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 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

*Corresponding author: agustinus.murdjoko.papua@gmail.com 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 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.* 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 $140^{\circ}21$ ` – $140^{\circ}59$ ` E and $05^{\circ}50$ ` – $06^{\circ}42$ ` 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 selectivelylogged, 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 \geq 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 Kebutanan (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

N)	Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
1	1	Calophyllum peekelii Lauterb.	Calo_pe						
2	2	Knema sp.	Knem_sp	\checkmark					
3	3	Gonocaryum litorale (Blume) Sleumer	Gono_li						
4	4	Alstonia scholaris (L.) R. Br.	Alst_sc	\checkmark					
5	5	Guioa pleuropteris (Blume) Radlk.	Guio_pl	\checkmark					
6	6	Dysoxylum sp.	Dyso_sp	\checkmark					
7	7	Lepisanthes sp.	Lepi_sp						
8	8	Rhodomyrtus sp.	Rhod_sp	\checkmark					
9	9	Maasia glauca (Hassk.) Mols, Kessler & Rogstad	Maas_gl	\checkmark					
10	10	Octamyrtus sp.	Octa_sp	\checkmark					
11	11	Chisocheton sp.	Chis_sp						
12	12	Elaeocarpus arnhemicus F.Muell.	Elae_ar	\checkmark					
13	13	Haplolobus floribundus (K.Schum.) H.J.Lam	Hapl_fl	\checkmark					

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

N	0	Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
14	14	Brackenridgea sp.	Brac_sp.1						
15	15	Litsea sp.	Lits_sp	\checkmark					
16	16	Dysoxylum mollissimum Blume	Dyso_mo	\checkmark					
17	17	Antiaris toxicaria Lesch.	Anti_to	\checkmark					
18	18	Ficus variegata Blume	Ficu_va	\checkmark					
19	19	Gyrinops versteegii (Gilg) Domke	Gyri_ve	\checkmark					
20	20	Litsea guppyi (F. Muell.) F. Muell. ex Forman	Lits_gu	\checkmark					
21	21	Maranthes corymbosa Blume	Mara_co	\checkmark					
22	22	Mastixiodendron sp.	Mast_sp	\checkmark					
23	23	Vavaea amicorum Benth.	Vava_am	\checkmark					
24	24	Calophyllum caudatum Kaneh. & Hatus.	Calo_ca	\checkmark					
25	25	Parastemon versteeghii Merr. & L.M.Perry	Para_ve	V					
26	26	Calophyllum laticostatum P.F.Stevens	Calo_la	V					
27	27	Garcinia sp.	Garc_sp	V					
28	28	Gemostoma sp.	Geni_sp	N					
29	1	Sloanea pulchra (Schltr.) A.C.Sm.	Sloa_pu		N				
30	2	Canarium sp.	Cana_sp		N				
31	3	<i>Horsfieldia</i> sp.	Hors_sp		N				
32	4	Melicope sp.	Meli_sp		N				
33	5	<i>Sterculia</i> sp.	Ster_sp		N				
34	6	Trema orientalis (L.) Blume	Trem_or		N				
35	7	Trema sp.	Trem_sp		N				
36	8	Trema tomentosa (Roxb.) H. Hara	Trem_to		N				
37	9	Harpulha cupanioides Roxb.	Harp_cu		N				
38	10	Sloanea sp.	Sloa_sp		N				
39	11	Planchonella sp.	Plan_sp		N				
40	12	Artabotrys sp.	Arta_sp		N,				
41	13	Archidendron parinflorum Pulle	Arch_pa		N				
42	14	<i>Elaeocarpus culminicola</i> Warb.	Elae_cu		V				
43	15	<i>Diospyros papuana</i> Valeton ex Bakh.	Dios_pa		\checkmark				
44	16	Myristica globosa Warb.	Myri_gl		\checkmark				
45	17	Glochidion sp.	Gloc_sp		\checkmark				
46	18	Macaranga bifoveata J.J.Sm.	Maca_bi		\checkmark				
47	19	Melicope elleryana (F. Muell.) T.G. Hartley	Meli_el		\checkmark				
48	20	Kibara coriacea (Blume) Hook. f. & A. Thomps.	Kiba_co		\checkmark				
49	21	Timonius timon (Spreng.) Merr.	Timo_ti		\checkmark				
50	1	<i>Нореа рариапа</i> Diels	Hope_pa			\checkmark			
51	2	Elaeocarpus angustifolius Blume	Elae_an			\checkmark			
52	3	Ficus sp.	Ficu_sp			\checkmark			
53	4	R <i>uta</i> sp.	Ruta_sp			\checkmark			
54	5	Garcinia latissima Miq.	Garc_la			\checkmark			
55	6	Schefflera actinophylla (Endl.) Harms	Sche_ac			\checkmark			
56	7	Campnosperma brevipetiolatum Volkens	Camp_br			\checkmark			
57	8	Goniothalamus sp.	Goni_sp			\checkmark			
58	9	Corynocarpus laevigatus J.R.Forst. & G.Forst.	Cory_la			\checkmark			
59	10	Adenanthera pavonina L.	Aden_pa			\checkmark			
60	11	Aglaia spectabilis (Miq.) S.S.Jain & S.Bennet	Agla_sp			\checkmark			
61	12	Dillenia alata (R.Br. ex DC.) Banks ex Martelli	Dill_al			\checkmark			
62	13	Dillenia indica L.	Dill_in						
63	14	Diospyros sp.	Dios_sp			\checkmark			
64	15	Fagraea sp.	Fagr_sp			\checkmark			
65	16	Flindersia pimenteliana F.Muell.	Flin_pi			\checkmark			
66	17	Gynotroches sp.	Gyno_sp			\checkmark			
67	18	Manilkara fasciculata (Warb.) H.J.Lam & Maas Geest.	Mani_fa			\checkmark			

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85 15 Prachine Margaba (Mkg) Beume es K.Heyne PraL h \vee 86 16 Mania Larmas Mani, Lr \vee 87 17 Jegen jamular (Blume) Kalkman Jage_ja \checkmark 88 1 Commine Biosynam Wild. Cans_hi \checkmark 89 2 Populatia sp. Poly.sp \checkmark 90 3 Virols intrinamesii (Rol. ex Roth) Warb. Viro.su \checkmark 91 4 Plandomilia materidipin (C.T.White & W.D.Francis ex Lane-Poole) Plan_an \checkmark 91 5 Diracotomola da (Blanco) Merr. & Rotife Dirac, da \checkmark 92 5 Diracotomola da (Blanco) Merr. & Rotife Dirac, da \checkmark 93 6 Magnafia triampaca (L.) Fight & Noot. Magn_1s \checkmark 94 7 Actination biologia Teschner Actination biologia (Roth) Mild. Arg. Viet 95 8 Senecarbur popuma Latterb. Seys_an \checkmark 95 10 Cristanthar oblogigian (Roxb.) Mill.Arg. Cicl_ob \checkmark 96 9 Plandomilia keyresir H.J.Lam Plan_ke	84	14	Gluta papuana Ding Hou	Glut_pa				V		
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892Polyatha sp.PolyathaV903Vinela sirianamati (Rol. ex Roth) Warb.Viro_suVi914Planeboella anticridijra (C.T.White & W.D.Francis ex Lane-Poole) H.J.LamPlan_anVi936Magnetic riticmpaca (L.) Figlar & Noot.Magn_tsVi936Magnetic riticmpaca (L.) Figlar & Noot.Magn_tsVi947Artinodophue inkla TeschnerArtinodophue inkla TeschnerVi958Semearpus papuana Lauterb.Seme_paVi969Planchonella keynsir H.J.LamPlan_keVi9710Syrggium anonadum Lauterb.Syrg_anVi9811Chinatibus oblogifulus (Rosb) Müll.Arg.Clei_obVi9912Homatium fortidum BenthHom_afoVi10114Canariun indicam LCana_inVi10215Pinnekamon ankinicum Hask.Pinne_amVi10316Blomeodendron tokini (Blumc) KurzBlum_toVi10417Aglia arguton taken (Blume) KurzMamm_spVi10518Gnetun gnoon LGnet_gnVi10619Mammes sp.Neol_spVi10720Vatica rusuk BlumeKat_aspVi10821Fagras rusemia JackFagr_raVi10922Steratha thilingkari F.Muell,Ster_shVi11023Neolitera sp.Lad_spVi11124	88	1	Canarum hirsutum Willd.	Cana_hi					v	.1
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103 16 Blumeodendrom tokbrai (Blume) Kurz Blum_to N 104 17 Aglaia argentea Blume Agla_ar N 105 18 Gnetum gnemon L. Gnet_gn N 106 19 Mammea sp. Mamm_sp N 107 20 Vatica rassak Blume Vati_ra N 108 21 Fagraea racemosa Jack Fagr_ra N 109 22 Sterulia sbillinglawii F.Muell. Ster_sh N 110 23 Neolitsea sp. Neol_sp N 111 24 Elaeocarpus sp. Elae_sp N 112 25 Endiandra rubescens (Blume) Miq. Endi_ru N 113 26 Endiandra sp. Endi_sp N 114 27 Hopea iriana Slooten Hope_ir N 115 28 Prunus arborea (Blume) Kalkman Prun_ar N 116 29 Lasianthus sp. Lasi_sp N 117 30 Terminalia copelandi Elmer Term_co.1 N 118 <td< td=""><td>102</td><td>15</td><td>Pimelodendron amboinicum Hassk.</td><td>Pime_am</td><td></td><td></td><td></td><td></td><td></td><td>V</td></td<>	102	15	Pimelodendron amboinicum Hassk.	Pime_am						V
10417Aglaia argentea BlumeAgla_ar $$ 10518Gnetum gnemon L.Gnet_gn $$ 10619Mammea sp.Mamm_sp $$ 10720Vatica rassak BlumeVati_ra $$ 10821Fagraea racemosa JackFagr_ra $$ 10922Sterulia sbillinglawii F.Muell.Ster_sh $$ 10023Neolitsea sp.Ncol_sp $$ 11124Elaeocarpus sp.Elae_sp $$ 11225Endiandra rubescens (Blume) Miq.Endi_ru $$ 11326Endiandra sp.Endi_sp $$ 11427Hopea iriana SlootenHope_ir $$ 11528Prunus arborea (Blume) KalkmanPrun_ar $$ 11629Lasianthus sp.Lasi_sp $$ 11730Terminalia copelandi ElmerTerm_co.1 $$ 11831Sundacarpus amarus (Blume) C.N.PageSund_am $$ 11932Chisocheton ceramicus Miq.Chis_cce $$ 12033Teiismanniodendron beeoriense Koord.Teii bo $$	103	16	Blumeodendron tokbrai (Blume) Kurz	Blum_to						N
10518Gnetum gnemon L.Gnet_gnN10619Mammea sp.Mamm_spN10720Vatica rassak BlumeVati_raN10821Fagraea racemosa JackFagr_raN10922Sterulia sbillinglawii F.Muell.Ster_shN10023Neolitsea sp.Neol_spN11124Elaeocarpus sp.Elae_spN11225Endiandra rubescens (Blume) Miq.Endi_ruN11326Endiandra sp.Endi_spN11427Hopea iriana SlootenHope_irN11528Prunus arborea (Blume) KalkmanPrun_arN11629Lasianthus sp.Lasi_spN11730Terminalia copelandi ElmerTerm_co.1N11831Sundacarpus amarus (Blume) C.N.PageSund_amN11932Chisocbeton ceramicus Miq.Chis_ceN12033Teiismanniodendron beopriense Koord.Teii boN	104	17	Aglaia argentea Blume	Agla_ar						N
10619Mammea sp.Mammea sp.N10720Vatica rassak BlumeVati_ra $$ 10821Fagraea racemosa JackFagr_tra $$ 10922Sterculia sbillinglanii F.Muell.Ster_sh $$ 10023Neolitsea sp.Neol_sp $$ 11124Elaeocarpus sp.Elae_sp $$ 11225Endiandra rubescens (Blume) Miq.Endi_ru $$ 11326Endiandra sp.Hope_ir $$ 11427Hopea iriana SlootenHope_ir $$ 11528Prunus arborea (Blume) KalkmanPrun_ar $$ 11629Lasianthus sp.Lasi_sp $$ 11730Terminalia copelandi ElmerTerm_co.1 $$ 11831Sundacarpus amarus (Blume) C.N.PageSund_am $$ 11932Chisocheton ceramicus Miq.Chis_ce $$ 12033Teiismanniodendran beoriense Koord.Teii bo $$	105	18	Gnetum gnemon L.	Gnet_gn						N
10720 V atta rassak Blume \forall atta rassak Blume \forall 10821Fagraea racemosa JackFagr_ra $$ 10922Sterculia shillinglavii F.Muell.Ster_sh $$ 11023Neolitsea sp.Ncol_sp $$ 11124Elaeocarpus sp.Elae_sp $$ 11225Endiandra rubescens (Blume) Miq.Endi_ru $$ 11326Endiandra sp.Endi_sp $$ 11427Hopea iriana SlootenHope_ir $$ 11528Prunus arborea (Blume) KalkmanPrun_ar $$ 11629Lasianthus sp.Lasi_sp $$ 11730Terminalia copelandi ElmerTerm_co.1 $$ 11831Sundacarpus amarus (Blume) C.N.PageSund_am $$ 11932Chisocheton ceramicus Miq.Chis_ce $$ 12033Teiismanniodendron boeoriense Koord.Teii bo $$	106	19	Mammea sp.	Mamm_sp						N
10821Fagrae racemosa JackFagr_ra \vee 10922Sterculia shillinglawii F.Muell.Ster_sh \vee 11023Neolitsea sp.Neol_sp \vee 11124Elaecarpus sp.Elae_sp \vee 11225Endiandra rubescens (Blume) Miq.Endi_ru \vee 11326Endiandra sp.Endi_sp \vee 11427Hopea iriana SlootenHope_ir \vee 11528Prunus arborea (Blume) KalkmanPrun_ar \vee 11629Lasianthus sp.Lasi_sp \vee 11730Terminalia copelandi ElmerTerm_co.1 \vee 11831Sundacarpus amarus (Blume) C.N.PageSund_am \vee 11932Chisocheton ceramicus Miq.Chis_ce \vee 12033Teitsmanniodendron beopriense Koord.Teit bo \vee	107	20	V atica rassak Blume	Vati_ra						N
10922Steruna solutingiann F.Muell.Ster_sh \vee 11023Neolisea sp.Neol_sp $$ 11124Elaeocarpus sp.Elae_sp $$ 11225Endiandra rubescens (Blume) Miq.Endi_ru $$ 11326Endiandra sp.Endi_sp $$ 11427Hopea iriana SlootenHope_ir $$ 11528Prunus arborea (Blume) KalkmanPrun_ar $$ 11629Lasianthus sp.Lasi_sp $$ 11730Terminalia copelandi ElmerTerm_co.1 $$ 11831Sundacarpus amarus (Blume) C.N.PageSund_am $$ 11932Chisocheton ceramicus Miq.Chis_cce $$ 12033Teitsmanniodendron beopriense Koord.Teit bo $$	108	21	Fagraea racemosa Jack	Fagr_ra						N
11025Neonized sp.Neonized sp.Neonized sp.11124Elaeocarpus sp.Elae_sp $$ 11225Endiandra rubescens (Blume) Miq.Endi_ru $$ 11326Endiandra sp.Endi_sp $$ 11427Hopea iriana SlootenHope_ir $$ 11528Prunus arborea (Blume) KalkmanPrun_ar $$ 11629Lasianthus sp.Lasi_sp $$ 11730Terminalia copelandi ElmerTerm_co.1 $$ 11831Sundacarpus amarus (Blume) C.N.PageSund_am $$ 11932Chisocheton ceramicus Miq.Chis_ce $$ 12033Teitsmanniodendron beopriense Koord.Teit bo $$	1109	22	Steretuna sinungiann F.Muen.	Ster_sn						N
111 24 Endeodarphi s.p. Endeodarphi s.p. V 112 25 Endiandra rubescens (Blume) Miq. Endi_ru √ 113 26 Endiandra sp. Endi_sp √ 114 27 Hopea iriana Slooten Hope_ir √ 115 28 Prunus arborea (Blume) Kalkman Prun_ar √ 116 29 Lasianthus sp. Lasi_sp √ 117 30 Terminalia copelandi Elmer Term_co.1 √ 118 31 Sundacarpus amarus (Blume) C.N.Page Sund_am √ 119 32 Chisocheton ceramicus Miq. Chis_ce √ 120 33 Teijsmanniodendron beopriense Koord. Teij bo √	111	23	Elegesettus en	Flag. sp						N
1122.5Endiandra investeris (Bluffic) Shiq.Endi_nu11326Endiandra sp.Endi_sp $$ 11427Hopea iriana SlootenHope_ir $$ 11528Prunus arborea (Blume) KalkmanPrun_ar $$ 11629Lasianthus sp.Lasi_sp $$ 11730Terminalia copelandi ElmerTerm_co.1 $$ 11831Sundacarpus amarus (Blume) C.N.PageSund_am $$ 11932Chisocheton ceramicus Miq.Chis_ce $$ 12033Teijsmanniodendron beopriense Koord.Teij bo $$	111	24	Endiandra subassans (Bluma) Mia	Endi m						N
111 27 Hopea iriana Slooten Hope_ir √ 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 beooriense Koord. Teij bo √	113	26	Endiandra sp	Endi sp						V
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 beopriense Koord. Teij bo √	114	27	Hatea iriana Slooten	Hope ir						V
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 beopriense Koord. Teij bo √	115	28	Prunus arborea (Blume) Kalkman	Prun ar						v
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 Teitsmanniodendron boeoriense Koord. Teit bo √	116	29	Lasianthus sp.	Lasi sp						, V
118 31 Sundacarpus amarus (Blume) C.N.Page Sund_am √ 119 32 Chisocheton ceramicus Miq. Chis_ce √ 120 33 Teijsmanniodendron beooriense Koord. Teij bo √	117	30	Terminalia copelandi Elmer	Term co.1						, √
119 32 Chisocheton ceramicus Miq. Chis_ce √ 120 33 Teijsmanniodendron boeoriense Koord. Teij bo √	118	31	Sundacarpus amarus (Blume) C.N.Page	Sund_am						V
120 33 Teiismanniodendron bogoriense Koord. Teii bo	119	32	Chisocheton ceramicus Mig.	Chis ce						\checkmark
	120	.33	Teiismanniodendron bogoriense Koord.	Teij bo						

Table 1 Continued

Ne	5	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					\checkmark	
123	36	Cynometra ramiflora L.	Cyno_ra						
124	37	Canarium asperum Benth.	Cana_as					\checkmark	
125	38	Alstonia spectabilis R.Br.	Alst_sp					\checkmark	
126	39	Gymnacranthera farquhariana (Hook.f. & Thomson) Warb.	Gymn_fa					\checkmark	
127	40	Grewia sp.	Grew_sp					\checkmark	
128	41	Pometia acuminata Radlk.	Pome_ac					\checkmark	
129	42	Halfordia kendack Guillaumin	Half_ke					\checkmark	
130	43	Timonius rufescens (Miq.) Boerl.	Timo_ru					\checkmark	
131	44	Siphonodon celastrineus Griff.	Siph_ce					\checkmark	
132	45	Palaquium lobbianum Burck	Pala_lo					\checkmark	
133	46	<i>Grewia</i> eriocarpa Juss.	Grew_er					\checkmark	
134	47	Gynotroches axillaris Blume	Gyno_ax					\checkmark	
135	48	Planchonia careya (F.Muell.) R.Knuth	Plan_ca					\checkmark	
136	49	<i>Myristica</i> 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					\checkmark	
143	1	Adenanthera novo-guineensis Baker f.	Aden_no						N
144	2	Anisoptera thurifera subsp. polyandra (Blume) P.S.Ashton	Anis_th						\checkmark
145	3	Brachychiton sp.	Brac_sp						\checkmark
146	4	Calophyllum sp.	Calo_sp						\checkmark
147	5	Carallia brachiata (Lour.) Merr.	Cara_br						\checkmark
148	6	Celtis latifolia (Blume) Planch.	Celt_la						\checkmark
149	7	Cerbera floribunda K.Schum.	Cerb_fl						\checkmark
150	8	Diospyros pilosanthera Blanco	Dios_pi						\checkmark
151	9	Garcinia dulcis (Roxb.) Kurz	Garc_du						\checkmark
152	10	Maniltoa plurijuga Merr. & L.M.Perry	Mani_pl						\checkmark
153	11	Nageia wallichiana (C.Presl) Kuntze	Nage_wa						\checkmark
154	12	Santiria rubiginosa Blume	Sant_ru						\checkmark
155	13	Schizomeria katastega Mattf.	Schi_ka						\checkmark
156	14	Spathiostemon javensis Blume	Spat_ja						\checkmark
157	15	Sterculia macrophylla Vent.	Ster_ma						\checkmark
158	16	Terminalia sp.	Term_sp						\checkmark
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	\checkmark					
2	2	Siphonodon celastrineus Griff.	Siph_ce	\checkmark					
3	3	Lepisanthes sp.	Lepi_sp						
4	4	Rhodomyrtus sp.	Rhod_sp	\checkmark					
5	5	Garcinia latissima Miq.	Garc_la						
6	6	Alphitonia incana (Roxb.) Teijsm. & Binn. ex Kurz	Alph_in	\checkmark					
7	7	Dysoxylum sp.	Dyso_sp	\checkmark					
8	8	<i>Fagraea racemosa</i> Jack	Fagr_ra	\checkmark					
9	9	Flacourtia inermis Roxb.	Flac_in	\checkmark					
10	10	Guioa pleuropteris (Blume) Radlk.	Guio_pl	\checkmark					
11	11	Hopea papuana Diels	Hope_pa	\checkmark					

Table 1	Continued
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Ne	С	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	\checkmark					
17	1	<i>Trema</i> sp.	Trem_sp						
18	2	Gonocaryum litorale (Blume) Sleumer	Gono_li		\checkmark				
19	3	Kibara coriacea (Blume) Hook. f. & A. Thomps.	Kiba_co		\checkmark				
20	4	Canarium sp.	Cana_sp		\checkmark				
21	5	<i>Garcinia</i> picrorhiza Miq.	Garc_pi		\checkmark				
22	6	Dysoxylum mollissimum Blume	Dyso_mo		\checkmark				
23	7	Rhodamnia cinerea Jack	Rhod_ci		\checkmark				
24	8	Garcinia dulcis (Roxb.) Kurz	Garc_du		\checkmark				
25	9	Calophyllum sp.	Calo_sp		\checkmark				
26	1	Aglaia spectabilis (Mig.) S.S.Jain & S.Bennet	Agla sp						
27	2	Brackenridgea sp.	Brac sp						
28	3	Elaeocarbus culminicola Warb.	Elae cu						
29	4	Eagraged sp	Faor sp			Ń			
30	5	Flindersia amhainensis Poir	Flin am			ا			
31	6	Planchonella densinervia (K Krause) H I Lam	Plan de			Ń			
32	7	Terminalia sp	Term sp			J			
33	8	Slamea sp.	Sloa sp			J			
34	9	Teiismanniadendran baaariense Koord	Teij bo			1			
35	10	Canarium indicum I	Capa in			1			
36	11	Buchanania arhemerans (Blume) Blume	Buch ar			N			
37	12	Elessantus anostifolius Blume	Elee en			N			
20	12	Endeocarpus angustijonus Diutite	Diac_an			N al			
20	13	Maranna kifurata LI Sar	Prun_ar Masa hi			N			
39 40	14	Muitaranga byobeata J.J.Sm.	Maca_Di			N			
40	15	Myristica sp.	Myn_sp			N			
41	10	Magnona tstampacca (L.) Figiar & Noot.	Magn_ts			N			
42	1/	Massa glauca (Hassk.) Mols, Kessler & Rogstad	Maas_gi			N			
43	18	<i>Manikara fasciculata</i> (Warb.) H.J.Lam & Maas Geest.	Mani_fa			N			
44	19	Adenanthera pavonina L.	Aden_pa			N			
45	20	Alstonia scholaris (L.) R. Br.	Alst_sc			N			
46	21	Breoma chinensis (Lam.) Capuron	Breo_ch			N			
47	22	Corynocarpus laevigatus J.R.Forst. & G.Forst.	Cory_la			N			
48	23	Dillenia indica L.	Dill_in			N			
49	24	Diospyros pilosanthera Blanco	Dios_pi			N			
50	25	Genostoma sp.	Geni_sp			N			
51	26	Maasia sumatrana (Miq.) Mols, Kessler & Rogstad	Maas_su			N			
52	27	Ochrosia sp.	Ochr_sp			N			
53	28	Planchonella sp.	Plan_sp			N			
54	29	Siphonodon sp.	Siph_sp			N			
55	30	Syzygium acutangulum Nied.	Syzy_ac			N			
56	31	Timonius rufescens (Miq.) Boerl.	Timo_ru			V			
57	32	Actinodaphne nitida Teschner	Acti_ni			Ń			
58	33	Haplolobus floribundus (K.Schum.) H.J.Lam	Hapl_fl			V			
59	34	Mammea sp.	Mamm_sp			V			
60	1	Aglaia argentea Blume	Agla_ar				V		
61	2	Palaquium lobbianum Burck	Pala_lo				\checkmark		
62	3	Gnetum gnemon L.	Gnet_gn				\checkmark		
63	4	Maranthes corymbosa Blume	Mara_co				\checkmark		
64	5	Polyalthia sp.	Poly_sp				\checkmark		

Table 1 Continued

Ν	0	Species	Code	PF	X1LF	X5LF	X10LF X15LF	ALL	NON_AC
65	6	<i>Flindersia pimenteliana</i> F.Muell.	Flin_pi				\checkmark		
66	7	Maniltoa browneoides Harms	Mani_br				\checkmark		
67	8	Chisocheton sp.	Chis_sp				\checkmark		
68	9	Chisocheton ceramicus Miq.	Chis_ce				\checkmark		
69	10	Elaeocarpus arnhemicus F.Muell.	Elae_ar				\checkmark		
70	11	Ficus drupacea Thunb.	Ficu_dr				\checkmark		
71	12	Garcinia $ imes$ mangostana L.	Garc_žÿ				\checkmark		
72	13	Adenanthera novo-guineensis Baker f.	Aden_no				\checkmark		
73	14	Sloanea pullei O.C.Schmidt ex A.C.Sm.	Sloa_pu.1				\checkmark		
74	15	Calophyllum peekelii Lauterb.	Calo_pe				\checkmark		
75	16	Cynometra ramiflora L.	Cyno_ra				\checkmark		
76	17	Dracontomelon dao (Blanco) Merr. & Rolfe	Drac_da				\checkmark		
77	18	Prainea limpato (Miq.) Beumee ex K.Heyne	Prai_li				\checkmark		
78	19	Cleistanthus oblongifolius (Roxb.) Müll.Arg.	Clei_ob				\checkmark		
79	20	Glochidion sp.	Gloc_sp				\checkmark		
80	21	Harpullia cupanioides Roxb.	Harp_cu				\checkmark		
81	22	Pometia pinnata J.R.Forst. & G.Forst.	Pome_pi				\checkmark		
82	23	Ficus sp.	Ficu_sp				\checkmark		
83	24	Pisonia grandis R. Br.	Piso_gr				\checkmark		
84	1	Sterculia macrophylla Vent.	Ster_ma						
85	2	Nageia wallichiana (C.Presl) Kuntze	Nage_wa						
86	3	Pometia acuminata Radlk.	Pome_ac					\checkmark	
87	4	<i>Horsfieldia irya</i> (Gaertn.) Warb.	Hors ir						
88	5	<i>Canarium hirsutum</i> Willd.	_ Cana hi						
89	6	<i>Hopea iriana</i> Slooten	Hope ir						
90	7	Elaeocarbus 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 farauhariana (Hook.f. & Thomson) Warb.	Gvmn fa						
95	12	Planchonella anteridifera (C.T.White & W.D.Francis ex Lane-Poole) H.I.Lam	Plan_an					\checkmark	
96	13	Melicope elleryana (F. Muell.) T.G. Hartley	Meli_el						
97	14	Anisoptera thurifera subsp. polyandra (Blume) P.S.Ashton	Anis_th					\checkmark	
98	15	Calophyllum caudatum Kaneh. & Hatus.	Calo_ca					\checkmark	
99	16	Terminalia copelandi Elmer	Term_co.1					\checkmark	
100	17	Alstonia spectabilis R.Br.	Alst_sp					\checkmark	
101	18	Blumeodendron tokbrai (Blume) Kurz	Blum_to					\checkmark	
102	19	Sloanea pulchra (Schltr.) A.C.Sm.	Sloa_pu					\checkmark	
103	20	Garcinia sp.	Garc_sp						
104	21	Gironniera subaequalis Planch.	Giro_su					\checkmark	
105	22	Pimelodendron amboinicum Hassk.	Pime_am						
106	23	Parastemon versteeghii Merr. & L.M.Perry	Para_ve					\checkmark	
107	24	Lithocarpus rufovillosus (Markgr.) Rehder	Lith_ru						
108	25	Sundacarpus amarus (Blume) C.N.Page	Sund_am					\checkmark	
109	26	<i>Knema</i> sp.	Knem_sp						
110	27	<i>Endiandra</i> sp.	Endi_sp					\checkmark	
111	28	Campnosperma brevipetiolatum Volkens	Camp_br					\checkmark	
112	29	Prunus javanica (Teijsm. & Binn.) Miq.	Prun_ja					\checkmark	
113	30	Planchonella keyensis H.J.Lam	Plan_ke					\checkmark	
114	31	Syzygium anomalum Lauterb.	Syzy_an					\checkmark	
115	32	Cinnamomum sp.	Cinn_sp					\checkmark	
116	33	Halfordia kendack Guillaumin	Half_ke					\checkmark	
117	34	Planchonia careya (F.Muell.) R.Knuth	Plan_ca					\checkmark	

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

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; X10LF = fifteen years post selectively-logged forest; S0M = Soil Organic Matter (%); LF_C = Carbon content in litterfall (%); LF_N = Nitrogen content in litterfall (%); LF_DW = dry weight of litterfall (g)

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

Instruction of country or onto	A	Total In outin	
importance of components	CCA1	CCA2	Total merua
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; X11LF = fifteen years post selectively-logged forest; X10LF = 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 In outin	
	CCA1	CCA2	Total merua	
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

Edaphic factors	Df	Sums of square	Mean square	F.Model	\mathbb{R}^2	Р
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	

Table 4ANOVA 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)

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 selectivelylogged 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 selectivelylogged 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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