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Regeneration Potential of Woody Species at the Side of Secondary Roads Post-Logging of Loundoungou-Toukoulaka Forest Management Unit, Republic of the Congo

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Abstract

Natural regeneration is the basis of a dynamic and demographic balance of plant populations. The objective of this study was to assess the natural regeneration potential of woody species along secondary roads post-logging abandoned since 2008 and 2018. In the two Annual Allowable Cuts (AAC 2008 and AAC 2018), 24 regenerating sub-plots (*i.e.* 12 sub-plots for AAC 2008 and 12 sub-plots for AAC 2018) with a unit area of 5 m × 5 m were delimited with a total area of 0.06 ha (*i.e.* 0.03 ha for each AAC). The abundance and diversity of woody species were respectively inventoried and estimated. Two estimators of the specific richness were used to estimate the floristic diversity of each Annual Allowable Cuts (AAC). The results reveal globally 88 woody species in the AAC 2008 and 241 woody species in the AAC 2018, with respective average densities of 2933 stem/ha and 8033 stem/ha. There was a very highly significant difference between the mean densities of the two AAC (Kruskal-Wallis test; H = 2.36, p-value < 0.000). The results also highlight a great diversity and a relatively high abundance of woody species in the 2018 AAC compared to the 2008 AAC. Also, the spatial structuring of the sub-plots on the basis of Principal Component Analysis (PCA) demonstrates that the floristic composition of the two AAC is globally different. The study suggests silvicultural interventions and the long-term assessment of regenerating woody species along abandoned secondary roads in order to guarantee the sustainable management of their population.

Keywords

Regeneration Dynamics, Woody Species, Abandoned Secondary Roads, Forest Management Unit

1. Introduction

The central African moist forest form the second largest expanse of tropical forest in the world after the Amazon [1] [2]. These forest massifs now facing an increase in disturbances of anthropogenic origin (logging and mining, slash-and-burn agriculture, conversion, etc.) or climatic (dryness, change of rainfall regime, increase in their interannual variability) which will continue in the next decades [3] [4] [5]. A significant proportion of these forests (28%) is intended for the industrial production of wood. This activity is progressively expanding in view of its economic importance and its role in the development of Central African countries [2] [4].

Nonetheless, the industrial exploitation of wood from a forest massif can intervene at three levels: the creation of the base camp, the construction of one road network for the evacuation of timber and the realization of logging operations (cutting and skidding) [6] [7]. The establishment of one permanent and/or non-permanent road network corresponds to the destruction of about 5.5% - 8.5% of open forest area [8]. The edges of the secondary roads a few years after harvesting of timber abound a significant density of woody species which deserves refined knowledge in order to envisage sustainable management of their population. After logging activities, the natural regeneration processes are based on three compartments: the seminal advective potential, which corresponds to the seeds deposited on the ground, this is the seed rain; the seminal edaphic potential, which corresponds to the soil seed bank and the vegetative potential, which corresponds to the seedlings bank and/or the stems of future [9].

Nonetheless, if the literature exists on the soil seed bank in moist forests of Central Africa [10] [11] [12] [13]; seed rain is very little explored and more specifically in Cameroon [14]; the seedlings bank and/or stems future is the least well-documented compartment [15] [16]. Consequently, it is difficult to predict the regeneration potential and resilience of post-logging secondary roadside forests in the majority of logging concessions in Republic of Congo. Furthermore, studies relating to the regeneration potential (process based on forest reconstitution) integrate little the "seedlings bank and/or stems future" component which constitutes a reservoir of woody species and reflects the floristic composition of the vegetation from a place at a given time [17].

Knowledge of the floristic composition, density and diversity of woody species on the edges of post-logging secondary roads could provide precious data on the regeneration potential and/or resilience of logged forests [18] [19].

This study proposes to improve knowledge of the natural regeneration potential of woody species along post-logging secondary roads in the Loundoungou-Toukoulaka Forest Management Unit in the north of the Republic of Congo. Two following research hypotheses are formulated: 1) due to the different ages of exploitation of the two Annual Allowable Cuts (AAC), the density and floristic composition of regenerating woody species at the edges of post-logging secondary roads differ significantly; 2) the specific richness and the intra and inter AAC biological diversity of regenerating woody species vary according to the age of post-logging secondary roads.

2. Material and Methods

2.1. Study Sites and Installation of the Sub-Plots

The study was carried out in two Annual Allowable Cut (AAC) exploited in 2008 and 2018 within the Forest Management Unit (UFA) of Loundoungou- Toukoulaka, conceded to the Congolese company Industrial of Wood (CIB/OLAM) in Republic of the Congo. The geographic coordinates of Loundoungou- Toukoulaka UFA are 02˚18' - 02˚22'N and 17˚31' - 17˚34'E (**Figure 1**). The area is relatively flat with average altitudes between 430 m and 530 m. It displays a bimodal distribution of seasonal precipitation. The average annual rainfall and the average temperature are 1729 mm and 25˚C respectively [20]. Loundoungou-Toukoulaka UFA is a semi-deciduous forest, installed on clay soils of the Congolese basin [21] [22] [23]. It has been frequently disturbed in the past by traditional human activities (agricultural activities, hunting, etc) [24] [25]. It is composed of numerous light-demanding tree species such as *Erythrophleum suaveolens* (Guill. & Perr.) Brenan, *Celtis* spp., *Terminalia superba* Engl. & Diels, *Petersianthus macrocarpus* (P. Beauv.) Liben and *Triplochiton scleroxylon* K. Schum. Some parts of the undergrowth are invaded by lianas and giant herbaceous plants belonging to the Marantaceae and Zingiberaceae families [3] [21]. Some timber species the most exploited within of Loundoungou-Toukoulaka UFA are: *Khaya anthotheca* (Welw.) C. DC., *T. scleroxylon*, *Entandrophragma cylindricum* (Sprague) Sprague, *Entandrophragma utile* (Dawe & Sprague) Sprague, *Entandrophragma angolense* (Welw.) C. DC., *Millettia laurentii* De Wild., *Nauclea diderrichii* (De Wild. & T. Durand) Merr., *Guarea cedrata* (A. Chev.) Pellegr., *Autranella congolensis* (De Wild.) A. Chev., *E. suaveolens*.

The floristic inventory was carried out in two AAC (AAC 2008 and AAC 2018), and more precisely on the edges of the three post-logging secondary roads and equidistant from 5 km. On the edge of each post-logging secondary road, four square sub-plots (*i.e.* two sub-plots on either side of the post-logging secondary road) of dimensions 5 m × 5 m and equidistant of 30 m were installed. All the sub-plots of a post-logging secondary road were denominated "station", *i.e.* 3 stations corresponding to 3 post-logging secondary roads (S1 = station 1; S2 = station 2 and S3 = station 3). Overall, 24 sub-plots (*i.e.* 12 sub-plots within AAC 2008 and 12 sub-plots within AAC 2018) were delimited on an area

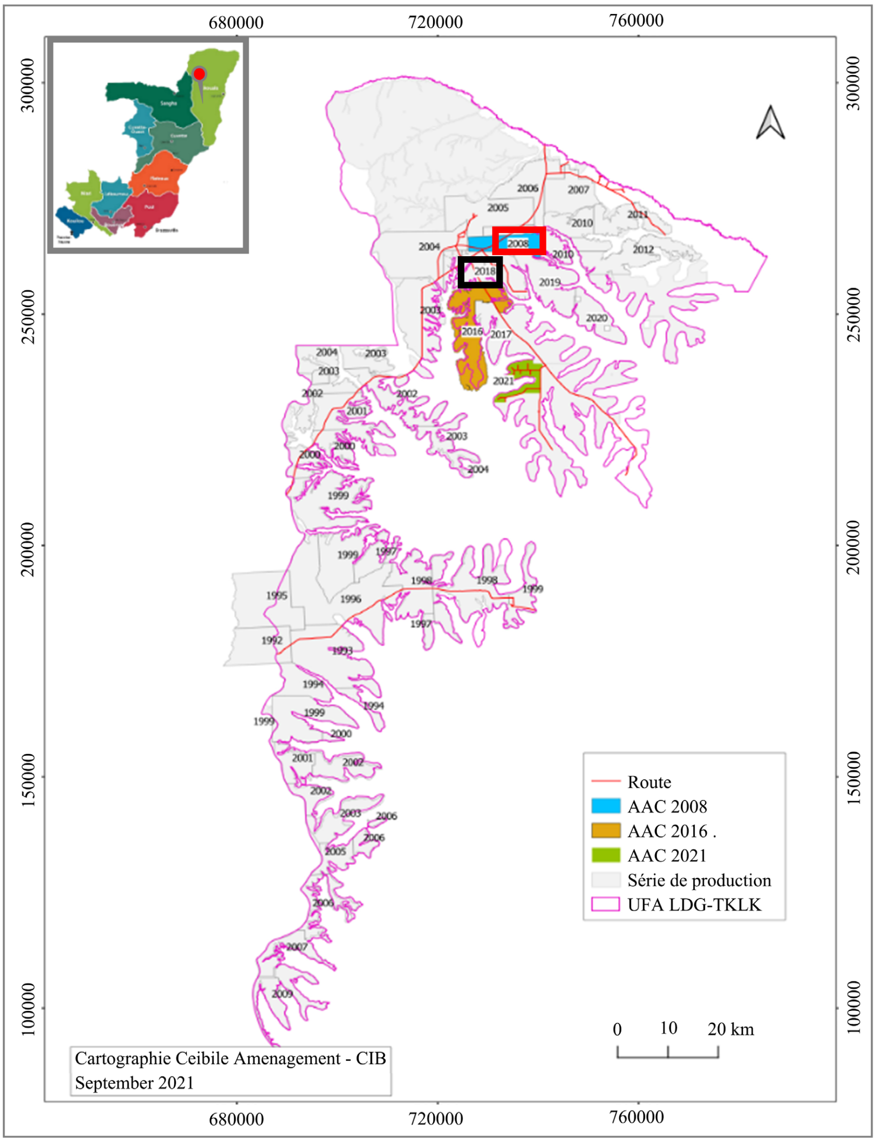

Figure 1. Location of study site in the Forest Management Unit of Loundoungou-Toukoulaka, CIB/OLAM forest concession (framed in red = Annual Allowable Cut 2008, "AAC 2008" and framed in black = Annual Allowable Cut 2018, "AAC 2018").

per AAC of 0.03 ha. Within each sub-plot, the inventory was random type and focused on regenerating woody species whose diameter was between 1 cm and 14.99 cm. Regenerating woody species were measured at the collar using vernier calipers and diametric ribbons [26] [27]. Voucher specimens were collected and regenerating woody species were identified by botanists (Isaac Dzombo and Gilbert Nsongola). We have followed the taxonomy of Geneva Herbarium Catalog (http://www.ville-ge.ch/musinfo/bd/cjb/chg), as well as the manual described by [28].

2.2. Data Analysis

To characterize regenerating woody species, the following parameters were used:

absolute density, *AD* (100 × number of individuals of a given species/sampling area) stem/ha, relative density, *RD* (100 × number of individuals of a given species/total number of individuals of all species), relative frequency, *RF* (100 × frequency of a species/total frequencies of all species) and the Importance Value Index (IVI) of the species calculated as the sum of *RD* and *RF* [29] [30] [31] [32]. To identify the indicator species of each Annual Allowable Cut, we calculated "the indicator value of the species" (*IndVal*), using the labdsv package implemented in the R environment [33]. The significant difference was set at $p < 0.05$.

This described index is defined as follows [34]:

$$INDVAL = A_{ij} \times B_{ij} \times 100\%$$

$$A_{ij} = N_{individuals\ ij} / N_{individuals\ i} \tag{1}$$

$B_{ij} = N_{sites\ ij} / N_{sites\ j}$;

INDVAL = the Indicator Value of species in site group *j*;

A_{ij}, is a measure of specificity (based on the abundance of species *i*);

$N_{individuals\ ij}$, is the mean number of individuals of species *i* in the sites of group *j*;

$N_{individuals\ i}$, is the number of individuals of species *i* in all groups;

B_{ij}, is a measure of fidelity (based on incidence of species *i*);

$N_{sites\ ij}$, is the number of sites in the group *j* where species *i* is present;

$N_{sites\ j}$, is the total number of sites in that group.

In the case of the present study, there were two groups constituted of the two Annual Allowable Cut (AAC 2008 and AAC 2018). The differences in woody species densities between the two AAC were tested using a non-parametric Kruskal-Wallis test. Finally, the specificity of the sub-plots and/or AAC in terms of species exclusively present in each sub-plot and AAC was determined by reporting these "exclusive" species to the total number of species recorded in the sub-plot and/or AAC (% *Sexcl*). In terms of specific diversity, we first calculated the observed specific richness noted *Sobs*. But, as Sobs is very dependent on sampling effort and is considered an unreliable estimator of the total species richness [35], we then calculated the estimated species richness using two most relevant estimators: Chao2, *Schao2* (based on incidence) and Jackknife1, *Sjack1* (based on abundance) [36] [37] [38] [39], using the program Estimates 9.1.0 [40]. These species richness estimators are defined as follows [41] [42] [43] [44]:

$$S_{Chao2} = S_{obs} + \frac{Qi^2}{2Q_i} \tag{2}$$

$$S_{Jack1} = S_{obs} + \left[\frac{Q_1(m-1)}{m}\right] \tag{3}$$

S_{obs}: observed species richness;

Q_1: number of species detected in a single sample (unique);

Q_2: number of species detected in two samples (duplicate);

m: total number of individuals sampled.

The rarefaction curves of each AAC were derived from the observed and estimated species richness to assess the representativeness of the sampling effort. To compare the floristic composition of the two AAC, we performed a Principal Component Analysis (PCA) based on the abundance data of regenerating woody species (12 sub-plots per site). This analysis makes no assumptions about the data and is considered among the appropriate methods for the graphical representation of floristic ordination [45] [46] [47]. It was applied in the R environment, with the R package MASS [48]. Shannon's (H') and Pielou's Equitability (E) indices were respectively used to assess the specific diversity and the equitable distribution of future stems between the two AAC [49] [50]. To study the variations of the diversity indices between the two AAC, we used the analysis of variance (ANOVA) with a single classification criterion by combining the qualitative factor (sub-plot) and the quantitative factor (each diversity index). We then realized a non-parametric test of ANOVA commonly called Kruskall- Wallis test. Finally, we performed post-hoc pairwise multiple comparisons between the means for a probability p-value < 0.05.

3. Results

3.1. The Density and Floristic Composition of Regenerating Woody Species at the Sides Post-Logging Secondary Roads

We recorded 88 woody species in AAC 2008 and 241 woody species in AAC 2018, with average densities of 2933 stem/ha and 8033 stem/ha, respectively (**Table 1**). There was a very highly significant difference between the mean densities of the two AAC (Kruskal-Wallis test; H = 2.36, p-value < 0.000).

In the 2008 AAC, woody species belonged to 33 species, whose the most represented are 13 species of *Pterocarpus soyauxii* Taub. (40%), 11 species of *Tetrorchidium didymostemon* (Baill.) Pax & K. Hoffm (33%) and 9 species of *Macaranga spinosa* Müll. Arg. (27%). However, in the AAC 2018, woody species also belonged to 33 species, whose the most represented were: 99 species of *Macaranga spinosa* Müll. Arg. (62%), 30 species of *Aoranthe cladantha* (K. Schum.) (19%), 20 species of *Macaranga barteri* Müll. Arg. (13%) and 10 species of *Croton haumaniamus* J. Léonard (6%) (**Table 1**). Regarding indicator species, the 2018 AAC displayed four indicator species: *A. cladantha* (IndVal = 0.645%; p-value = 0.004), *M. barteri* (IndVal = 0.50%; p-value = 0.018), *M. spinosa* (IndVal = 0.917%; p-value = 0.001) and *Nauclea diderrichii* (IndVal = 0.519%; p-value = 0.017). While the 2008 AAC did not present any indicator species (**Table 1**).

The observed species richness (*Sobs*) of the AAC 2008 is estimated at 33 woody species, while the specific richness estimators *Sjack1* and *Schao2* estimate 34 and 37 woody species respectively (**Figure 2**). However, the observed species richness of the AAC 2018 is estimated at 33 woody species, while the *Sjack1* and *Schao2* estimators display 35 and 37 woody species respectively (**Figure 2**). Nonetheless, the *Sobs* curve does not clearly approach the asymptote, but

Table 1. Floristic composition and densities of regenerating woody species of the two annual allowable cuts studied (AAC 2008 and AAC 2018). *AD* = absolute density, *RD* = relative density, *RF* = relative frequency, *IVI* = species Importance Value Index, *Indval* = indicator value index and its p-value. Ns = not significant.

Taxon	Family	Number of stems	AD (n/ha)	RD (%)	RF (%)	IVI	Indval	p-value
AAC 2008 (33 species)								
Albizia ferruginea (Guil. & Perr.) Benth.	Fabaceae-Mimosoïdeae	1	33.33	1.14	0.04	1.18	0.083	Ns
Aoranthe cladantha (K. Schum.) Somers	Rubiaceae	1	33.33	1.14	0.04	1.18	0.003	Ns
Bombax buonopozense P. Beauv.	Malvaceae-Sterculioïdeae	2	66.67	2.27	0.08	2.35	0.042	Ns
Canarium schweinfurthii Engl.	Burseraceae	2	66.67	2.27	0.08	2.35	0.167	Ns
Clausena anisata (Willd.)	Rutaceae	1	33.33	1.14	0.04	1.18	0.083	Ns
Cleistanthus caudatus Pax	Phyllanthaceae	2	66.67	2.27	0.08	2.35	0.083	Ns
Discoglypremna caloneura Var. membranacée Pax	Euphorbiaceae	2	66.67	2.27	0.08	2.35	0.042	Ns
Duboscia macrocarpa Bocq.	Malvaceae-Sterculioïdeae	1	33.33	1.14	0.04	1.18	0.083	Ns
Entandrophragma candollei Harms	Meliaceae	2	66.67	2.27	0.08	2.35	0.083	Ns
Erythrophleum sauveolens Brenan	Fabaceae-Caesalpinioïdeae	3	100	3.41	0.12	3.53	0.188	Ns
Funtumia africana (Benth.) Stapf	Apocynaceae	1	33.33	1.14	0.04	1.18	0.083	Ns
Gilbertiodendron dewevrei (De Wild.) J. Léonard	Fabaceae-Caesalpinioïdeae	3	100	3.41	0.12	3.53	0.062	Ns
Lepidobotrys staudtii Engl.	Lepidobotryaceae	1	33.33	1.14	0.04	1.18	0.083	Ns
Macaranga barteri Müll. Arg.	Euphorbiaceae	3	100	3.41	0.12	3.53	0.022	Ns
Macaranga spinosa Müll. Arg.	Euphorbiaceae	9	300	10.23	0.35	10.58	0.035	Ns
Margaritaria discoidea (Baill.) Webster	Phyllanthaceae	1	33.33	1.14	0.04	1.18	0.083	Ns
Myrianthus arboreus P. Beauv.	Urticaceae	1	33.33	1.14	0.04	1.18	0.083	Ns
Nauclea diderrichii (De. Wild. & T. Durand) Merr.	Rubiaceae	1	33.33	1.14	0.04	1.18	0.009	Ns
Oncoba welwitschii Oliv.	Achacariaceae	3	100	3.41	0.12	3.53	0.042	Ns
Pauridiantha dewevrei (De Wild. & T. Durand) Bremek.	Rubiaceae	2	66.67	2.27	0.08	2.35	0.111	Ns
Pentaclethra macrophylla Benth.	Fabaceae-Mimosoïdeae	1	33.33	1.14	0.04	1.18	0.083	Ns
Petersianthus macrocarpus (P. Beauv.) Liben	Lecythidaceae	1	33.33	1.14	0.04	1.18	0.021	Ns
Psydrax subcordata DC	Rubiaceae	1	33.33	1.14	0.04	1.18	0.083	Ns
Pterocarpus soyauxii Taub.	Fabaceae-Faboïdeae	13	433.33	14.77	0.50	15.28	0.406	Ns
Ricinodendron heudelotii (Baill.) Pierre ex Heckel	Euphorbiaceae	2	66.67	2.27	0.08	2.35	0.083	Ns

Continued

Rinorea oblongifolia (CH Wright) Marquand ex Chipp	Violaceae	5	166.67	5.68	0.19	5.88	0.083	Ns
Strombosia grandifolia hoot. F.	Olacaceae	1	33.33	1.14	0.04	1.18	0.083	Ns
Tetrapleura tetraptera (Schumach. & Thonn.) Taub.	Fabaceae-Mimosoïdeae	1	33.33	1.14	0.04	1.18	0.083	Ns
Tetrorchidium didymostemon (Baill.) Pax & K. Hoffm.	Euphorbiaceae	11	366.67	12.50	0.43	12.93	0.338	Ns
Thomandersia hensii De Wild.	Thomandersiaceae	3	100	3.41	0.12	3.53	0.167	Ns
Treculia africana Decne. Var. africain	Moraceae	2	66.67	2.27	0.08	2.35	0.083	Ns
Trema orientalis (L.) Blume	Cannabaceae	4	133.33	4.55	0.15	4.70	0.111	Ns
Zanthoxylum heitzii (Aubrév. &. Pellegr.) P. G. Waterman	Rutaceae	1	33.33	1.14	0.04	1.18	0.028	Ns
Total		88	2933.33	100				
AAC 2018 (33 species)								
Albizia adiauthifolia (Schumach.) W. Wight	Fabaceae-Mimosoïdeae	1	33.33	0.41	0.01	0.42	0.08	Ns
Albizia glaberrima (Schumach. & Thonn.) Benth.	Fabaceae-Caesalpinioïdeae	1	33.33	0.41	0.01	0.42	0.08	Ns
Alstonia boonei De Wild.	Apocynaceae	5	166.67	2.07	0.03	2.10	0.33	Ns
Antrocaryon klaineanum Pierre	Anacardiaceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Aoranthe cladantha (K. Schum.) Somers	Rubiaceae	30	1000	12.45	0.15	12.60	0.65	0.004
Barteria fistulosa Mât.	Passifloraceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Blighia welwitschii (Hiern) Radlk.	Sapindaceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Bombax buonopozense P. Beauv.	Malvaceae-Sterculioïdeae	2	66.67	0.83	0.01	0.84	0.08	Ns
Ceiba pentandra (L.) Gaertn.	Malvaceae-Bombacoïdeae	1	33.33	0.41	0.01	0.42	0.08	Ns
Cleistopholis patens (Benth.) Engl. & Diels	Annonaceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Cola lateritia K. Schum.	Malvaceae-Sterculioïdeae	2	66.67	0.83	0.01	0.84	0.08	Ns
Croton haumaniamus J. Léonard	Euphorbiaceae	10	333.33	4.15	0.05	4.20	0.25	Ns
Discoglypremna caloneura Var. membranacée Pax	Euphorbiaceae	6	200	2.49	0.03	2.52	0.25	Ns
Erythrophleum sauveolens Brenan	Fabaceae-Caesalpinioïdeae	1	33.33	0.41	0.01	0.42	0.02	Ns
Ficus wildemaniana Warb.	Moraceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Gilbertiodendron dewevrei (De Wild.) J. Léonard	Fabaceae-Caesalpinioïdeae	5	166.67	2.07	0.03	2.10	0.10	Ns
Leptactina involucrata Hook. F.	Rubiaceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Lophira alata Banks ex CF Gaertn.	Ochnaceae	1	33.33	0.41	0.01	0.42	0.08	Ns

Continued

Macaranga barteri Müll. Arg.	Euphorbiaceae	20	666.67	8.30	0.10	8.40	0.58	0.018
Macaranga spinosa Müll. Arg.	Euphorbiaceae	99	3300	41.08	0.51	41.59	0.92	0.001
Musanga cecropioïdes R. Br. ex Tedlie	Urticaceae	11	366.67	4.56	0.06	4.62	0.33	Ns
Nauclea diderrichii (De. Wild. & T. Durand) Merr.	Rubiaceae	8	266.67	3.32	0.04	3.36	0.52	0.017
Oncoba welwitschii Oliv.	Achacariaceae	9	300	3.73	0.05	3.78	0.31	Ns
Pauridiantha dewevrei (De Wild. & T. Durand) Bremek.	Rubiaceae	1	33.33	0.41	0.01	0.42	0.03	Ns
Petersianthus macrocarpus (P. Beauv.) Liben	Lecythidaceae	3	100	1.24	0.02	1.26	0.19	Ns
Pteleopsis hylodendron Mildbr.	Combretaceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Pterocarpus soyauxii Taub.	Fabaceae-Faboïdeae	3	100	1.24	0.02	1.26	0.05	Ns
Terminalia superba Engl. & Diels.	Combretaceae	1	33.33	0.41	0.01	0.42	0.08	Ns
Tetrorchidium didymostemon (Baill.) Pax & K. Hoffm.	Euphorbiaceae	5	166.67	2.07	0.03	2.10	0.14	Ns
Trema orientalis (L.) Blume	Cannabaceae	2	66.67	0.83	0.01	0.84	0.03	Ns
Xylopia aethiopica (Dunal) A. Rich.	Annonaceae	2	66.67	0.83	0.01	0.84	0.17	Ns
Xylopia hypolampa Mildbr.	Annonaceae	3	100	1.24	0.02	1.26	0.25	Ns
Zanthoxylum heitzii (Aubrév. &. Pellegr.) P. G. Waterman	Rutaceae	2	66.67	0.83	0.01	0.84	0.11	Ns
Total		241	8033.33	100				

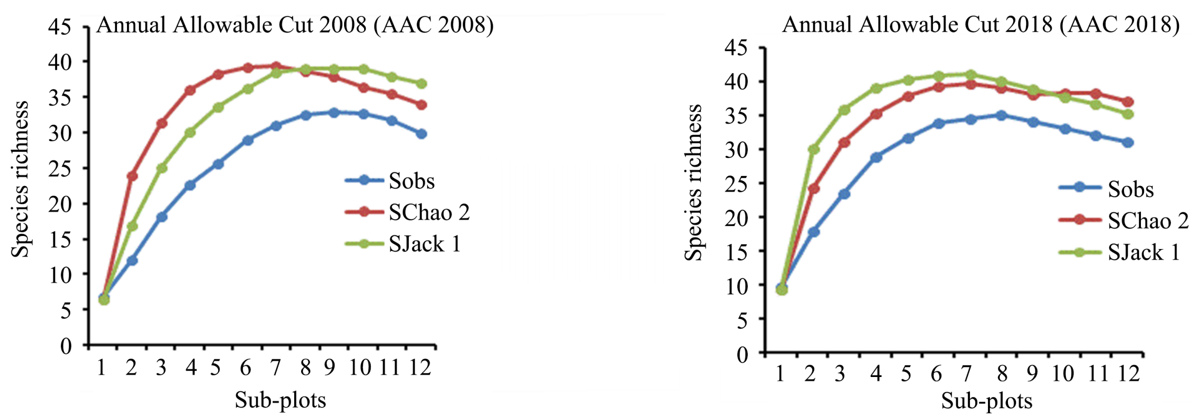

Figure 2. Curves of rarefaction of the two Annual Allowable Cut (AAC 2008: Annual Allowable Cut 2008 and AAC 2018: Annual Allowable Cut 2018).

increases progressively with the increase of number of samples. Thus, the sampling effort is relatively satisfying in the two CAA studies (**Figure 2**).

Nonetheless, the floristic composition illustrated by the Principal Component Analysis (PCA) demonstrates that there is a spatial structuring of the sub-plots confirming that the regenerating woody species of the two AAC are globally different (**Figure 3**).

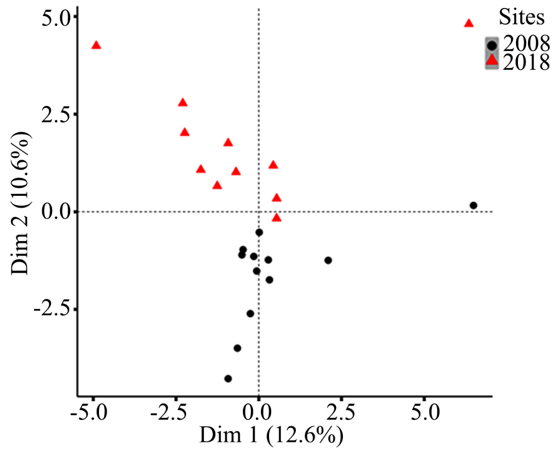

Figure 3. Principal component analysis (PCA) of regenerating sub-plots of the two Annual Allowable Cut (AAC 2008 and AAC 2018).

3.2. The Specific Richness and the Intra and Inter Biological Diversity Annual Allowable Cut (AAC) of the Regenerating Woody Species

The species richness observed (*Sobs*) at the level of each station demonstrates that the AAC 2018 presents relatively high values compared to those of the AAC 2008 which seem constant in the first two stations and, higher in the last station (**Table 2**). The *SJack1* and *SChao2* estimators respectively estimate 13 and 11 species for station 1 (*S1*), 12 and 11 species for station 2 (*S2*), and finally, 25 and 21 species for station 3 (*S3*). However, 15 to 20 observed species were recorded in the 2018 AAC. The *SJack1* and *SChao2* estimators estimate 28 and 26 species for station 1 (*S1*), 20 and 18 species for station 2 (*S2*) and finally 16 and 15 species for station 3 (*S3*) (**Table 2**). Moreover, 54.55 and 70% of exclusive species were recorded for the 2008 AAC. While the AAC 2018 displays 38.89 and 45% of exclusive species (**Table 2**). Also, the average densities illustrated in **Table 2** obviously show that AAC 2018 has a relatively higher average density with 520 ± 846.17 stem/ha, 457.89 ± 712.83 stem/ha and 422.22 ± 872.83 stem/ha, respectively for the station 3 (*S3*), station 1 (*S1*) and station 2 (*S2*). However, the 2008 AAC presents relatively low densities compared to those of the 2008 AAC with 281.82 ± 177.87 stem/ha, 236.36 ± 250.09 stem/ha and 155 ± 88.70 stem/ha, respectively for stations 1, 2 and 3 (**Table 2**). Nonetheless, the values of the Shannon index vary from 2.03 to 2.83 and from 1.85 to 2.32, respectively in the stations of the two Annual Allowable Cut (AAC 2008 and AAC 2018) (**Table 3**).

On the other side, those of the Equitability of Piélou vary from 0.85 to 0.96 and from 0.67 to 0.77, respectively in the stations of the two AAC (**Table 3**). Overall, the Shannon index and the Piélou Equitability values are relatively higher in the 2008 AAC stations than in those of 2018 (**Table 3**). Nevertheless, the analysis of the variations on the indices of diversity between stations sampled by the Kruskall-Wallis test allowed to demonstrate that there are no significant differences between the stations of each Annual Allowable Cut studied (p-value > 0.05) (**Figure 4**).

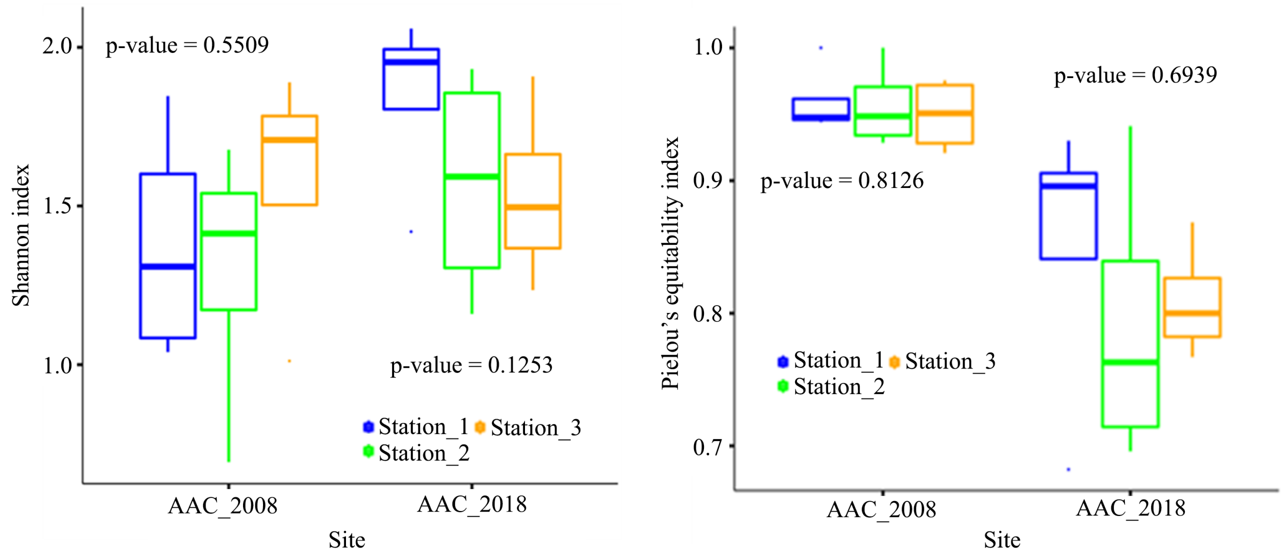

Figure 4. Variation of the diversity indices of regenerating sub-plots for the three stations (three secondary post-logging roads) of the two Annual Allowable Cut (AAC 2008 and AAC 2018).

Table 2. Characteristics of the regenerating sub-plots for the three stations (three secondary post-logging roads) of the two Annual Allowable Cut (AAC 2008 and AAC 2018). *Sobs* = species richness observed; *Schao2* = specific richness estimated according to the approach Chao2; *Sjack1* = specific richness estimated according to the approach Jackknife 1, *Sexclu* (*%*) = percentage of exclusive woody species in each station; *Density* = Mean (±SD) of number of woody species per unit area.

Stations	*AAC 2008*					*AAC 2018*				
	Sobs	*Sexclu* (*%*)	*Schao2*	*Sjack1*	*Average density* (*stem/ha*)	*Sobs*	*Sexclu* (*%*)	*Schao2*	*Sjack1*	*Average density* (*stem/ha*)
S1	11	54.55	11	13	281.82 ± 177.87	20	45	26	28	457.89 ± 712.83
S2	11	70	11	12	236.36 ± 250.09	18	38.89	18	20	422.22 ± 872.83
S3	20	54.55	21	25	155 ± 88.70	15	40	15	16	520 ± 846.17

Table 3. Biological diversity of the regenerating sub-plots for the three stations (three post-logging secondary roads) of the two Annual Allowable Cut (AAC 2008 and AAC 2018).

	AAC 2008			*AAC 2018*		
	Abundance	*Shannon*	*Equitability*	*Abundance*	*Shannon*	*Equitability*
S1	31	2.22	0.93	87	2.32	0.77
S2	26	2.03	0.85	76	1.93	0.67
S3	31	2.86	0.96	78	1.85	0.70

4. Discussion

4.1. The Density and Floristic Composition of Regenerating Woody Species at the Edges Post-Logging Secondary Roads Differ Significantly

The results of this study demonstrated average densities of 2933 stem/ha and

8033 stem/ha, respectively for the 2008 Annual Allowable Cut (AAC 2008) and the 2018 Annual Allowable Cut (AAC 2018). The difference between mean densities was very highly significant (p-value = 0.000). This difference could be explained on the one hand, by the fact that the AAC 2008 seems older than the AAC 2018. Indeed, when a forest tends towards maturity, the canopy is relatively closed, which tends to impede the growth and development of other woody species (light-demanding species). On the other hand, as part of the silvigenetic cycle described by [51], when an environment tends towards maturity, we tend to observe natural mortality of short-lived pioneer species such as *Musanga cecropioides*, *Macaranga* spp…, to leave the place to the long-lived pioneer species such as *Nauclea diderrichii*, *Erythrophleum suaveolens* [52]. Nonetheless, *Musanga cecropioides* and *Macaranga* spp are fast-growing species growing on relatively rich clay soils. These species are generally sensitive to drought. Their abundance in a given area marks their resilience to forest anthropogenic disturbances [31] [32]. This very highly significant difference in the average densities tends to confirm the very distinct spatial distribution of regenerating sub-plots by Principal Component Analysis (PCA) observed between the individuals inventoried within the two Annual Allowable Cut (AAC 2008 and AAC 2018). Our results widely exceed the works of [52] [53], which demonstrates an average density of 34 stem/ha in Gabon. Let us recall that the authors inventoried from a threshold of 10 cm in diameter. Such a difference could be due to the variety of methodologies adopted. Our results are also superior to the works of [53] who demonstrated average densities of 2500 stem/ha and 2200 stem/ha, respectively in sub-plot 1 and sub-plot 2 in Cameroon.

Nonetheless, this study revealed four indicator species (*Aorenthe cladantha*, *Macaranga barteri*, *Macaranga spinosa*, *Nauclea diderrichii*) in the AAC 2018, which could be explained by the fact that the recently exploited forest harbors short-lived pioneer species that tend to initiate natural regeneration after disturbance [54] [55]. The presence of the species *N. diderrichii*, which is a long-lived pioneer species would be explained by the fact that it produces fruits containing a large quantity of dormant seeds of small sizes susceptible to remain viable in the soil bank for several years [55] [56]. However, the AAC 2008 did not present any indicator species. This could be explained by the fact that this latter has not yet reached the mature stage and would be possibly in a process of recolonization [56] [57]. Also, [58] tend to confirm that in the tropical forest of Africa, zoochory is the most widespread mode of dissemination with approximately 80% to 90%. In the case of the present study, this could be justified by the fact that abandoned secondary roads would be much more attractive to the animals due to abundance of herbs as food sources, as has been demonstrated for gorillas [59] [60] [61] [62]. Recently, in central Africa, the creation of roads and skid trails by logging operations leads to changes in the structure of forest landscapes that could influence wildlife movements. For example, significantly higher the relative abundance indices (RAI) on secondary roads were observed for buffalos (*Syncerus caffer*), forest elephants (*Loxodonta cyclotis*), and bongos

(*Tragelaphus eurycerus*) [63].

4.2. The Specific Richness and the Intra and Inter Annual Allowable Cut (AAC) Biological Diversity of Regenerating Woody Species Vary According to the Age of the Post-Logging Secondary Roads

This study demonstrated that the diversity of regenerating species is relatively high with 329 woody species belonging to 51 species. These results also show a very high diversity of woody species in secondary or heavily disturbed areas. Our results confirm the assumptions of [62], who confirmed that recently disturbed areas harbor a high diversity of regenerating woody species. On the other side, our results tend to confirm the works of [16] who demonstrated 321 ligneous species belonging to 26 species. Such a difference could be due to the variety of methodologies adopted insofar as the latter worked on the regeneration of species at the edges of secondary roads through remote sensing, whereas in the case of the present study, we directly confronted the reality of the ground.

Regarding the diversity indices, the values of the Shannon index varied from 2.03 to 2.83 and from 1.85 to 2.32 respectively in the 2008 and 2018 AAC stations. On the other side, those of the Equitability of Pielou vary from 0.85 to 0.96 and from 0.67 to 0.77, respectively in the 2008 and 2018 AAC stations. This biological diversity demonstrates that the values of the Shannon and Piélou Equitability indices are relatively very high in the 2008 AAC compared to the 2018 AAC. This could imply that the AAC 2008 presents a more diversified and equitable species richness than that of AAC 2018. Overall, the two AAC presents a diversified and equitable specific richness. Our results converge with the works of [64] which stipulate that when the equitability is high, the dispersion of the elements of biodiversity would be equitable. Finally, the correlation between the age of the road and the indices of diversity showed that there is no link between the ages of secondary roads post-logging and the indices of diversity (p-value > 0.005).

Nonetheless, the Shannon index was negatively correlated with the age of the road ($R = -0.488$), which could mean that the older the road, the less woody species would be diversified. The pielou equitability index was positively correlated with the age of the road ($R = 0.683$), which tends to confirm that the older the road, the more species are fairly distributed in the environment. This implies that post-logging secondary roads present a significant proportion of woody species.

5. Conclusion

This study consisted to assess the natural regeneration potential of regenerating woody species at the edges of post-logging secondary roads. The results highlighted the interest that woody species could play in natural regeneration at the edges of post-logging secondary roads. We have demonstrated that the floristic composition of woody species at the edges of post-logging secondary roads depends on the seniority of the roads. Overall, the results of this study reveal that: 1) the density of regenerating woody species was very high in the 2018 Annual Allowable Cut (AAC 2018) compared to the 2008 Annual Allowable Cut (AAC 2008); 2) the woody species of Annual Allowable Cut 2008 were largely dominated by species such as *Pterocarpus soyauxii*, *Tetrorchidium didymostemon* which are secondary forest species that can be found also in mature forests; 3) short-lived and fast-growing pioneer species such as *Musanga cecropioïdes*, *Macaranga* spp. were much more abundant in the 2018 Annual Allowable Cut and 4) commercial tree species were not well represented among the woody species inventoried in the two AAC. Consequently, the reforestation of commercial species in the post-logging Annual Allowable Cut is necessary to sustainably manage these forests devoted to intensive timber exploitation. Nonetheless, some research options on the potential of natural regeneration stay misknown and/or little explored. This type of study could also be carried out in felling gaps to improve knowledge on the quantity and quality of regenerating woody species. This component will allow us to compare the natural regeneration potential in the felling gaps compared to post-logging secondary roads.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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