RECOVERY OF RESIDUAL FOREST ECOSYSTEM AS AN IMPACT OF SELECTIVE LOGGING IN SOUTH PAPUA: AN ECOLOGICAL APPROACH

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ABSTRACT

Papua has been experiencing heavy logging activity in its forests for decades. However, only several studies focused on the effect of logging in the forest ecosystem. This research was aimed to analyze recovery processes of the forest ecosystem. The research was conducted in the logged tropical rainforest in South Papua using ecological approach which used tree communities as biotic and soil condition as abiotic indicators. Data were collected in the logging area of PT Tunas Timber Lestari located in the tropical rainforest of South Papua. There were five groups of forests used in this research i.e. unlogged, one year post selectively-logged, five years post selectively-logged, ten years post selectively-logged and fifteen years post selectively-logged forests. Thirty nested plots were laid on each forest group. Canonical Correspondence Analysis (CCA) was applied to analyze the understory and upperstory plant communities. Understory and upperstory plant communities formed different patterns due to logging. Plant communities in the ten and fifteen years post-selectively logged forests were not similar to those in the unlogged forest. Soil organic matter (SOM) content in the selectively logged forests was lower than that in the unlogged forest. These occurrences indicated that the selectively logged forests were still recovering and required more than fifteen years to be fully recovered.

Keywords: Canonical correspondence analysis, edaphic factor, logged tropical forest, plant community, soil organic matter

INTRODUCTION

Tropical rainforests play an important role in ecosystem services, such as logging production (Whitfeld *et al*. 2014; Putz & Romero 2014). The process of production mechanism in the tropical rainforest has a significant impact on abiotic and biotic elements (Zambrano *et al*. 2014). Those conditions result in the change in the tropical rainforest as an ecosystem and some circumstances of the secondary successional process take place as a response to ecological alterations. Furthermore, most of the tropical rainforests are experiencing the alterations and the selective logging has a significant impact on ecological factors (Corrià-Ainslie *et al*. 2015; Flores *et al*. 2014). Hence, the logged tropical rainforests are counting on the ability of forest recovery itself. Most indicators to analyse forest recovery are based on tree density, basal area (Whitfeld *et al*. 2014; Rutten *et al*. 2015) and growth rate of residual trees (Do *et al*. 2016; Hoang *et al*. 2011; West *et al*. 2014; Sist *et al*. 2014; Susanty *et al*. 2015) in the logged forests. However, the recovery of disturbed forests should not only be considered based on sustainable timber production, but the ecological elements such as soil conditions and residual trees should also be taken into account as forest recovery indicators.

Some areas in lowland tropical forests in South Papua were intended as logging concession for decades (Kuswandi & Murdjoko 2015; Murdjoko

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2013; Kuswandi 2014). Few studies concerning the effects of logging in Papua logged forests were conducted. Some studies focused only on damages, changes in basal area (Gandhi & Mitlöhner 2014), population dynamics of remaining trees (Murdjoko 2013; Kuswandi & Murdjoko 2015; Murdjoko *et al.* 2016b) and biomass stock change (Hendri *et al.* 2012). Therefore, it is necessary to analyze forest recovery using the ecological approach in South Papua. In this analysis, the primary forest was considered as a stable forest ecosystem (Pennington *et al.* 2015).

Ecological approach took tree communities as biotic factors where many processes such as tree associations, ecological responses of the tree to ecological change as well as successional development can be analyzed based on patterns of tree communities. Besides that, soil condition alters after selective logging (Hattori *et al.* 2013) mainly the amount of soil properties decrease such as Nitrogen content (Asase *et al.* 2014), soil organic matter (SOM) (Prasetyo *et al.* 2015) and other nutrients (Duah-Gyamfi *et al.* 2014; Wasrin & Putera 1999; Edwards *et al.* 2014; Imai *et al.* 2012). Consequently, the edaphic conditions were considered as abiotic indicators to support the explanation of the change in tree communities.

This research was aimed to analyze recovery process of selectively logged tropical rainforest ecosystem in South Papua using ecological approach. Our hypotheses were: 1. tree communities in a selectively logged tropical rainforest were considered to be recovered when tree communities in the rainforest were similar to those in the primary forest; 2. the selectively logged tropical rainforest was considered to be recovered when the edaphic indicators in the rainforest were similar to those in the primary forest.

MATERIALS AND METHODS

Study Area

Research was conducted in the logging area of PT Tunas Timber Lestari located in the tropical rainforest of South Papua with geographical position between 140°21` – 140°59` E and 05°50` – 06°42` S (Fig.1). The annual rainfall was between

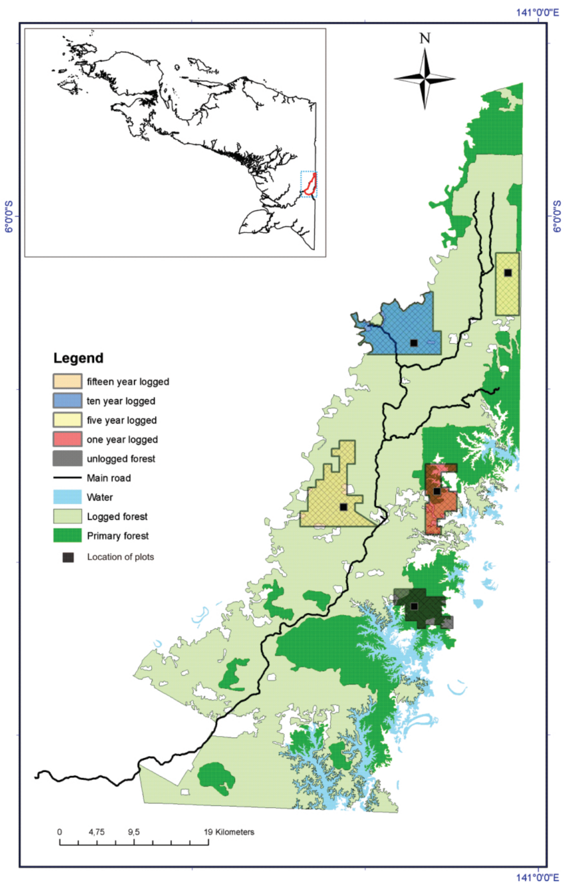

Figure 1 Study area in logging concession of PT Tunas Timber Lestari (Murdjoko *et al.* 2016c)

3,000 and 4,000 mm with daily moisture range of 75 - 85 %. The edaphic condition was typified as lowland forest with almost flat topography with soil formed by alluvial process (Petocz 1989). The vegetation was dominated by trees belong to *Dipterocarpaceae*, *Lauraceae* and *Myrtaceae* families (Gandhi & Mitlöhner 2014; Kuswandi *et al.* 2015). Several other plants such as lianas, rattans, ferns, palms, herbs, orchids and pandanus grew and interacted with trees in this forest (Murdjoko *et al.* 2016a).

Five groups of forests were used in this research i.e. unlogged, one year post selectively-logged, five years post selectively-logged, ten years post selectively-logged and fifteen years post selectively-logged forests. The unlogged forest was taken as a primary forest which was a stable forest ecosystem. The selectively logged forests were compared to the unlogged forest to observe the recovery process. The selective logging was carried out by selectively cutting commercial trees having diameter of ≥ 40 cm.

Sampling and Data Collection

Samples were collected in each forest group using systematic sampling plots. The first plot was placed at 200 m from the main road to avoid edge effect. The plots were rectangular with various sizes i.e. 1. 20 x 20 m for trees (D) having DBH (diameter at breast height) of ≥ 20 cm; 2. 10 x 10 m for poles (C) having DBH of 10 to < 20 cm; 3. 5 x 5 m for saplings (B) having height of > 1.5 m and DBH of < 10 cm; and 2 x 2 m for seedlings (A) having height of < 1.5 m. The four plots were set as nested plot (Fig. 2a). Thirty

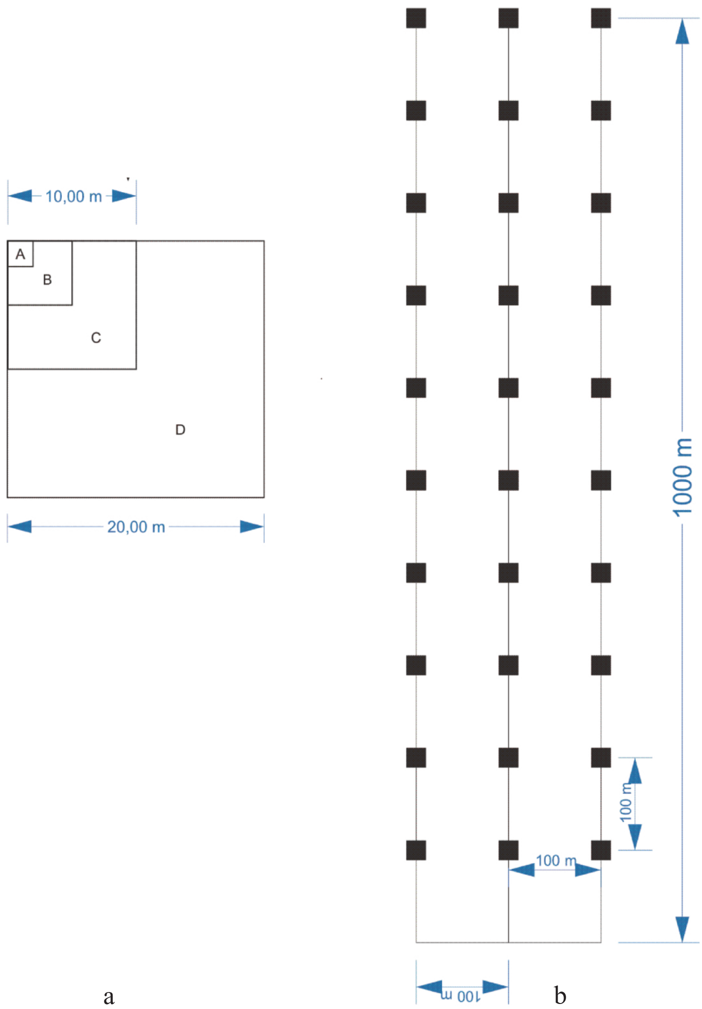

Figure 2 Nested plots to measure individual plant in both unlogged and selectively-logged forests

Note: A = plot for seedlings; B = plot for saplings; C = plot for for poles; D = plot for trees; (a) Distance between plots = 100 m; (b) The 30 nested plots were laid on each forest group (unlogged, one year, five years, ten years and fifteen years post selectively-logged forests) nested plots were laid in each forest (Fig. 2b) making a total of 150 nested plots for the 5 forest groups (unlogged, one year, five years, ten years and fifteen years post selectively-logged forests). Seedlings and saplings were sampled as understory, while poles and trees were sampled as upperstory in both unlogged and selectively logged forests.

Data collected from seedlings, saplings, poles and trees consisted of numbers of individuals, diameter of individuals for those having DBH ≥ 10 cm and species name of individuals. Species identification was carried out by two herbarium technicians. Unidentified samples were set as voucher specimens and sent to the herbarium of "*Balai Penelitian dan Pengembangan Lingkungan Hidup dan Kehutanan (BP2LHK) Manokwari*" and Herbarium Manokwariense (MAN) *Pusat Penelitian Keanekaragaman Hayati Universitas Papua* (*PPKH-UNIPA*), *Manokwari*. Validation of the species names of the individuals was checked online at http://www.theplantlist.org/; http://plants.jstor.org and www.ipni.org/ipni/.

Soil samples were taken from the center and four corners of the 20 x 20 m plot. The litterfall samples were collected from each plot by making 1 x 1 m rectangular subplots in each plot. The soil and litterfall samples were sent to the laboratory of *Balai Pengkajian Teknologi Pertanian Yogyakarta* for determining the content of soil organic matter (SOM) for soil samples as well as Carbon (C) content, Nitrogen (N) content and dry weight for litterfall samples.

Data and Statistical Analysis

Canonical Correspondence Analysis (CCA) was applied to show the relationship among tree species using stem density and environmental factors (SOM, C, N contents and dry weight of litterfall) (ter Braak 1987; ter Braak 1986; Khairil *et al.* 2014). Plants communities were grouped as: a) understory consisted of small individuals (seedlings and saplings); and b) upperstory consisted of large individuals (poles and trees). Tree communities were formed as a result of interaction among tree species, SOM, C content, N content, dry weight of litterfall and forest groups (unlogged, one year, five years, ten years and fifteen years post selectively-logged). The CCA was computed using R statistical software version 3.3.1. with VEGAN package (R Core Team 2014; Oksanen *et al.* 2013). The tree communities were grouped using Euclidean distance among tree species. The Euclidean distance among tree communities was calculated as the average and confidence interval of 95%.

RESULTS AND DISCUSSION

Tree Communities

Total tree species in the study area were 163 species and classified as understory (159 species) and upperstory (127 species) (Table 1). Within tree species, there were 106 species consisted of both understory and upperstory.

Table 1 Understory (a) and upperstory (b) tree communities formed due to logging activities

a. Understory

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
1	1	*Calophyllum peekelii* Lauterb.	Calo_pe	√					
2	2	*Knema* sp.	Knem_sp	√					
3	3	*Gonocaryum litorale* (Blume) Sleumer	Gono_li	√					
4	4	*Alstonia scholaris* (L.) R. Br.	Alst_sc	√					
5	5	*Guioa pleuropteris* (Blume) Radlk.	Guio_pl	√					
6	6	*Dysoxylum* sp.	Dyso_sp	√					
7	7	*Lepisanthes* sp.	Lepi_sp	√					
8	8	*Rhodomyrtus* sp.	Rhod_sp	√					
9	9	*Maasia glauca* (Hassk.) Mols, Kessler & Rogstad	Maas_gl	√					
10	10	*Octamyrtus* sp.	Octa_sp	√					
11	11	*Chisocheton* sp.	Chis_sp	√					
12	12	*Elaeocarpus arnhemicus* F.Muell.	Elae_ar	√					
13	13	*Haplolobus floribundus* (K.Schum.) H.J.Lam	Hapl_fl	√					

Note: PF = unlogged forest; X1LF = one year post selectively-logged forest; X5LF = five years post selectively-logged forest; X10LF = ten years post selectively-logged forest; X15LF = fifteen years post selectively-logged forest; ALL = present in all forest groups; NON_AC = not associated

Table 1 Continued

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
14	14	*Brackenridgea* sp.	Brac_sp.1	√					
15	15	*Litsea* sp.	Lits_sp	√					
16	16	*Dysoxylum mollissimum* Blume	Dyso_mo	√					
17	17	*Antiaris toxicaria* Lesch.	Anti_to	√					
18	18	*Ficus variegata* Blume	Ficu_va	√					
19	19	*Gyrinops versteegii* (Gilg) Domke	Gyri_ve	√					
20	20	*Litsea guppyi* (F. Muell.) F. Muell. ex Forman	Lits_gu	√					
21	21	*Maranthes corymbosa* Blume	Mara_co	√					
22	22	*Mastixiodendron* sp.	Mast_sp	√					
23	23	*Vavaea amicorum* Benth.	Vava_am	√					
24	24	*Calophyllum caudatum* Kaneh. & Hatus.	Calo_ca	√					
25	25	*Parastemon versteeghii* Merr. & L.M.Perry	Para_ve	√					
26	26	*Calophyllum laticostatum* P.F.Stevens	Calo_la	√					
27	27	*Garcinia* sp.	Garc_sp	√					
28	28	*Geniostoma* sp.	Geni_sp	√					
29	1	*Sloanea pulchra* (Schltr.) A.C.Sm.	Sloa_pu		√				
30	2	*Canarium* sp.	Cana_sp		√				
31	3	*Horsfieldia* sp.	Hors_sp		√				
32	4	*Melicope* sp.	Meli_sp		√				
33	5	*Sterculia* sp.	Ster_sp		√				
34	6	*Trema orientalis* (L.) Blume	Trem_or		√				
35	7	*Trema* sp.	Trem_sp		√				
36	8	*Trema tomentosa* (Roxb.) H. Hara	Trem_to		√				
37	9	*Harpullia cupanioides* Roxb.	Harp_cu		√				
38	10	*Sloanea* sp.	Sloa_sp		√				
39	11	*Planchonella* sp.	Plan_sp		√				
40	12	*Artabotrys* sp.	Arta_sp		√				
41	13	*Archidendron parviflorum* Pulle	Arch_pa		√				
42	14	*Elaeocarpus culminicola* Warb.	Elae_cu		√				
43	15	*Diospyros papuana* Valeton ex Bakh.	Dios_pa		√				
44	16	*Myristica globosa* Warb.	Myri_gl		√				
45	17	*Glochidion* sp.	Gloc_sp		√				
46	18	*Macaranga bifoveata* J.J.Sm.	Maca_bi		√				
47	19	*Melicope elleryana* (F. Muell.) T.G. Hartley	Meli_el		√				
48	20	*Kibara coriacea* (Blume) Hook. f. & A. Thomps.	Kiba_co		√				
49	21	*Timonius timon* (Spreng.) Merr.	Timo_ti		√				
50	1	*Hopea papuana* Diels	Hope_pa			√			
51	2	*Elaeocarpus angustifolius* Blume	Elae_an			√			
52	3	*Ficus* sp.	Ficu_sp			√			
53	4	*Ruta* sp.	Ruta_sp			√			
54	5	*Garcinia latissima* Miq.	Garc_la			√			
55	6	*Schefflera actinophylla* (Endl.) Harms	Sche_ac			√			
56	7	*Campnosperma brevipetiolatum* Volkens	Camp_br			√			
57	8	*Goniothalamus* sp.	Goni_sp			√			
58	9	*Corynocarpus laevigatus* J.R.Forst. & G.Forst.	Cory_la			√			
59	10	*Adenanthera pavonina* L.	Aden_pa			√			
60	11	*Aglaia spectabilis* (Miq.) S.S.Jain & S.Bennet	Agla_sp			√			
61	12	*Dillenia alata* (R.Br. ex DC.) Banks ex Martelli	Dill_al			√			
62	13	*Dillenia indica* L.	Dill_in			√			
63	14	*Diospyros* sp.	Dios_sp			√			
64	15	*Fagraea* sp.	Fagr_sp			√			
65	16	*Flindersia pimenteliana* F.Muell.	Flin_pi			√			
66	17	*Gynotroches* sp.	Gyno_sp			√			
67	18	*Manilkara fasciculata* (Warb.) H.J.Lam & Maas Geest.	Mani_fa			√			

Table 1 Continued

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
68	19	*Melicope bonwickii* (F. Muell.) T.G. Hartley	Meli_bo			√			
69	20	*Prunus* sp.	Prun_sp			√			
70	21	*Santiria* sp.	Sant_sp			√			
71	1	*Prunus javanica* (Teijsm. & Binn.) Miq.	Prun_ja				√		
72	2	*Terminalia complanata* K.Schum.	Term_co				√		
73	3	*Diospyros calycantha* O.Schwarz	Dios_ca				√		
74	4	*Lithocarpus rufovillosus* (Markgr.) Rehder	Lith_ru				√		
75	5	*Pisonia grandis* R. Br.	Piso_gr				√		
76	6	*Horsfieldia irya* (Gaertn.) Warb.	Hors_ir				√		
77	7	*Cananga odorata* (Lam.) Hook.f. & Thomson	Cana_od				√		
78	8	*Carrierea* sp.	Carr_sp				√		
79	9	*Lepisanthes rubiginosa* (Roxb.) Leenh.	Lepi_ru				√		
80	10	*Mammea novoguineensis* (Kan. & Hat.) Kosterm.	Mamm_no				√		
81	11	*Pometia pinnata* J.R.Forst. & G.Forst.	Pome_pi				√		
82	12	*Semecarpus rufovelutinus* Ridl.	Seme_ru				√		
83	13	*Siphonodon* sp.	Siph_sp				√		
84	14	*Gluta papuana* Ding Hou	Glut_pa				√		
85	15	*Prainea limpato* (Miq.) Beumee ex K.Heyne	Prai_li				√		
86	16	*Maniltoa browneoides* Harms	Mani_br				√		
87	17	*Jagera javanica* (Blume) Kalkman	Jage_ja				√		
88	1	*Canarium hirsutum* Willd.	Cana_hi					√	
89	2	*Polyalthia* sp.	Poly_sp						√
90	3	*Virola surinamensis* (Rol. ex Rottb.) Warb.	Viro_su						√
91	4	*Planchonella anteridifera* (C.T.White & W.D.Francis ex Lane-Poole) H.J.Lam	Plan_an						√
92	5	*Dracontomelon dao* (Blanco) Merr. & Rolfe	Drac_da						√
93	6	*Magnolia tsiampacca* (L.) Figlar & Noot.	Magn_ts						√
94	7	*Actinodaphne* nińda Teschner	Acti_ni						√
95	8	*Semecarpus papuana* Lauterb.	Seme_pa						√
96	9	*Planchonella keyensis* H.J.Lam	Plan_ke						√
97	10	*Syzygium anomalum* Lauterb.	Syzy_an						√
98	11	*Cleistanthus oblongifolius* (Roxb.) Müll.Arg.	Clei_ob						√
99	12	*Homalium foetidum* Benth	Homa_fo						√
100	13	*Popowia* sp.	Popo_sp						√
101	14	*Canarium indicum* L.	Cana_in						√
102	15	*Pimelodendron amboinicum* Hassk.	Pime_am						√
103	16	*Blumeodendron tokbrai* (Blume) Kurz	Blum_to						√
104	17	*Aglaia argentea* Blume	Agla_ar						√
105	18	*Gnetum gnemon* L.	Gnet_gn						√
106	19	*Mammea* sp.	Mamm_sp						√
107	20	*Vatica rassak* Blume	Vati_ra						√
108	21	*Fagraea racemosa* Jack	Fagr_ra						√
109	22	*Sterculia shillinglawii* F.Muell.	Ster_sh						√
110	23	*Neolitsea* sp.	Neol_sp						√
111	24	*Elaeocarpus* sp.	Elae_sp						√
112	25	*Endiandra rubescens* (Blume) Miq.	Endi_ru						√
113	26	*Endiandra* sp.	Endi_sp						√
114	27	*Hopea iriana* Slooten	Hope_ir						√
115	28	*Prunus arborea* (Blume) Kalkman	Prun_ar						√
116	29	*Lasianthus* sp.	Lasi_sp						√
117	30	*Terminalia copelandi* Elmer	Term_co.1						√
118	31	*Sundacarpus amarus* (Blume) C.N.Page	Sund_am						√
119	32	*Chisocheton ceramicus* Miq.	Chis_ce						√
120	33	*Teijsmanniodendron bogoriense* Koord.	Teij_bo						√

Table 1 Continued

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
121	34	*Sloanea pullei* O.C.Schmidt ex A.C.Sm.	Sloa_pu.1					√	
122	35	*Maasia sumatrana* (Miq.) Mols, Kessler & Rogstad	Maas_su					√	
123	36	*Cynometra ramiflora* L.	Cyno_ra					√	
124	37	*Canarium asperum* Benth.	Cana_as					√	
125	38	*Alstonia spectabilis* R.Br.	Alst_sp					√	
126	39	*Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb.	Gymn_fa					√	
127	40	*Grewia* sp.	Grew_sp					√	
128	41	*Pometia acuminata* Radlk.	Pome_ac					√	
129	42	*Halfordia kendack* Guillaumin	Half_ke					√	
130	43	*Timonius rufescens* (Miq.) Boerl.	Timo_ru					√	
131	44	*Siphonodon celastrineus* Griff.	Siph_ce					√	
132	45	*Palaquium* lobbianum Burck	Pala_lo					√	
133	46	*Grewia* eriocarpa Juss.	Grew_er					√	
134	47	*Gynotroches axillaris* Blume	Gyno_ax					√	
135	48	*Planchonia careya* (F.Muell.) R.Knuth	Plan_ca					√	
136	49	*Myristica* sp.	Myri_sp					√	
137	50	*Garcinia picrorhiza* Miq.	Garc_pi					√	
138	51	*Gironniera subaequalis* Planch.	Giro_su					√	
139	52	*Buchanania arborescens* (Blume) Blume	Buch_ar					√	
140	53	*Hopea celtidifolia* Kosterm.	Hope_ce					√	
141	54	*Endospermum medullosum* L.S.Sm.	Endo_me					√	
142	55	*Rhodamnia cinerea* Jack	Rhod_ci					√	
143	1	*Adenanthera novo-guineensis* Baker f.	Aden_no						√
144	2	*Anisoptera thurifera* subsp. *polyandra* (Blume) P.S.Ashton	Anis_th						√
145	3	*Brachychiton* sp.	Brac_sp						√
146	4	*Calophyllum* sp.	Calo_sp						√
147	5	*Carallia brachiata* (Lour.) Merr.	Cara_br						√
148	6	*Celtis latifolia* (Blume) Planch.	Celt_la						√
149	7	*Cerbera floribunda* K.Schum.	Cerb_fl						√
150	8	*Diospyros pilosanthera* Blanco	Dios_pi						√
151	9	*Garcinia dulcis* (Roxb.) Kurz	Garc_du						√
152	10	*Maniltoa plurijuga* Merr. & L.M.Perry	Mani_pl						√
153	11	*Nageia wallichiana* (C.Presl) Kuntze	Nage_wa						√
154	12	*Santiria rubiginosa* Blume	Sant_ru						√
155	13	*Schizomeria katastega* Mattf.	Schi_ka						√
156	14	*Spathiostemon javensis* Blume	Spat_ja						√
157	15	*Sterculia macrophylla* Vent.	Ster_ma						√
158	16	*Terminalia* sp.	Term_sp						√
159	17	*Vavaea* sp.	Vava_sp						√

b. Upperstory

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
1	1	*Terminalia complanata* K.Schum.	Term_co	√					
2	2	*Siphonodon celastrineus* Griff.	Siph_ce	√					
3	3	*Lepisanthes* sp.	Lepi_sp	√					
4	4	*Rhodomyrtus* sp.	Rhod_sp	√					
5	5	*Garcinia latissima* Miq.	Garc_la	√					
6	6	*Alphitonia incana* (Roxb.) Teijsm. & Binn. ex Kurz	Alph_in	√					
7	7	*Dysoxylum* sp.	Dyso_sp	√					
8	8	*Fagraea racemosa* Jack	Fagr_ra	√					
9	9	*Flacourtia inermis* Roxb.	Flac_in	√					
10	10	*Guioa pleuropteris* (Blume) Radlk.	Guio_pl	√					
11	11	*Hopea papuana* Diels	Hope_pa	√					

Table 1 Continued

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
12	12	*Litsea timoriana* Span.	Lits_ti	√					
13	13	*Nauclea orientalis* (L.) L.	Nauc_or	√					
14	14	*Calophyllum laticostatum* P.F.Stevens	Calo_la	√					
15	15	*Myristica globosa* Warb.	Myri_gl	√					
16	16	*Octomeles sumatrana* Miq.	Octo_su	√					
17	1	*Trema* sp.	Trem_sp		√				
18	2	*Gonocaryum litorale* (Blume) Sleumer	Gono_li		√				
19	3	*Kibara coriacea* (Blume) Hook. f. & A. Thomps.	Kiba_co		√				
20	4	*Canarium* sp.	Cana_sp		√				
21	5	*Garcinia* picrorhiza Miq.	Garc_pi		√				
22	6	*Dysoxylum mollissimum* Blume	Dyso_mo		√				
23	7	*Rhodamnia cinerea* Jack	Rhod_ci		√				
24	8	*Garcinia dulcis* (Roxb.) Kurz	Garc_du		√				
25	9	*Calophyllum* sp.	Calo_sp		√				
26	1	*Aglaia spectabilis* (Miq.) S.S.Jain & S.Bennet	Agla_sp			√			
27	2	*Brackenridgea* sp.	Brac_sp			√			
28	3	*Elaeocarpus culminicola* Warb.	Elae_cu			√			
29	4	*Fagraea* sp.	Fagr_sp			√			
30	5	*Flindersia amboinensis* Poir.	Flin_am			√			
31	6	*Planchonella densinervia* (K.Krause) H.J.Lam	Plan_de			√			
32	7	*Terminalia* sp.	Term_sp			√			
33	8	*Sloanea* sp.	Sloa_sp			√			
34	9	*Teijsmanniodendron bogoriense* Koord.	Teij_bo			√			
35	10	*Canarium indicum* L.	Cana_in			√			
36	11	*Buchanania arborescens* (Blume) Blume	Buch_ar			√			
37	12	*Elaeocarpus angustifolius* Blume	Elae_an			√			
38	13	*Prunus arborea* (Blume) Kalkman	Prun_ar			√			
39	14	*Macaranga bifoveata* J.J.Sm.	Maca_bi			√			
40	15	*Myristica* sp.	Myri_sp			√			
41	16	*Magnolia tsiampacca* (L.) Figlar & Noot.	Magn_ts			√			
42	17	*Maasia glauca* (Hassk.) Mols, Kessler & Rogstad	Maas_gl			√			
43	18	*Manilkara fasciculata* (Warb.) H.J.Lam & Maas Geest.	Mani_fa			√			
44	19	*Adenanthera pavonina* L.	Aden_pa			√			
45	20	*Alstonia scholaris* (L.) R. Br.	Alst_sc			√			
46	21	*Breonia chinensis* (Lam.) Capuron	Breo_ch			√			
47	22	*Corynocarpus laevigatus* J.R.Forst. & G.Forst.	Cory_la			√			
48	23	*Dillenia indica* L.	Dill_in			√			
49	24	*Diospyros pilosanthera* Blanco	Dios_pi			√			
50	25	*Geniostoma* sp.	Geni_sp			√			
51	26	*Maasia sumatrana* (Miq.) Mols, Kessler & Rogstad	Maas_su			√			
52	27	*Ochrosia* sp.	Ochr_sp			√			
53	28	*Planchonella* sp.	Plan_sp			√			
54	29	*Siphonodon* sp.	Siph_sp			√			
55	30	*Syzygium acutangulum* Nied.	Syzy_ac			√			
56	31	*Timonius rufescens* (Miq.) Boerl.	Timo_ru			√			
57	32	*Actinodaphne nitida* Teschner	Acti_ni			√			
58	33	*Haplolobus floribundus* (K.Schum.) H.J.Lam	Hapl_fl			√			
59	34	*Mammea* sp.	Mamm_sp			√			
60	1	*Aglaia argentea* Blume	Agla_ar				√		
61	2	*Palaquium lobbianum* Burck	Pala_lo				√		
62	3	*Gnetum gnemon* L.	Gnet_gn				√		
63	4	*Maranthes corymbosa* Blume	Mara_co				√		
64	5	*Polyalthia* sp.	Poly_sp				√		

Table 1 Continued

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
65	6	*Flindersia pimenteliana* F.Muell.	Flin_pi				√		
66	7	*Maniltoa browneoides* Harms	Mani_br				√		
67	8	*Chisocheton* sp.	Chis_sp				√		
68	9	*Chisocheton ceramicus* Miq.	Chis_ce				√		
69	10	*Elaeocarpus arnhemicus* F.Muell.	Elae_ar				√		
70	11	*Ficus drupacea* Thunb.	Ficu_dr				√		
71	12	*Garcinia* × *mangostana* L.	Garc_žÿ				√		
72	13	*Adenanthera novo-guineensis* Baker f.	Aden_no				√		
73	14	*Sloanea pullei* O.C.Schmidt ex A.C.Sm.	Sloa_pu.1				√		
74	15	*Calophyllum peekelii* Lauterb.	Calo_pe				√		
75	16	*Cynometra ramiflora* L.	Cyno_ra				√		
76	17	*Dracontomelon dao* (Blanco) Merr. & Rolfe	Drac_da				√		
77	18	*Prainea limpato* (Miq.) Beumee ex K.Heyne	Prai_li				√		
78	19	*Cleistanthus oblongifolius* (Roxb.) Müll.Arg.	Clei_ob				√		
79	20	*Glochidion* sp.	Gloc_sp				√		
80	21	*Harpullia cupanioides* Roxb.	Harp_cu				√		
81	22	*Pometia pinnata* J.R.Forst. & G.Forst.	Pome_pi				√		
82	23	*Ficus* sp.	Ficu_sp				√		
83	24	*Pisonia grandis* R. Br.	Piso_gr				√		
84	1	*Sterculia macrophylla* Vent.	Ster_ma					√	
85	2	*Nageia wallichiana* (C.Presl) Kuntze	Nage_wa					√	
86	3	*Pometia acuminata* Radlk.	Pome_ac					√	
87	4	*Horsfieldia irya* (Gaertn.) Warb.	Hors_ir					√	
88	5	*Canarium hirsutum* Willd.	Cana_hi					√	
89	6	*Hopea iriana* Slooten	Hope_ir					√	
90	7	*Elaeocarpus* sp.	Elae_sp					√	
91	8	*Vatica rassak* Blume	Vati_ra					√	
92	9	*Canarium asperum* Benth.	Cana_as					√	
93	10	*Hopea celtidifolia* Kosterm.	Hope_ce					√	
94	11	*Gymnacranthera farquhariana* (Hook.f. & Thomson) Warb.	Gymn_fa					√	
95	12	*Planchonella anteridifera* (C.T.White & W.D.Francis ex Lane-Poole) H.J.Lam	Plan_an					√	
96	13	*Melicope elleryana* (F. Muell.) T.G. Hartley	Meli_el					√	
97	14	*Anisoptera thurifera* subsp. *polyandra* (Blume) P.S.Ashton	Anis_th					√	
98	15	*Calophyllum caudatum* Kaneh. & Hatus.	Calo_ca					√	
99	16	*Terminalia copelandi* Elmer	Term_co.1					√	
100	17	*Alstonia spectabilis* R.Br.	Alst_sp					√	
101	18	*Blumeodendron tokbrai* (Blume) Kurz	Blum_to					√	
102	19	*Sloanea pulchra* (Schltr.) A.C.Sm.	Sloa_pu					√	
103	20	*Garcinia* sp.	Garc_sp					√	
104	21	*Gironniera subaequalis* Planch.	Giro_su					√	
105	22	*Pimelodendron amboinicum* Hassk.	Pime_am					√	
106	23	*Parastemon versteeghii* Merr. & L.M.Perry	Para_ve					√	
107	24	*Lithocarpus rufovillosus* (Markgr.) Rehder	Lith_ru					√	
108	25	*Sundacarpus amarus* (Blume) C.N.Page	Sund_am					√	
109	26	*Knema* sp.	Knem_sp					√	
110	27	*Endiandra* sp.	Endi_sp					√	
111	28	*Campnosperma brevipetiolatum* Volkens	Camp_br					√	
112	29	*Prunus javanica* (Teijsm. & Binn.) Miq.	Prun_ja					√	
113	30	*Planchonella keyensis* H.J.Lam	Plan_ke					√	
114	31	*Syzygium anomalum* Lauterb.	Syzy_an					√	
115	32	*Cinnamomum* sp.	Cinn_sp					√	
116	33	*Halfordia kendack* Guillaumin	Half_ke					√	
117	34	*Planchonia careya* (F.Muell.) R.Knuth	Plan_ca					√	

Table 1 Continued

No		Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
118	35	*Endiandra rubescens* (Blume) Miq.	Endi_ru					√	
119	36	*Homalium foetidum* Benth	Homa_fo					√	
120	37	*Virola surinamensis* (Rol. ex Rottb.) Warb.	Viro_su					√	
121	38	*Cananga odorata* (Lam.) Hook.f. & Thomson	Cana_od					√	
122	39	*Grewia eriocarpa* Juss.	Grew_er					√	
123	1	*Barringtonia* sp.	Barr_sp						√
124	2	*Cochlospermum gillivraei* Benth.	Coch_gi						√
125	3	*Gluta papuana* Ding Hou	Glut_pa						√
126	4	*Maranthes* sp	Mara_sp						√
127	5	*Syzygium branderhorstii* Lauterb.	Syzy_br						√

Those species existed in each forest group (unlogged, one year, five years, ten years and fifteen years post selectively-logged). Patterns of tree communities were formed for each forest group, especially for understory mostly occurred after logging activities. Upperstory were mainly recruited from understory of remnant trees. Several upperstory species were present before logging activities occurred in the forests. Our study presented the results of understory and upperstory communities influenced by logging activities and edaphic conditions.

There were three patterns established in our study i.e. 1. tree species formed a tree community in a forest group; 2. tree species present in all forest groups; and 3. tree species did not form a community. Presence of certain tree species as understory in all forest groups was facilitated by ecological alterations, including logging activities. Several tree species existed in all forest groups indicating that those tree species were not influenced by ecological alterations.

Distribution of understory tree community was depicted using CCA having 55.34% of the variation for two axes; variation for axis 1 was 30% and variation for axis 2 was 25.34% (Fig. 3; Table 2). ANOVA showed that the model was significant with $p < 0.05$.

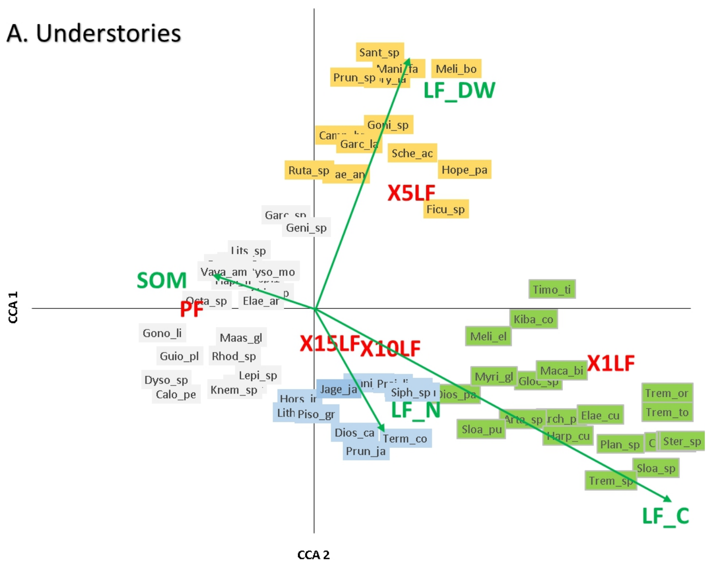

Figure 3 Understory of four tree communities formed due to logging activities symbolized as grey (species grown in PF), green (species grown in X1LF), yellow (species grown in X5LF) and blue (species grown in X10LF-X15LF)

Note: PF = unlogged forest; X1LF = one year post selectively-logged forest; X5LF = five years post selectively-logged forest; X10LF = ten years post selectively-logged forest; X15LF = fifteen years post selectively-logged forest; SOM = Soil Organic Matter (%); LF_C = Carbon content in litterfall (%); LF_N = Nitrogen content in litterfall (%); LF_DW = dry weight of litterfall (g)

Table 2 Summary of Canonical Correspondence Analysis (CCA) for understory tree community

Importance of components	Axes		Total Inertia
	CCA1	CCA2	
Eigenvalue	0.2152	0.1818	0.7175
Proportion explained	0.3	0.2534	
Cumulative proportion	0.3	0.5534	

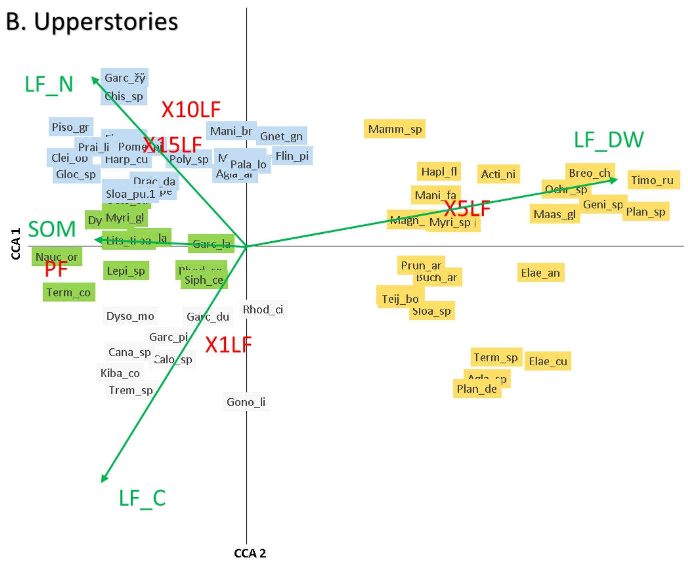

Figure 4 Upperstory of four tree communities formed due to logging activities symbolized as grey (species grown in PF), green (species grown in X1LF), yellow (species grown in X5LF) and blue (species grown in X10LF-X15LF)
Note: PF = unlogged forest; X1LF = one year post selectively-logged forest; X5LF = five years post selectively-logged forest; X10LF = ten years post selectively-logged forest; X15LF = fifteen years post selectively-logged forest; SOM = Soil Organic Matter (%); LF_C = Carbon content in litterfall (%); LF_N = Nitrogen content in litterfall (%); LF_DW = dry weight of litterfall (g)

Table 3 Summary of Canonical Correspondence Analysis (CCA) for upperstory tree community

Importance of components	Axes		Total Inertia
	CCA1	CCA2	
Eigenvalue	0.1961	0.1697	0.6277
Proportion explained	0.3124	0.2703	
Cumulative proportion	0.3124	0.5826	

Canonical Correspondence Analysis (CCA) grouped the understory tree species into four tree communities i.e. 28 species in the unlogged forest; 21 species in the one year post selectively-logged forest; 21 species in the five years post selectively-logged forest and 17 species in the ten and fifteen years post selectively-logged forest (Table 1a). Distribution of upperstory tree community was shown of having variation of two axes of 58.26% with 31.24% variation for axis 1 and 27.03% variation for axis 2 (Fig. 4; Table 3). The CCA model was significant at $p < 0.05$.

Edaphic Factors

Interactions among SOM, C content, N content, dry weight of litterfall and forest groups (unlogged, one year, five years, ten years and fifteen years post selectively-logged forests) were analyzed using CCA to figure out the fitting edaphic factors as the indicators of logged forest recovery. Results of CCA showed that SOM tended to be higher in the unlogged forest, dry weight of litterfall tended to be higher in the five years post selectively-logged forest and C content of litterfall was higher in the one-year post selectively-logged forest (Fig. 3 & 4; Table 4).

Based on this analysis, the ten and fifteen years post selectively-logged forests were still in the recovery process, indicated by lower SOM content in those two logged forests compared to

Table 4 ANOVA of CCA to analyze interactions among SOM, C content, N content, dry weight of litterfall and forest groups (unlogged, one year, five years, ten years and fifteen years post selectively-logged forests)

Edaphic factors	Df	Sums of square	Mean square	F.Model	R^2	P	
SOM	1	0.746	0.74644	2.438868	0.01442	0.001	*
LF_C	1	0.692	0.6916	2.259688	0.01336	0.001	*
LF_N	1	0.543	0.54259	1.772822	0.01048	0.005	*
LF_DW	1	0.795	0.79469	2.596517	0.01536	0.001	*
Residuals	161	49.27566	0.30606		0.94638		
Total	165	52.05166			1		

Note: *= significant at $p < 0.05$

the unlogged forest. In contrast, dry weight of litterfall tended to be higher in all logged forests. These results were not in line with research results obtained from logged Bornean rainforest, in which one year post-logged forest produced less litterfall compared to that in the Bornean primary forest. The amount of litterfall in Bornean primary forest was similar to those in the Bornean five years post-logged forest (Prasetyo *et al.* 2015). This condition suggested that responses of logged forests were depended on ecological circumstances. Furthermore, specific silvicultural treatments should be designed carefully by considering forest condition.

Ecological Changes as a Response to Selective Logging

Tree communities in the unlogged forest were different from those in the logged forests. The differences were due to ecological changes caused by logging activities resulted in alteration of species composition (Arbainsyah *et al.* 2014; Verburg & van Eijk-Bos 2003; Lozada *et al.* 2012), tree density (Decocq *et al.* 2014), tree growth rate (Murdjoko *et al.* 2016b) and association patterns among biotic factors, light availability, ambient moisture, temperature, soil properties and litterfall stock as abiotic factors (Murdjoko *et al.* 2016c). Tree communities were formed as responses of each tree characteristics toward different ecological circumstances in logged forests. Understory and upperstory tree communities had different reactions toward ecological changes (Murdjoko *et al.* 2016a; Zhu *et al.* 2015b). Therefore, there were understory and upperstory tree communities consisted of the same species. Tree communities consisted of seedlings and saplings stages that required more light (Karsten *et al.* 2014; Flores *et al.* 2014). This is the reason why logged forests had altered tree compositions compared to those in the primary forest. Each logged forest has different species composition of the understory tree community. Species composition of the understory tree community was different among the logged forests. Understory tree community in the one year post selectively-logged forest had very different species composition compared to those in the unlogged forest (Fig. 3). Understory tree community in the five years post selectively-logged forest had very different species composition compared to those in the ten and fifteen years post selectively-logged forests (Fig. 3). These differences in species composition were influenced by changes in environmental conditions (Corrià-Ainslie *et al.* 2015; Schnitzer & Walter 2013; Duah-Gyamfi *et al.* 2014).

The CCA showed that understory tree community in the one year post selectively-logged forest was mainly influenced by Carbon content of litterfall. Understory tree community in the five years post selectively-logged forest was formed as a response toward dry weight of litterfall. The nitrogen content of litterfall affected the establishment of understory tree community in the ten and fifteen years post selectively-logged forests. Understory tree community in the unlogged forest was influenced by SOM content. Alterations of soil characteristics in the logged forests were caused by the change of microclimate conditions (Asase *et al.* 2014; Imai *et al.* 2012). Logging activities were responsible for the widening canopy gap leading to the increase of light availability toward understory tree community (Schwartz 2016). Logging activities were also responsible for the decrease of tree density causing the changes in tree growth rates (Verburg & van Eijk-Bos 2003; Cannon *et al.* 1998; Do *et al.* 2016). These conditions triggered space and light competitions among tree species, especially in the seedlings and saplings stages(Laurans *et al.* 2014).

Upperstory tree community had different patterns from the understory tree community. In the unlogged forest, species composition of understory was different from that of upperstory tree community. Conspecific association occurred in the unlogged forest. Not all species grown in the understory tree community grew in the upperstory tree community of unlogged forest (Murdjoko *et al.* 2016a). Ecological condition occurred in the upperstory tree community was similar to that in the understory tree community. Trees in tropical forest experienced more diameter growth in the upperstory tree community (Zhu *et al.* 2015a). Upperstory tree community in the unlogged forest had very different species composition compared to those in the five years post selectively-logged forest (Fig. 4). However, similar species composition was observed among upperstory tree communities in the unlogged forest, one year post selectively-logged forest, ten and fifteen years post selectively-logged forests (Fig. 4). Tree species located in the five years post selectively-logged forest was the results of species competition caused by the change of ecological conditions. Thus, the current species were not the same as the previous species because of the duration of the ecological process. Upperstory tree community in the logged forests showed a dynamic establishment of tree community. Each species had different growth rate as a response to logging impact (Murdjoko *et al.* 2016b). Some species had higher population growth rate than others leading to higher survival rate (Murdjoko 2013; Zuidema *et al.* 2009). Although recovery process was seen to be happening in the ten and fifteen years post selectively-logged forests, the process still requires more time to reach the fully recovered stage.

Implication of Ecological Approach for Sustainable Forest Management

This study proposed an ecological approach to determine whether logged forests were recovered in fifteen years. Existing tree communities and edaphic factors, especially SOM, in the unlogged forest were used as a reference of logged forest reaching recovered condition. SOM plays an important role to support nutrient absorption in soil (Mutiso *et al.* 2013). The soil of South Papua is mainly classified as Ultisols, so the characteristic of soil is infertile (Marshall & Beehler 2012). Selective logging activities did not seem to totally change ecological condition. The logged forest was declared to be fully recovered when its conditions had reached similar condition as those in unlogged (primary) forest, especially in terms of ecological aspects such as the content of SOM, stem density and species composition. Therefore, it is imperative to set permanent sample plots in the unlogged (primary) and logged forests, to conduct intensive and persistent monitoring of ecological conditions and tree growth (Krisnawati & Wahjono 2010; Ruslandi *et al.* 2017a; Ruslandi *et al.* 2017b). The monitoring results would be valuable as basic information to further evaluate the silviculture protocol. Useful modifications could be designed by taking ecological perspective into account.

CONCLUSIONS

Understory and upperstory tree communities formed different patterns due to logging activities. Species composition existed in the tree communities in the ten and fifteen years post selectively-logged forests were not similar to that in the unlogged forest, meaning that the logged forests were still in the recovery process. SOM content in the logged forest was lower compared to that in the unlogged forest, indicating that the logged forests were not fully recovered. These occurrences indicated that it took more than fifteen years for the logged forests to be fully recovered. Long-term studies are necessary to continuously monitor the ecological process in the logged forest in reaching the recovery stage. The recorded influential ecological factors obtained from this study can be used as indicators for logged forest recovery.

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