesia and the local communities could benefit from this management further research and planning is necessary. Instead of grazing the area continuously, brakes are important. This allows seeds to germinate and trees to grow without cows destroying them every now and then. Also, the impact of the cows on the soil has to be considered and analyzed before implementing the grazing.

Trial areas could help in getting more information.

Annex 12 – Continued

Ecological restoration and fauna rehabilitation

In post-mine rehabilitation not only the establishment of trees is important but also the ecological restoration and fauna rehabilitation has to be addressed.

An ecological approach for rehabilitation has to include the whole ecosystem and should be in line with a reference ecosystem (Gastauer et al., 2017; McDonald et al., 2016; Sayer, Chokkalingam, & Poulsen, 2004).

The aim of the whole restoration program has to be an ecosystem that fits the region, conserves biodiversity and delivers ecosystem goods and services to stakeholders (McDonald et al., 2016).

The use of adapted (native/endemic) tree species is as important as fauna rehabilitation (Brennan, Nichols, & Majer, 2005; Cristescu, Frère, & Banks, 2012). According to Cristescu et al. (2012), the "methods combining the use of fresh topsoil with the addition of seeds and seedlings were most successful for fauna recolonization, both in term of fauna density and richness" (p.60).

Although flora and fauna restoration belong together, fauna recolonization of rehabilitated areas does not necessarily correlate with flora criteria (Cristescu, Rhodes, Frére, & Banks, 2013).

In addition to the restoration of topography and vegetation, measures for fauna rehabilitation are necessary to allow quick colonization of the area with mammals, birds, reptiles, amphibians and insects. For example, many animals rely on dead trees as their habitat and in newly rehabilitated areas almost no decaying wood is present (Burton, Zahedi, & White, 2012).

- Adding habitat logs can be a rather cheap but effective method to create deadwood habitats on the rehabilitation area (Brennan et al., 2005).
  For this, logs and woody debris from forests that are cleared for mining can be moved to the rehabilitation area and spread there.
- Re-introducing threatened species (Burton et al., 2012) can also be a good measure to restore fauna diversity; especially, if these species have a low range of recolonization.

Since 2018, PT Adaro Indonesia is involved in a program that promotes the cultivation of stingless bees for local farmers. Stingless bees occur naturally in the forests of Borneo (Samejima, Marzuki, Nagamitsu, & Nakasizuka, 2004) and collection of honey is common. In the past collection of honey in the wild involved the felling of big trees that had a nest in the inside of its hollow trunk or branch (Tornyie & Kwapong, 2015).

The use of the rehabilitation forests for honey production can be done in a sustainable way with the cooperation of PT Adaro Indonesia and the local farmers. This prevents damage to existing trees and overexploitation of the wild stingless bee colonies.

For this to be possible, the forest has to be attractive for the bees and bee farmers.