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Carbon Stock Recovery after Selective Logging in the East Region of Cameroon

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Abstract

Tropical forests have large carbon stocks and their conservation is a very important mitigation measure against global warming. However, this carbon pool is the most vulnerable to anthropogenic activities like selective logging and little is known about its recovery. This study aimed to determine the carbon stock recovery after selectively logging using different allometric equations in six 1 ha permanent monitoring plots established in logged and unlogged forest types. Each 1 ha was divided into 25, 20 × 20 m and the DBH of all trees ≥ 2 cm was measured in 2005/2006 and re-measured in 2011/2012. The logged forests had the highest % change in the species richness indicating the impacts of logging. The presence of exploitable commercial trees in both forest types suggests their recruitment after logging. The insignificant difference in the AGB using different allometric equations is an indication that the Pan tropical equation is a good reference for the calculations of AGB in moist tropical forests. The 59.4% recovery rate in forests of 21 YAL indicates that 30 years is not enough for the recovery of the Carbon timber stock as the unlogged forests had a 77.7%. This calls for a review of forest management silvicultural activities for sustainable forest management.

Keywords

Above-Ground Biomass, Allometric Equations, Logged Forests, Unlogged Forests and Timber Species

1. Introduction

The current anthropogenic climate change and its global impact have increased the urgent need for reliable estimates of biomass and carbon pools for terrestrial ecosystems (Brown, 2002). Tropical forests are the most important forest vegetation type with large carbon stocks that have the potential to offset global warming through the removal of atmospheric Carbon dioxide (CO_2) (Löf et al., 2019). Sub-Saharan Africa has 25% (2.1 Gt per year) of the global carbon stock of the forests (Pearson et al., 2017) with the largest from above-ground tree biomass (≥80%), mostly held in stems, wood and branches (Henry et al., 2010). However, this carbon pool is the most vulnerable to anthropogenic activities causing deforestation for agriculture and forest degradation through selective logging (Hairiah & Rahayu, 2007) to directly affect the aboveground biomass of trees (Gibbs et al., 2007). In contrast to deforested areas that are used for agriculture and grazing, most buffering capacity and resilience are high in selectively logged forests that are well managed (Asner et al., 2006) and may recover carbon stocks (West et al., 2014). However, carbon stock from tropical forest regrowth is subject to high uncertainties (Sierra et al., 2012).

Selective logging can diminish timber resources, carbon reserves and habitat quality for local fauna (Poudyal et al., 2018) slowing its recovery (Hu et al., 2020); but these disturbances also create environmental conditions that are favorable for the regeneration and recovery of other tree species and forest biomass (Goulamoussene et al., 2017; Mokake et al., 2024) and thus the capture and recovery of carbon (Herault & Piponiot, 2018). This recovery forms part of the reincorporation of carbon into both the soil and the forest biomass (Houghton, 2005). However, the recovery of forest areas as a result of disturbances generated from selective logging has received little attention as little is known about recovery and the dynamics of their carbon stock. Though some studies have been carried out in tropical Africa especially Ghana, (Duah-Gyamfi et al., 2014), most focused on the regeneration of commercial timber species as was the case with Mokake et al. (2022) in Eastern Cameroon, without taking into consideration the recovery of the whole forest biomass and carbon stock especially in the East Region of Cameroon. More importantly, uncertainty remains about the rate of biomass recovery in secondary and primary forests in the landscape (Sierra et al. 2012). Therefore, it is necessary to accurately estimate the carbon stocks of primary and secondary forests in order to determine biomass accumulation at the different stages of succession after disturbances in order to rebuild the ecological functions provided by the forests.

Before using allometric equations, which is a non destructive method of determining the above ground biomass, their validity within a particular area needs to be tested (Chave et al., 2005) in order to be sure of the carbon stored by the forest taking into consideration that the biomass in the tropics is affected by topography, climatic condition and woody species composition along with other factors like natural and anthropogenic disturbances like selective logging. The main source of error in the estimation of biomass and carbon stock is thus the choice of the allometric equation (Chave et al., 2005, 2014) which depends greatly on the number of trials carried out and the site in question (Chave et al., 2014). Thus a considerable uncertainty exists in the spatial distribution of biomass. Pantropical models based on large compiled datasets contain more community-level variation in specific forests than local models (Brown et al., 1989; Chave et al., 2005; Djomo et al., 2010), as site specific equations are usually fitted using a limited number of trees and species (Kenzo et al., 2009), which may not be representative of species pool in other regions (Fayolle et al., 2013). However significant bias in the estimates of Carbon has been reported by Henry et al. (2010), Alvarez et al. (2012) and Lima et al. (2012) in Ghana, Columbia and Brazil, respectively using pantropical equations. Therefore, there's a need to investigate if a substantial difference exist between the pantropical, regional and site-specific allometric equations in the estimation of tree/wood plant biomass and carbon of African tropical forests in order to avoid misinformation in the development of specific allometric models for Africa improving on the quality of biomass estimates under the UN-REDD + programme as locally developed allometric equations are thought to provide more accurate estimates of the aboveground biomass (AGB).

For countries without specific allometric equations two options exist based on the IPCC (2006). The first option is tier 1 which uses existing generalized equations for their national forests; attained in Africa by Brown et al. (1989) and Chave et al. (2005) and Cameroon by Mokake et al. (2022, 2023). The second option is tier 2 which explores the need and subsequent process of developing country or region-specific allometric equations with few specific allometric equations in tropical African forests in general (in Cameroon by Fayolle et al., 2013, 2018) with consequences in the variation in the attainment of Tier-2 and Tier-3 (tier 3 is the site specific allometric equation attained in Cameroon by Djomo et al. (2010) approaches of the IPCC. Therefore pantropical equations may not be appropriate in reflecting specific growth patterns or conditions. It was against this backdrop that this study sought to determine the carbon stock recovery after selectively logged while assessing the validity of using pantropical multi-species, regional and site specific allometric equations to estimate the biomass of trees in the East Region of Cameroon thereby contributing to the information gap that exists in Africa in general and Cameroon in particular. It was therefore hypothesized that:

- selectively logged sites recovered their Carbon stock faster than the unlogged forests;
- a site specific model is a better estimator of above ground biomass than the general Pantropical model.

The specific objectives were to:

- determine the carbon stock recovery after selective logging;
- assess the difference between the estimates of the local model and the pan tropical model.

2. Methodology

2.1. Study Site

The East Region lies between latitude 3˚08 to 3˚18 North and longitude 14˚31 to14˚52 East, occupying an area of 109,011 km^2 with a ferralitic soil. It has a wet equatorial climate, an average temperature of 24˚C and lacks traditional seasons. It has an average annual total precipitation between 1500 - 2000 mm except in the extreme Eastern and Northern portions of the region, where it is slightly less. Relative humidity is highest in the month of June-December. The stratified forest is composed of hardwood evergreens of species, some of which grow to heights of 70 m or more (Fitzpatrick, 2002).

This study was carried out in six 1.0ha permanent forest monitoring plots established by the Centre for Tropical Forest Society (CTFS) and World Wide Fund for Nature (WWF)-Cameroon in 2005/2006 at the Société Forestiére Industrielle de Lokoundje (SFIL) (FMU10-052) and Green Valley Incorporated (GVI) (FMU10-021) belonging to la Groupe Decolvenaere (GDC) timber company located at the Boumba and Ngoko Division of the East Region to establish baseline conditions of the forest. Permanent monitoring plots were established in Forest Management Unit (FMU) 10-052 and 10-021 (**Figure 1** and **Table 1**). A recensus was done between June 2011 and December 2012 where Plots 1 and 2 were the unlogged forests, Plots 3 and 4 were the forests of 11 Years After Logging (YAL) and plots 5 and 6 were the forests of 21 Years After Logging (YAL) (**Table 1**).

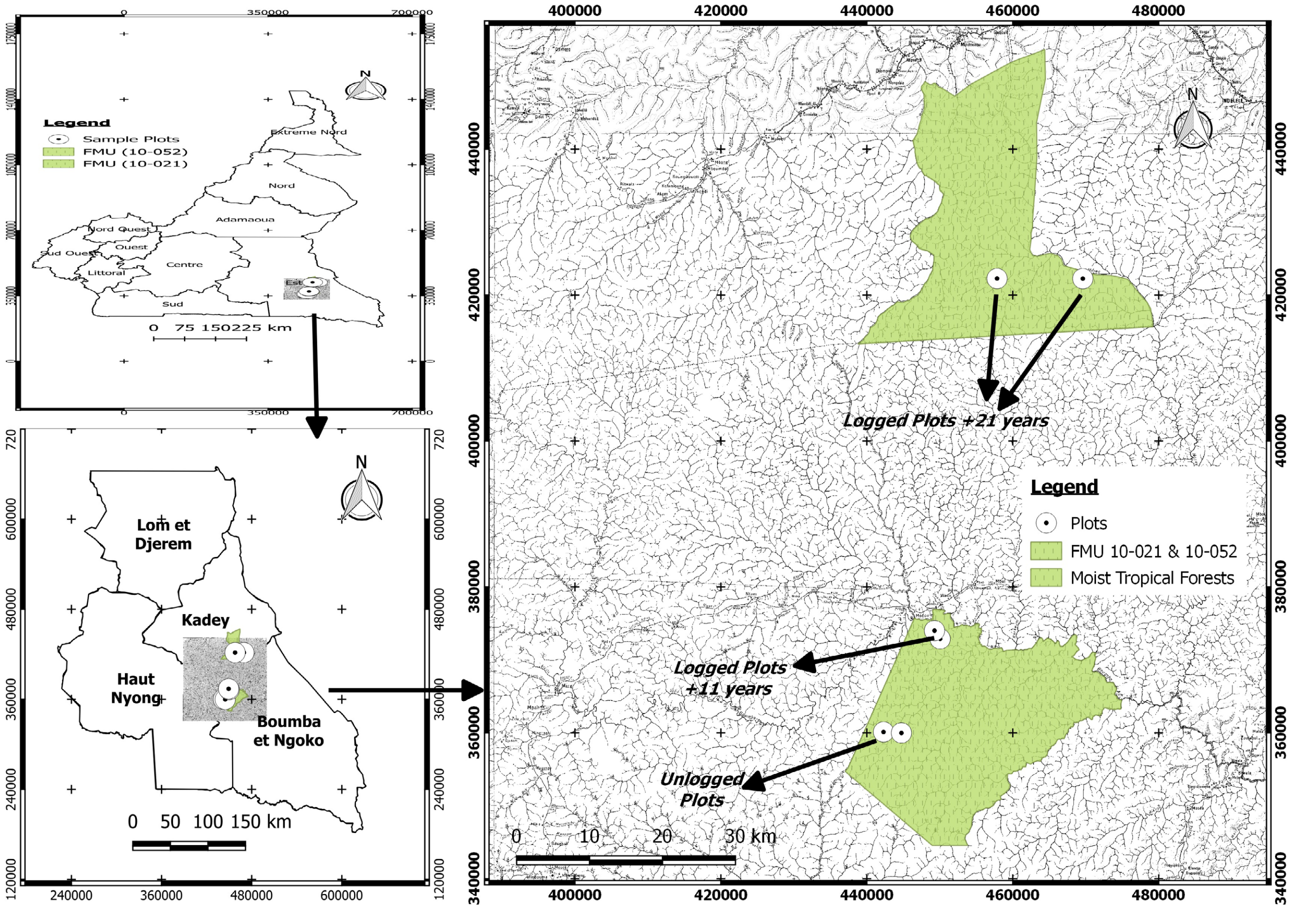


Figure 1. Localization of the six 1.0 ha permanent forest monitoring plots established by CTFS and WWF-Cameroon in 2005 and 2006.

Table 1. Location of some permanent forest monitoring plots in the East Region of Cameroon.

PLOTS	YAL (2005)	YAL (2011)	Location	Datum	Utm 33n Easting	Utm 33n Northing
1	0	0	Green Valley, south end 1	WGS84	442,288	360,111
2			Green Valley, south end 2	WGS84	444,740	359,972
3	5	11	Green Valley near mill 3	WGS84	450,047	372,871
4			Green Valley near mill 4	WGS84	449,274	373,999
5	15	21	Green Valley SOTREF 5	WGS84	469,601	422,247
6			Green Valley SOTREF 6	WGS84	457,847	422,263

WGS = World Geodetic System, YAL = Years After Logging.

2.2. Field Design and Sampling

Plot demarcation was carried out in 2005/2006 using the standard protocols by Condit (1998) for long-term permanent monitoring plots. Each 1.0 ha plot was divided into 25 nested 20 × 20m subplots or quadrats and each 20 × 20 m quadrat was subdivided into 16 nested 5 × 5m sub-quadrats, using temporary demarcated posts at 5 m intervals, and nylon rope around each 5 × 5 m subquadrat.

In 2005/2006, all woody plants with DBH ≥ 2 cm were measured at 1.3 m from the ground. They were assigned a unique tag number and painted at the point of measurement to guide future measurements. The location of each censured stem within the plot was determined by the X and Y coordinates within each 5 m × 5 m subquadrat and pooled for the whole plot. In the first re-census in 2011/2012, we received the entire data sets for the six sites, and we were able to trace all the tagged plants. We then remeasured the old and new woody stems in 2011/2012 corresponding to 6 years interval after the initial measurement. During the re-census the recruits (new individuals that enter the diameter size of ≥ 2 cm) were treated in a similar manner with new number tags and their positions mapped to the nearest 5 cm. Every individual was identified by a team of botanists and voucher specimens collected were matched with herbarium specimens at the National herbarium in Yaounde according to the Angiosperm Phylogeny Group (APG) III system classification (APG, 2009).

A) Assessment of the stand compositional change after selective logging in the East Region of Cameroon.

The tree species density and richness determined the stand composition. Species density was determined as the number of individuals of the different species/ha (Mueller-Dombois & Ellenberg, 1974) in each site. Species richness (S) was the number of species and was determined by tallying living stems (Yap et al., 2016). These were used to estimate the % change in species richness and plant density, Importance Value Index (IVI) and the Family Importance Value (FIV).

The Species Importance Value Index (IVI) was calculated as described by Curtis (1959);

$$=\text{Species Relative Density} + \text{Species Relative Dominance} + \text{Species Relative Frequency} \quad \text{Equation 1}$$

The Family Important Value Index (FIV) was calculated as described by Mori et al. (1983);

$$=\text{Family Relative Density} + \text{Family Relative Dominance} + \text{Family Relative Frequency} \quad \text{Equation 2}$$

B) Evaluation of the Aboveground Carbon Stock (ACS) recovered after selective logging in the East Region of Cameroon.

The Above Ground Biomass (AGB) recovered was determined using the pantropical regression model of Chave et al. (2005), regional and site specific allometric equations.

- The Chave et al. (2005) equation used was:

$$AGB = \rho_s \times \exp[-1.499 + 2.148 \times \text{In}(DBH) + 0.207 \times \text{In}(DBH)^2 - 0.0281 \times \text{In}(DBH)^3] \quad \text{Equation 3}$$

- The regional allometric equation of Fayolle et al. (2013) used was:

$$AGB = \rho \times \exp(-1.183 + 1.940 \times \text{In}(D) + 0.239 \times (\text{In}(D))^2 - 0.0285 \times (\text{In}(D))^3 \quad \text{Equation 4}$$

- The site specific allometric equation of Djomo et al. (2010) used to determine the AGB was:

$$AGB = \exp(-1.8623 + 2.4023 \ln(D) - 0.3414 \ln(\rho)) \quad \text{Equation 5}$$

Where DBH or D = diameter at breast height in centimeter, ρ_s or ρ = specific wood density in all equations. For species without wood densities, an average for the genera or family was used.

The data was sub-sample into two categories: individuals with diameter < 10 cm and individuals with diameter ≥ 10 cm) in order to assess tree stands of the different diameter class that occupy different strata. The AGB values of individual stems were summed to get the total AGB of each forest type. Hence, for each forest type, the following were calculated:

i) Changes in AGB over time;

$$AGB_{2011} - AGB_{2005} \quad \text{Equation 6}$$

ii) Annualized net change in AGB for each forest types as;

$$AGB_{2011} - AGB_{2005}/T \quad \text{Equation 7}$$

iii) Recovery rates of AGB as;

$$((X_{2011} - X_{2005})/X_{2005}) \times 100 \quad \text{Equation 8}$$

(According to Martin et al. (2013) with slight modification)

The Aboveground Carbon Stock (ACS) was determined according to Zapfack et al. (2013) which basically estimates the amount of Carbon stock by multiplying the biomass by 0.47.

C) Evaluation of the Belowground biomass Carbon Stock (BCS) after selective logging in the East Region of Cameroon.

The Belowground biomass (BGB) was determined using recommendations from:

- Mokany et al. (2006): BGB = 0.21 × AGB Equation 9
- Cairns et al. (1997): BGB = Exp (−1.085 + 0.9256 × ln(ABG)) Equation 10

The difference in their estimations of BGB was compared and BCS calculated according to Zapfack et al. (2013).

D) Soil Organic Carbon after selective logging in the East Region of Cameroon.

Soil samples of the different forest types were collected in triplicates across soil depths of 0 - 5 cm, 5 - 15 cm and 15 - 30 cm using a soil corer and auger. This was air dried, sieved using a 2 mm sieve, put in zip lock bags with codes and analyzed at the University of Dschang soil laboratory. Soil Organic Carbon (%SOC) was evaluated by chromic acid digestion and spectrophotometric analyses (Haynes, 1984).

2.3. Statistical Analyses

We calculated the aboveground biomass of each plot by summing the estimated biomass of each stem for species. We separated the size classes of all the stems into two groups (<10 cm ≥10 cm) and compared the forest type means of the aboveground biomass estimated by the allometry equations. To test for differences in the means, One-way analysis of variance (ANOVA) was used where *P*-values less than 0.05 were considered significant. We used MINITAB version 17 for all summary statistics (measures of central tendencies) and inferential statistics (ANOVA and t-test). The Turkey's Honesty Test was used to separate means which differed from one another. Multivariate statistics such as the Principal Component Analysis (PCA) was used to describe the variation of selected timber species by forest types. Diversity indices (Shannon-Weiner) and Jaccard similarity were all computed in PAST statistical package.

3. Results

3.1. Stand Composition after Selective Logging in the East Region of Cameroon

The six, 1 ha permanent monitoring plots sampled for trees ≥ 2 cm dbh contained on average 3744 stems/ha in 2005, with the highest obtained from the unlogged forest (4191 ± 46.9 stems/ha) and the least obtained from forests of 11YAL (3808 ± 51.2 stems /ha). In 2011, the average number of individuals decreased to 2993 stems/ha with the unlogged forest having the highest plant density (3405 ± 39.3 stems/ha) and the least in the forests of 11YAL (2440 ± 27.0 stems/ha). This led to 79.9% of the initial plants being censured and a reduction of 20% (**Table 2**).

The percentage change in plant density and species richness was highest in the forests of 11YAL. The species richness (294 - 281 in 2011), number of genera (162 - 157 in 2011) and number of identified families (51 - 50 in 2011) decreased with the highest in the forests of 21 YAL in both inventories. Proportions of fully identified and unidentified families did not differ between logged and unlogged forest (**Table 2**).

Table 2. Plant density and species richness after selective logging in the East Region of Cameroon.

Forest type	Plant density (stems/ha)			Species richness (S/ha)			Number of genera			N/S ratio		Number of identified families	
	2005	2011	%C	2005	2011	%C	2005	2011	%C	2005	2011	2005	2011
Unlogged	4191 ± 46.9	3405 ± 39.3	18.8	279 ± 8.0	266 ± 7.6	4.7	171(2)	163(2)	4.7	15.0	**12.8**	50 (2)*	49(3)*
11 YAL	3235 ± 36.6	2440 ± 27.0	**24.6**	297 ± 7.8	280 ± 7.3	**5.7**	154(5)	147(5)	4.5	10.9	8.7	**50 (1)***	**50(3)***
21 YAL	3808 ± 51.2	3134 ± 40.1	21.8	306 ± 8.2	298 ± 7.5	2.6	161 (3)	163(6)	**−1.2**	12.5	10.5	51 (3)*	51(3)*
TOTAL (3 ha)	11234 ± 134.7	8979 ± 106.4	20.1	882	844	4.3	486	473	2.6	38.4	32	151 (6)	150 (9)
Total/ha	3744	2993	20.1	294	281	4.4	162	157	3.1	12.8	10.7	51	50
% Recensured		(79. 9%)											

Values for plant density and species richness were reported in mean ± standard error while for number of genera and families the values in ()*represent unidentified individuals. Figures in bold indicate the highest or the lowest.

3.2. Temporal Change of the Most Important Species (IVI) and Family (FIV) after Selective Logging in the East Region of Cameroon

After selective logging there was no change in the most important species in the forests of 21 YAL and the unlogged forests as *Sloetiopsis usambarensis* was the most important species in 2005 and 2011. However, there was a change in the forests of 11YAL from *Meiocarpidium lepidotium* to *Keayodendron bridelioides*. Contrarily, there was a constant change in the most important family for all the forest types with the Euphorbiaceae being the most important in the unlogged forest (31.6) and forests of 11YAL (31.6) in 2011. The Violaceae (43.38) family was the most important family in the forests 21 YAL and it had the highest FIV in the whole study in 2011. The least FIV was found in Euphorbiaceae in the forests of 11YAL and the unlogged forest (31.64). The number of families increased from 50 to 51 families from 2005 to 2011 as the logged forests maintained their number of families, while the unlogged forest had a decrease (Table 3).

Table 3. Change in the most important species (IVI) and family (FIV) after selective logging in the East Region of Cameroon.

Forest types	Census Year	Most important species	IVI	Most important family	FIV
Unlogged	2005	*Sloetiopsis usambarensis*	17.51	Putrangivaceae	36.63
	2011	*Sloetiopsis usambarensis*	19.37	Euphorbiaceae	31.64
11YAL	2005	*Meiocarpidium lepidotium*	15.69	Annonaceae	31.30
	2011	*Clerodendron bridelioides*	28.21	Euphorbiaceae	31.64
21 YAL	2005	*Sloetiopsis usambarensis*	26.70	Sterculiaceae	35.58
	2011	*Sloetiopsis usambarensis*	27.20	Violaceae	43.38

Figures in bold indicate the highest or the lowest.

3.3. The Most Common Species after Selective Logging in the East Region of Cameroon

Sloetiopsis usambarensis was the most common species in the unlogged forests

Table 4. Most common tree species after selective logging in the East Region of Cameroon.

Forest type	Census Year	Most common species	Family	Abundance	% Abundance
Unlogged	2005	*Sloetiopsis usambarensis*	Moraceae	616	15.8
	2011	*Sloetiopsis usambarensis*	Moraceae	538	14.7
11YAL	2005	*Rinorea sciaphila*	Violaceae	303	9.4
	2011	*Rinorea sciaphila*	Violaceae	214	8.8
21 YAL	2005	*Sloetiopsis usambarensis*	Moraceae	711	18.6
	2011	*Sloetiopsis usambarensis*	Moraceae	553	**17.7**

Figures in bold indicate the highest or the lowest.

Table 5. 10 most common tree species after selective logging in the East Region of Cameroon.

		2005 CENSUS						2011 CENSUS							
SPECIES	FAMILY	Unlogged		11 YAL		21 YAL		Unlogged		11 YAL		T3		Overall	
		A	R	A	R	A	R	A	R	A	R	A	R	A	R
Sloetiopsis usambarensis	**Moraceae**	**616**	**1**	**0**	**0**	**711**	**1**	**538**	**1**	**0**	**0**	**553**	**1**	**1091**	**1**
Meiocarpidium Lepidotum	Annonaceae	0	0	196	4	0	0	0	0	164	3	0	0	164	10
Rinorea sciaphila	**Violaceae**	**98**	**10**	**302**	**1**	**128**	**7**	**86**	**8**	**214**	**1**	**115**	**6**	**415**	**5**
Millettia barteri	**Fabaceae**	**267**	**3**	**284**	**2**	**253**	**2**	**207**	**3**	**192**	**2**	**202**	**2**	**601**	**2**
Rinorea dentata	Violaceae	312	2	0	0	93	10	252	2	0	0	79	10	331	7
Musanga cecropioides	Urticaceae	0	0	135	7	0	0	0	0	60	7	0	0	60	14
Drypetes preussii	Putrangivaceae	100	9	0	0	0	0	82	9	0	0	0	0	82	13
Diospyros sp	**Ebenaceae**	**148**	**7**	**166**	**5**	**183**	**3**	**121**	**7**	**126**	**5**	**152**	**3**	**399**	**4**
Rinorea brachypetala	**Violaceae**	**216**	**4**	**210**	**3**	**181**	**4**	**170**	**4**	**160**	**4**	**150**	**4**	**480**	**3**
Drypetes molunduana	Putrangivaceae	199	5	0	0	0	0	163	5	0	0	0	0	163	11
Tabernaemontana brachyantha	**Apocynaceae**	**155**	**6**	**159**	**6**	**145**	**6**	**124**	**6**	**116**	**6**	**112**	**7**	**352**	**6**
Drypetes ivorensis	Putrangivaceae	0	0	85	8	155	5	0	0	57	8	120	5	177	9
Trichilia rubescens	**Meliaceae**	**103**	**8**	**78**	**9**	**117**	**8**	**77**	**10**	**54**	**9**	**90**	**8**	**221**	**8**
Pennianthus sp	Menispermaceae	0	0	59	10	0	0	0	0	48	10	0	0	48	15
Rinorea oblongifolia	Violaceae	0	0	0	0	107	9	0	0	0	0	84	9	84	12

A = Abundance, R=Ranking. Figures in bold represent species present in all forest types while figures in red represent species that maintained a particular rank in both inventories. Figures in bold indicate the highest or the lowest.

and forests of 21 YAL; while in the forests of 11 YAL *Rinorea sciaphila* was the most common. The forests of 21 YAL had the highest abundance of common species; accounting for 17.7% of the total abundance (Table 4). However, the top 10 most abundant species in every forest type accounted for almost half of the overall abundance of the most common species. The 50 abundant common species in the various forest types are noted in Appendix. Some of the 10 most exploitable species in Cameroon like *Entandrophragma cylindricum* (Sapeli) *Triplochiton scleroxylon* (Ayous) *Pterocarpus soyauxii* (Red padouk), *Erythrophleum sauveolens* (Tali), *Milicia excelsa* (Iroko) and *Terminalia superba* (Frake) were recorded in the forests of 11YAL and forests of 21 YAL respectively in 2011 (Table 5).

Rinorea sciaphila, Millettia barteri, Diospyros sp, Rinorea brachypetala, Tabernaemontana brachyantha, and *Trichillia rubescens* were present in all the forest. *Rinorea brachypetala* and *Sloetiopsis usambarensis* held the same rank in all the forest types (Table 5).

3.4. Tree Species Rarity and Singletons after Selective Logging in the East Region of Cameroon

Tree species became rare in 2011 for all forest types. The forests of 11YAL had the highest number of singletons (142/ha in 2005 and 143/ha in 2011) while the least was found in the unlogged forests (97/ha in 2005 and 100/ha in 2011), making the forests of 11YAL having the rarest species (Table 6).

Table 6. Tree species rarity after selective logging in the East Region of Cameroon.

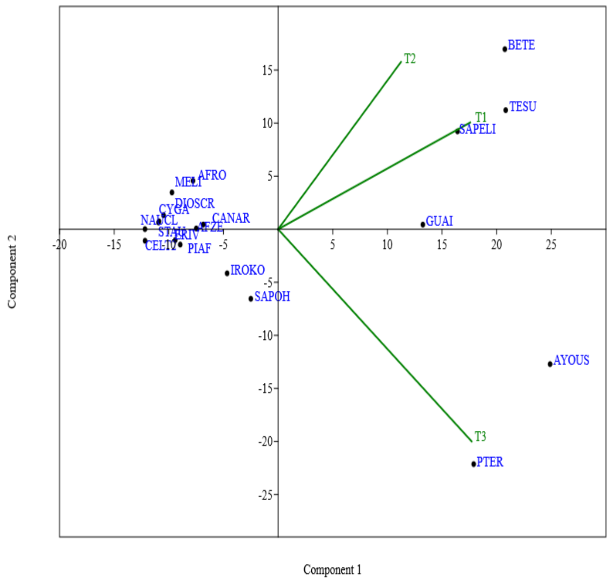
Forest types	Census year	Number of singletons	Rarity	% rarity
Unlogged	2005	97	0.3	34.8
	2011	100	0.4	**37.6**
11YAL	2005	142	0.5	47.8
	2011	143	0.5	**51.1**
21 YAL	2005	138	0.5	45.1
	2011	142	0.5	47.7

Figures in bold indicate the highest or the lowest.

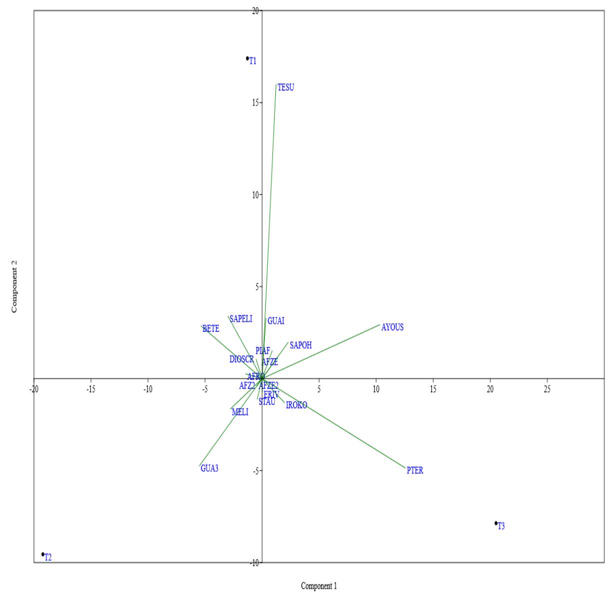
3.5. Tree Species Ordination

In order to determine the variation of identified timber species among plots in each forest type, we carried out a Principal Component Analysis (PCA) which is direct ordination analysis. The result indicated that there was an increase in the timber species over time among all forest types (Figure 2). In 2005, the timber species present were *Guarea thompsonii, Mansonia altissima, Entandrophragma cylindricum, and Terminalia superba* in the unlogged forests and forests logged 5 years ago (T1 and T2 respectively) indicating their similarity. While the timber species present in T3 were *Pterocarpus soyauxii and Triplochiton scleroxylon.* In 2011, there was an increase in the timber species in T1 with the species *Mansonia altissima, Entandrophragma cylindricum, Pericopsis elata and Diospyros crassifolia.* In T2, the timber species were *Guarea thompsonii, Afzelia* sp., and *Entan-*

drophragma utile. In T3, the timber species were *Pterocarpus soyauxii,Erythrophleum suaveolens, Milicia excelsa, Staudtii gabonensis, Ficus sp. and Afzelia sp.* Thus there was generally an increase in all forest types with the forest logged 21 years ago having the highest amount of timber (**Figure 2**).



(a)



(b)

Figure 2. The variation of identified exploitable timber species in 2005 (a) and 2011 (b). **T1** is an unlogged plot, **T2** is logged 11 years and **T3** is logged 21 years.

SAPELI = *Entandrophragma cylindricum*, SAPO = *Gambeya boukokoensis,* STERT = *Sterculia rhinopetala,* AFRO = *Pericopsis elata, AFZE = Afzelia sp,* ALBO = *Alstonia boonei,* MELI = *Entandrophragma utile,* EROB = *Eribroma oblongum,* DESBO = *Desbordesia glaucescens,* NAUCL = *Nauclea diderrichii,* BETE = *Man-*

sonia altissima CANAR = *Canarium schweinfurthii, FRIV = Ficus sp.* COMAF = *Combretodendron africanum,* CYGA = *Cylicodiscus gabonensis*, PYCN = *Pycnanthus angolensis,* PIAF = *Piptadeniastrum africanum*, NEPA = *Nesogordonia papaverifera,* ERIV = *Erythrophleum suaveolens,* TESU = *Terminalia superba*, IROKO = *Milicia excelsa*, CELT2 = *Celstis tessmannii,* PTER = *Pterocarpus soyauxii*, DIOSCR = *Diospyros crassifolia*, GUAI = *Guarea thompsonii,* AYOUS = *Triplochiton scleroxylon., AFZ2 = Afzelia sp, STAU = Staudtii gabonensis, AFZE2 = Afzelia sp.*

3.6. Forest Diversity after Selective Logging in the East Region of Cameroon

Diversity decreased in the unlogged forests, maintained in forests of 11YAL and increased in forests of 21 YAL. However, the unlogged forests were more even (0.24) than the logged forests while the unlogged forest and the forest 21 YAL were most similar (0.97) than the forests of 11YAL (Table 7).

Table 7. Diversity and similarity after selective logging in the East Region of Cameroon.

	Shannon		Evenness		Similarity index		
Forest type	**2005**	**2011**	**2005**	**2011**	**Unlogged**	**11 YAL**	**21YAL**
Unlogged	3.9	3.8	0.24	**0.23**			
11 YAL	3.7	3.7	0.21	0.22	**0.63**		
21 YAL	3.6	3.7	0.18	0.19	**0.97**	0.95	

Figures in bold indicate the highest or the lowest.

We observed species found in Cameroon's commercial list of exploitable species at different diameter size classes. However, the exploitable species in the < 10 cm dbh had the highest number of individuals especially in the forests of 11YAL (Figure 3).

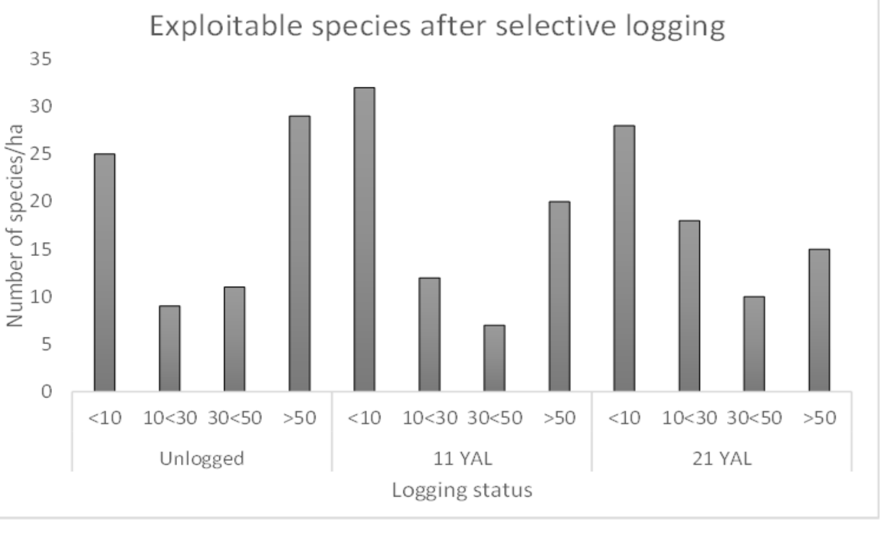


Figure 3. Diameter class distribution of exploitable tree species after selective logging in the East Region of Cameroon.

3.7. Carbon Stock Recovery after Selective Logging in the East Region of Cameroon

a) Aboveground Carbon Stock (ACS)

There was no significant difference in the determination of the AGB using the Pantropical equation of Chave et al. (2005) and the regional and site specific allometric equations of Fayolle et al. (2013) and Djomo et al. (2010) respectively (**Table 8**). *Triplochiton scleroxylon* had the highest AGB and consequently the ACS in the unlogged and the forests of 21 YAL in both inventories. In the forests of 11YAL, there was a change in the highest AGB and ACS from 2005 (*Triplochiton scleroxylon*) to 2011 from (*Polyalthia suaveolens*) (**Table 9**).

Table 8. Mean AGB using different allometric equations in the East Region of Cameroon.

Forest	YAL	DBH size class (cm)	Chave et al. (2005)	Fayolle et al. (2013)	Djomo et al. (2010)	F-value	P-value
1	UNLOGGED	<10	115.5 ± 26.7	112.0 ± 25.8	154.5 ± 43.8	0.5	0.604
		≥10	4418 ± 1274	5006 ± 1433	6111 ± 1995	0.29	0.749
2	UNLOGGED	<10	119.5 ± 25.6	116.0 ± 24.7	136 ± 27.3	0.19	0.831
		≥10	4108 ± 1088	4690 ± 1252	5078 ± 1528	0.14	0.869
3	11 YAL	<10	92.3 ± 23.0	89.6 ± 22.3	122.2 ± 29.7	0.52	0.597
		≥10	2793 ± 692	3191 ± 797	3450 ± 909	0.17	0.844
4	11 YAL	<10	95.7 ± 23.7	92.9 ± 22.9	111.8 ± 24.6	0.19	0.831
		≥10	3775 ± 808	4258 ± 907	5267 ± 1299	0.55	0.578
5	21 YAL	<10	115.9 ± 34.3	112.5 ± 33.2	157.4 ± 58.3	0.33	0.719
		≥10	4439 ± 1292	4982 ± 1441	5241 ± 1553	0.08	0.922
6	21 YAL	<10	116.3 ± 27.9	112.8 ± 27.0	133.7 ± 27.8	0.17	0.848
		≥10	3695 ± 1302	4192 ± 1456	4911 ± 2001	0.14	0.866

Table 9. Tree species with the highest Above ground biomass Carbon Stock (ACS) after selective logging in the East Region of Cameroon.

Forest type		Species	AGB (Mg/ha)	ACS (Mg/ha)
Unlogged	2005	*Triplochiton scleroxylon*	81.8	38.5
	2011	*Triplochiton scleroxylon*	97.7	45.9
11YAL	2005	*Triplochiton scleroxylon*	37.6	17.7
	2011	*Polyalthia suaveolens*	59.6	28.0
21 YAL	2005	*Triplochiton scleroxylon*	101.3	47.6
	2011	*Triplochiton scleroxylon*	99.9	47.0

Figures in bold indicate the highest or the lowest.

While mean AGB values varied numerically, the differences were not significant ($P \leq 0.83$) with an increase over time from 541.4 - 961.8 Mg/ha in 2011. The unlogged forests had the highest AGB and ACS (961.8 Mg/ha and 452.1 Mg/ha) while the forests of 11YAL had the least (650.8 Mg/ha and 305.9 Mg/ha) respectively (**Table 10**). The mean AGB increased in all forest types for stems > 10 cm diameter size class with the highest in the unlogged forest and least in the forests of 11YAL. The mean AGB decreased in all forest types in stems < 10 cm except in the unlogged forest. A change in the AGB over time indicated that individuals in the < 10 cm had the least change in AGB in logged forests while individuals in the > 10 cm had the highest change in all forest types. However all forest types recovered more than 50% of its AGB with the forests of 11YAL (80.7%) having the highest and the forests of 21YAL (59.4%) having the least.

Table 10. Mean AGB and ACS after selective logging in the East Region of Cameroon.

	Unlogged (Mg/ha)				11YAL (Mg/ha)				21 YAL (Mg/ha)			
Exploitation year	**2005**		**2011**		**2005**		**2011**		**2005**		**2011**	
DBH	<10 cm	>10 cm	<10 cm	>10 cm	<10 cm	>10 cm	<10 cm	>10 cm	<10 cm	>10 cm	<10 cm	>10 cm
Mean AGB	0.08 ± 0.01	3.5 ± 0.8	0.10 ± 0.02	5.3 ± 0.9	0.06 ± 0.02	2.8 ± 0.6	4.6 ± 0.8	0.05 ± 0.01	0.08 ± 0.02	3.2 ± 0.9	0.07 ± 0.02	4.3 ± 0.1
Total AGB	541.4		**961.8**		359		**650.8**		446.7		713.1	
ACS	254.5		**452.1**		168.7		**305.9**		210		335.2	
Change in AGB	-	-	4.1	416.5	-	-	−2.1	291.9	-	-	−0.91	266.7
% Recovered	77.7				**80.7**				59.4			

Figures in bold indicate the highest or the lowest.

b) Belowground biomass Carbon Stock (BCS) after selective logging in the East Region of Cameroon.

There was no significant difference in the BGB using the formulae of Cairns et al. (1997) and Mokany et al. (2006) in the calculations of the BGB of the different forest types (**Table 11**). The BGB was highest in unlogged forests and least in the forests of 11YAL in both inventories (**Table 11**). However the BCS was highest in the forests 21YAL and least in the unlogged forests after logging (**Table 11**).

Table 11. Determination of the BGB and BCS after selective logging in the East Region of Cameroon.

DBH size class	Cairns et al. (1997)		Mokany et al. (2006)		BCS	
	2005	**2011**	**2005**	**2011**	**2005**	**2011**
Unlogged	**1.1 ± 0.2**	**1.0 ± 0.2**	**0.7 ± 0.2**	**1.5 ± 0.3**	**1594 ± 374**	3353 ± 701
11 YAL	0.8 ± 0.1	1.4 ± 0.5	0.5 ± 0.1	2.6 ± 1.1	1212 ± 249	5796 ± 2503
21YAL	1.0 ± 0.3	1.4 ± 0.4	0.4 ± 0.2	2.6 ± 0.9	1429 ± 398	**5854 ± 1936**
P-value	0.3	0.4	0.3	0.4		
F-value	1.1	1.1	1.1	1.1		

Figures in bold indicate the highest or the lowest.

c) Soil Organic Carbon (SOC) after selective logging in the East Region of Cameroon.

The SOC was not significantly ($p \geq 0.65$) different across the different forest types and soil depth ($p \geq 0.1$). The mean % SOC was highest in forests of 11YAL (4.1 ± 1.2) and least in the unlogged forests (3.5 ± 0.1) with a decrease of the % SOC with an increase in soil depth in all forest types (**Table 12**).

Table 12. Percentage Soil Organic Carbon (SOC) after selective logging at different soil depths in the East Region of Cameroon.

Soil depth	0 - 5 cm	5 - 15 cm	15 - 30 cm	Mean
Unlogged	3.6%	3.5%	**3.4%**	3.5 ± 0.1
11 YAL	**5.4%**	3.9%	3.1%	**4.1 ± 1.2**
21 YAL	4.9%	**4.0%**	3.3%	4.1 ± 0.8

Figures in bold indicate the highest or the lowest.

4. Discussion

The objective of this study was to determine the carbon stock recovery of a tropical forest after selective logging using different allometric equations in the East Region of Cameroon. A 20% reduction in the number of recensured plants may be due to natural causes (tree fall, mortality) and anthropogenic activities (illegal logging and farming activities) in the logged and unlogged forests decreasing the number of individuals. However, the logged forests had the highest % change in the stand composition due to collateral damages and death of individuals, species and genera after logging. Our findings were consistent with previous studies that have investigated how the removal of large-size trees altered the composition and structure of the forest (Diway et al., 2023; Hayward et al., 2021).

There were commercial species of exploitable diameter that were still present in all the forest types. It is unsurprising that there were more trees above harvestable size in the unlogged forests, but the relatively high abundance of exploitable tree species of harvestable sizes in the logged forest especially in the ≥ 50 cm suggests that trees of commercial species in the remnant cohort survived within or were recruited into the logged areas after logging. Commercial trees of ≥ 50 cm DBH size classes in logged forests could also be potential seed/pollen sources left during logging as their absence would generally reduce recruitment and regeneration of species and individuals. Also there was a high density of individuals in the < 10 cm DBH size-class in the forests of 11 YAL. With canopy openness after selective logging, seeds in the soil seed bank and nearby secondary forests became activated due to the presence of light and then eventually germinated to increase the number of species in the < 10 cm DBH size-class. This highlights the potential for regeneration in logged forest and therefore indicates the necessity of an assessment of natural regeneration in selectively logged forests as a useful tool for sustainable forest management. This also calls for silvicultural management of selectively logged sites. This result is consistent with other studies in Sabah, Malaysia (Berry et al., 2008). However, a reduction in the density of individuals in unlogged forests for DBH size classes 10 - 40 cm may be due to illegal logging being carried out or the growth of remnant cohorts to higher DBH size classes. Evidence from the comparisons of PCA axis scores between logged and unlogged forest, indicated that natural regeneration will not be enough even 21YAL to control the effects of selectively logging; thus the need for silvicultural management. This is in line with the studies of Hayward et al. (2021) who indicated that the effect of selective logging can still be observed 23 - 35 YAL.

Though the diversity decreased in the unlogged forest, species evenness was highest which may be due to canopy formation that prevents seed establishment from nearby vegetation. The forests of 21 YAL, though having a canopy, had already been opened to received seeds from the nearby forest vegetation thereby increasing its diversity. This high diversity in the logged forests is different from the results obtained from other selectively logged forests that had lower diversity in Peninsular Malaysia (Okuda et al., 2003) and Central Kalimantan, Indonesia (Brearley et al., 2004). This difference may be due to additional disturbance in the logged forests leading to further degradation and thus decreasing the diversity. Maximum diversity is predicted with repeated local disturbances that are frequent enough to prevent competitive exclusion over an entire area, but not so frequent as to eliminate most species (Whittaker et al., 2001). The unlogged forests and forests of 21 YAL were greatly similar in diversity, indicating their change towards a stable primary forest; consistent with studies carried out in the forest of 13 YAL (Bischoff et al., 2005) and 5 - 20 YAL (Verburg & van Eijk-Bos, 2003). The lack of difference in alpha diversity seen here suggests that the disturbance from logging was not severe enough to prevent the maintenance of a species-rich tree community.

The insignificant difference in the AGB estimate using Pan tropical, regional and site specific allometric equations is an indication firstly that mixed-species regression equations provide good estimates of the total aboveground biomass when the diameter and wood density are input variables. Djomo et al. (2010) in the Campo-Ma'an forest in Cameroon using only diameter as input variable, indicated an average error of only 7.4%. This was confirmed by Fayolle et al. (2018) in Central African forests who indicated that the diameter and wood density had a significant influence on the calculations of AGB. Secondly, this is an indication that the equation of Chave et al. (2005) is a good reference for the calculations of AGB in moist tropical forests as it takes into consideration both the wood density and the DBH (Gourlet-Fleury et al., 2013) which are the variables which have a significant difference in the calculations of the AGB using allometric equations (Brown, 2002). Also the Chave et al. (2005) pantropical allometric equation is attributed to a large input of dataset of 2410 trees ≥ 5 cm diameter from 27 study sites across the tropics used for the development of this equation and one of such sites is in the South eastern part of Cameroon (Djomo et al., 2010; Chave et al., 2005; Fayolle et al., 2013). Site-specific allometric equations are required only in localized sites when the generalized equations may not adequately represent all forest types (Gibbs et al., 2007). This may be true where forest types have specific growth patterns, and unique species compositions such as young regenerating forests, areas of shifting cultivation mosaic, areas undergoing heavy selective cutting resulting in stunted trees, and abandoned plantations.

The more than 50% of recovery rates of the ACS, may be due to the fact that during regeneration, the recuperation of forest composition, biomass and carbon is initiated, promoting the recovery of the forest areas to a state of maturity or at least to a state prior to that of the disturbance, in a few decades. This is similar to the studies of Rutishauser et al. (2015) who indicated that 7 - 21 years is required to recover their initial ACS, in the Amazon and Butarbutar et al. (2019) who indicated that the recovery time of the aboveground carbon is between 26 - 46 years even after silvicultural treatment in the tropical forest of Indonesia. Thus ours study indicates that at 21 years, the forest had already recovered more than 50% of the initial ACS.

The observed pattern showed an increase in the growth of biomass in logged compared to unlogged forests as reported in GourletFleury et al. 2013. The highest AGB in the forests of 11 YAL may be due to the fast growth of the remnant cohort of species after logging (Fayolle et al., 2013). As observed by some authors (Gourlet-Fleury et al., 2004; Suarez et al., 2019), openings increased the growth of remaining trees and the recruitment of new trees, with an increase in the proportion of fast-growing pioneers. Specifically, Suarez et al. (2019) indicated that the biomass accumulation rate of secondary forests (≤20 years) in Africa is 5.8 times that of primary forests. Gourlet-Fleury et al. (2013) in a similar study found that after selective logging, the gain in biomass proved to be high leading to fast recovery rates of the AGB. The gain however, decreased with time since the forests of 21 YAL had a lower AGB in our study; due to competition which increased as stands accumulated biomass.

The observed decreased in AGB and ACS 21YAL may be due to the forests losing large timber species after disturbance mostly which are light demanding timber species (non-pioneer timber species) which have high wood density which takes time to recover (as in the forests of 21 YAL) as opposed to the pioneer species which immediately sprout up after logging (11YAL) with low wood density. With time these pioneer species fade out giving way to non-pioneer species. In literature, it has been well established that it is impossible for a first-time-logged tropical forest to recover its timber stock within the usual duration of a felling cycle (synthesis in Putz et al., 2012). Rutishauser et al. (2015) found that the aboveground carbon pool recovered within 75 - 85 years after disturbance as Bourgoin et al. (2024) indicated that tropical moist forests don't significantly recover from canopy loss, after 30 years following disturbance such as fire and selective logging. Additionally, Poorter et al. (2016) reported the annual ACS recovery for tropical forest is 1 - 3 Mg C/ha/yr in a decade after logging and 3 – 5 Mg C/ha/yr in two decades. These findings are supported by our study with a net annual recovery of 4.3 and 2.1 Mg C/ha/yr after selective logging in the forests of 11 and 21 YAL respectively. Thus, further research is required to determine the required time to get to the initial climax carbon pool in Cameroon.

A higher ACS in the unlogged forests than in the similar forests of 21 YAL may be due to the fact that in the process of forest succession, plant community composition has an important impact on biomass stocks. At the early stages of succession, fast-growing species have a higher contribution, while the contribution of slow-growing is significant at later stages of succession (Shimamoto et al., 2014), due to the change in biomass accumulation patterns over time; plant composition along successional trajectories and the different succession stages that have different biomass allocation patterns under light-limited conditions. This is in line with Vieira et al. (2004) who observed that the 10 - 20 cm DBH size class which is more prominent in the logged forests contains as much as 14% of total ACS and may be highly dynamic in some Amazonian forests.

The high BCS in the forests logged 21YAL may be due to the increased number of individuals that arise after logging. The removal of timber tree species decreases the ACS and subsequently the BCS. This however increases as the forest gets back to a stable primary state. Optimal partitioning theory suggests that plants allocate more resources to the organ that acquires the most limiting resource (Johnson & Thornley, 1987). Accordingly, plants would allocate more carbon to roots if the limiting resources are belowground, i.e. water and nutrients, and would allocate more carbon aboveground when the limiting resource is light or CO_2. In the forests logged 21YAL the limiting factor is water and nutrients due to a rapid increase in the number of individuals just after logging, thus an increase in the BCS. Also the destruction of the canopy encourages the growth of individuals in the <10 cm DBH size class which presumably invest more biomass below ground to take up nutrients and water for fast growth and survival.

The non-significant alteration in soil organic carbon encountered in this study revealed that selective logging doesn't extensively change the soil entirely but acts locally in the area of logging. However, the amount of most nutrients increased in the logged sites. This could be related to high release of nutrients via the decomposition processes thereby reflecting the greater input from organic matter from the logging process. Additionally, the decrease in soil carbon stock with soil depth might be due to the decomposition of litter at the top soil, which contains more nutrients at the top soil than at the lower soil depths. The effect of selective logging 21 YAL indicates that the impact is felt after a very long time. The duration of nutrients released from decomposed stems, twigs and leaves of trees damaged by logging may thus explain the substantial but long-duration release of nutrients on these nutrient-poor soils.

Implications for Forest Management and Climate Change

The study goal was to determine the change of the forest and subsequently the carbon stock recovery in a tropical forest using different allometric equations after selective logging. This was to fill the information gaps for forest managers and decision makers and practical guidance to define sustainable harvest intensities or cutting rotations that at the same time ensure long-term timber harvest, maintenance of biodiversity and carbon stocks. This provides forest managers and policy makers with preliminary information before any effective conclusive decision can be made, taking into consideration that alternative management methods like the Reduced Impact Logging (RIL) exist to maximize a compromise between timber production and preservation of the environment.

One of the targets of sustainable forestry would be continuous timber production in every term of logging practice. Our results indicate that though there was a high forest stem density of timber species after logging, the composition and timber stock was still different from the initial forests. It is therefore recommended that the high timber density in the smaller DBH size class after logging should be maintained through silvicultural activities which will ensure future timber exploitation. This is also a call for timber exploiters to think of the exploitation of lesser known timber species with similar commercial timber qualities such as *Polyalthia suaveolens* which is a lesser known species was abundant in this study. With respect to climate change the real problem lies in the recovery rate of the carbon stock after selective logging as this study concluded that a 30-years cycle is not sufficient for carbon stock recovery in the East Region of Cameroon. Thus further research is required to confirm the rotation cycle of 30 years stipulated by the 1994 Forestry law of Cameroon in order to know the exact time for timber stock recovery that is very necessary to combat climate change.

5. Conclusion

In a nutshell, this study showed that carbon and biomass recovery after selective logging in a tropical forest like the Eastern forest in Cameroon do not accumulate at the same rate as the unlogged forests due to the change in the species composition after the removal of key commercial species. Thus, further research over a larger surface area and on a longer time frame is required for more conclusive information on the Carbon stock recovery after selective logging; as on a regional scale, alternative management methods of exploitation may coexist to maximize a compromise between timber production and preservation of the environment.

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Author's Contribution

Seraphine E. Mokake: In charge of the research design, supervision of field work and data collection, guided analysis and interpretation, and wrote manuscript. Chuyong George was the CTFS representative and project coordinator who suggested the topic and the research design, contributed in perfecting the methodology and analyses and reviewed the manuscript. Egbe E. Andrew contributed in research concept and design and reviewed the manuscript. Lyonga M. Ngoh: analysed data collected, contributed in the research concept and design and methodology. Also contributed in data interpretation and review of manuscript.

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Data Availability Statement

Data are available within the article and/or its supplementary materials.

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

The authors all accept the publication of this work.

Conflicts of Interest

The authors declare that they have no competing interests.

References

Alvarez, E., Duque, A., Saldarriaga, J., Cabrera, K., de las Salas, G., del Valle, I. et al. (2012). Tree Above-Ground Biomass Allometries for Carbon Stocks Estimation in the Natural Forests of Colombia. *Forest Ecology and Management, 267,* 297-308. https://doi.org/10.1016/j.foreco.2011.12.013

Angiosperm Phylogeny Group III: An Update of the Angiosperm Phylogeny Group (APG) (2009). Classification of the Orders and Families of Flowering Plants: APG III. *Botanical Journal of Linnean Society, 85,* 531-553.

Asner, G. P., Broadbent, E. N., Oliveira, P. J. C., Keller, M., Knapp, D. E., & Silva, J. N. M. (2006). Condition and Fate of Logged Forests in the Brazilian Amazon. *Proceedings of the National Academy of Sciences, 103,* 12947-12950. https://doi.org/10.1073/pnas.0604093103

Berry, N. J., Phillips, O. L., Ong, R. C., & Hamer, K. C. (2008). Impacts of Selective Logging on Tree Diversity across a Rainforest Landscape: The Importance of Spatial Scale. *Landscape Ecology, 23,* 915-929. https://doi.org/10.1007/s10980-008-9248-1

Bischoff, W., Newbery, D. M., Lingenfelder, M., Schnaeckel, R., Petol, G. H., Madani, L. et al. (2005). Secondary Succession and Dipterocarp Recruitment in Bornean Rain Forest after Logging. *Forest Ecology and Management, 218,* 174-192. https://doi.org/10.1016/j.foreco.2005.07.009

Bourgoin, C., Ceccherini, G., Girardello, M., Vancutsem, C., Avitabile, V., Beck, P. S. A. et al. (2024). Human Degradation of Tropical Moist Forests Is Greater than Previously Estimated. *Nature, 631,* 570-576. https://doi.org/10.1038/s41586-024-07629-0

Brearley, F. Q., Prajadinata, S., Kidd, P. S., Proctor, J., & Suriantata (2004). Structure and Floristics of an Old Secondary Rain Forest in Central Kalimantan, Indonesia, and a Comparison with Adjacent Primary Forest. *Forest Ecology and Management, 195,* 385-397. https://doi.org/10.1016/j.foreco.2004.02.048

Brown, S. (2002). Measuring Carbon in Forests: Current Status and Future Challenges. *Environmental Pollution, 116,* 363-372. https://doi.org/10.1016/s0269-7491(01)00212-3

Brown, S., Gillespie, A. J. R., & Lugo, A. E. (1989). Biomass Estimation Methods for Tropical Forests with Applications to Forest Inventory Data. *Forest Science, 35,* 881-902. https://doi.org/10.1093/forestscience/35.4.881

Butarbutar, T., Soedirman, S., Neupane, P. R., & Köhl, M. (2019). Carbon Recovery Following Selective Logging in Tropical Rainforests in Kalimantan, Indonesia. *Forest Ecosystems, 6,* 1-14. https://doi.org/10.1186/s40663-019-0195-x

Cairns, M. A., Brown, S., Helmer, E. H., & Baumgardner, G. A. (1997). Root Biomass Allocation in the World's Upland Forests. *Oecologia, 111,* 1-11. https://doi.org/10.1007/s004420050201

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D. et al. (2005). Tree Allometry and Improved Estimation of Carbon Stocks and Balance in Tropical Forests. *Oecologia, 145,* 87-99. https://doi.org/10.1007/s00442-005-0100-x

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C. et al. (2014). Improved Allometric Models to Estimate the Aboveground Biomass of Tropical Trees. *Global Change Biology, 20,* 3177-3190. https://doi.org/10.1111/gcb.12629

Condit, R. (1998). *Tropical Forest Census Plots: Methods and Results from Barro Colorado Island, Panama and a Comparison with Other Plots* (211 p.). Springer-Verlag and R. G. Landes Company.

Curtis, J. T. (1959). *The Vegetation of Wisconsin; an Ordination of Plant Communities*. University of Wisconsin Press.

Diway, B., Yiing, L. C., Wasli, M. E., & Takeuchi, Y. (2023). Forest Structure and Recovery in Selectively Logged Forests in Sarawak, Malaysia. *Tropics, 32,* 1-14. https://doi.org/10.3759/tropics.ms22-07

Djomo, A. N., Ibrahima, A., Saborowski, J., & Gravenhorst, G. (2010). Allometric Equations for Biomass Estimations in Cameroon and Pan Moist Tropical Equations Including Biomass Data from Africa. *Forest Ecology and Management, 260,* 1873-1885. https://doi.org/10.1016/j.foreco.2010.08.034

Duah-Gyamfi, A., Swaine, E. K., Adam, K. A., Pinard, M. A., & Swaine, M. D. (2014). Can Harvesting for Timber in Tropical Forest Enhance Timber Tree Regeneration? *Forest Ecology and Management, 314,* 26-37. https://doi.org/10.1016/j.foreco.2013.11.025

Fayolle, A. N., Michel, M., Nicolas, B., Yannick, B., Faustin, B., Pierre, C. et al. (2018). A Regional Allometry for the Congo Basin Forests Based on the Largest Ever Destructive Sampling. *Annals of Forest Science, 66,* 1-21.

Fayolle, A., Doucet, J., Gillet, J., Bourland, N., & Lejeune, P. (2013). Tree Allometry in Central Africa: Testing the Validity of Pantropical Multi-Species Allometric Equations for Estimating Biomass and Carbon Stocks. *Forest Ecology and Management, 305,* 29-37. https://doi.org/10.1016/j.foreco.2013.05.036

Fitzpatrick, M. (2002). *"Cameroon", Lonely Planet West Africa* (5th ed.). Lonely Planet

Publications Pty Ltd.

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and Estimating Tropical Forest Carbon Stocks: Making REDD a Reality. *Environmental Research Letters, 2,* Article ID: 045023. https://doi.org/10.1088/1748-9326/2/4/045023

Goulamoussène, Y., Bedeau, C., Descroix, L., Linguet, L., & Hérault, B. (2017). Environmental Control of Natural Gap Size Distribution in Tropical Forests. *Biogeosciences, 14,* 353-364. https://doi.org/10.5194/bg-14-353-2017

Gourlet-Fleury, S., Favrichon, V., Schmitt, L., & Petronelli, P. (2004). Consequences of Silvicultural Treatments on Stand Dynamics at Paracou. In S. Gourlet-Fleury, J. M. Guehl, & O. Laroussinie (Eds.), *Ecology and Management of a Neotropical Rainforest: Lessons Drawn from Paracou, a Long-Term Experimental Research Site in French Guiana* (pp. 254-280). Elsevier.

Gourlet-Fleury, S., Mortier, F., Fayolle, A., Baya, F., Ouédraogo, D., Bénédet, F. et al. (2013). Tropical Forest Recovery from Logging: A 24 Year Silvicultural Experiment from Central Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences, 368,* Article ID: 20120302. https://doi.org/10.1098/rstb.2012.0302

Hairiah, K., & dan Rahayu, S. (2007). *Pengukuran Karbon Tersimpan di Berbagai Macam Penggunaan Lahan* (p. 110). World Agroforestry Centre.

Hari Poudyal, B., Maraseni, T., & Cockfield, G. (2018). Evolutionary Dynamics of Selective Logging in the Tropics: A Systematic Review of Impact Studies and Their Effectiveness in Sustainable Forest Management. *Forest Ecology and Management, 430,* 166-175. https://doi.org/10.1016/j.foreco.2018.08.006

Haynes, R. J. (1984). Lime and Phosphate in the Soil-Plant System. In *Advances in Agronomy* (pp. 249-315). Elsevier. https://doi.org/10.1016/s0065-2113(08)60456-3

Hayward, R. M., Banin, L. F., Burslem, D. F. R. P., Chapman, D. S., Philipson, C. D., Cutler, M. E. J. et al. (2021). Three Decades of Post-Logging Tree Community Recovery in Naturally Regenerating and Actively Restored Dipterocarp Forest in Borneo. *Forest Ecology and Management, 488,* Article ID: 119036. https://doi.org/10.1016/j.foreco.2021.119036

Henry, M., Besnard, A., Asante, W. A., Eshun, J., Adu-Bredu, S., Valentini, R. et al. (2010). Wood Density, Phytomass Variations within and among Trees, and Allometric Equations in a Tropical Rainforest of Africa. *Forest Ecology and Management, 260,* 1375-1388. https://doi.org/10.1016/j.foreco.2010.07.040

Hérault, B., & Piponiot, C. (2018). Key Drivers of Ecosystem Recovery after Disturbance in a Neotropical Forest. *Forest Ecosystems, 5,* 1-15. https://doi.org/10.1186/s40663-017-0126-7

Houghton, R. A. (2005). Aboveground Forest Biomass and the Global Carbon Balance. *Global Change Biology, 11,* 945-958. https://doi.org/10.1111/j.1365-2486.2005.00955.x

Hu, J., Herbohn, J., Chazdon, R. L., Baynes, J., & Vanclay, J. K. (2020). Above-Ground Biomass Recovery Following Logging and Thinning over 46 Years in an Australian Tropical Forest. *Science of the Total Environment, 734,* Article ID: 139098. https://doi.org/10.1016/j.scitotenv.2020.139098

IPCC (Intergovernmental Panel on Climate Change) (2006). *IPCC Guidelines for National Greenhouse Gas Inventories*. IGES, Japan.

Johnson, I. R., & Thornley, J. H. M. (1987). A Model of Shoot: Root Partitioning with Optimal Growth. *Annals of Botany, 60,* 133-142. https://doi.org/10.1093/oxfordjournals.aob.a087429

Kenzo, T., Ichie, T., Hattori, D., Itioka, T., Handa, C., Ohkubo, T. et al. (2009). Development of Allometric Relationships for Accurate Estimation of Above- and Below-Ground

Biomass in Tropical Secondary Forests in Sarawak, Malaysia. *Journal of Tropical Ecology, 25,* 371-386. https://doi.org/10.1017/s0266467409006129

Lima, A. J. N., Suwa, R., de Mello Ribeiro, G. H. P., Kajimoto, T., dos Santos, J., da Silva, R. P. et al. (2012). Allometric Models for Estimating Above- and Below-Ground Biomass in Amazonian Forests at São Gabriel Da Cachoeira in the Upper Rio Negro, Brazil. *Forest Ecology and Management, 277,* 163-172. https://doi.org/10.1016/j.foreco.2012.04.028

Löf, M., Madsen, P., Metslaid, M., Witzell, J., & Jacobs, D. F. (2019). Restoring Forests: Regeneration and Ecosystem Function for the Future. *New Forests, 50,* 139-151. https://doi.org/10.1007/s11056-019-09713-0

Martin, A. P., Palmer, W. M., Byrt, C. S., Furbank, R. T., & Grof, C. P. (2013). A Holistic High-Throughput Screening Framework for Biofuel Feedstock Assessment That Characterises Variations in Soluble Sugars and Cell Wall Composition in Sorghum Bicolor. *Biotechnology for Biofuels, 6,* Article No. 186. https://doi.org/10.1186/1754-6834-6-186

Mokake, S. E., Chuyong, G. B., & Egbe, E. A. (2024). Long-Term Impacts of Selective Logging in a Tropical Rainforest in the East Region of Cameroon. *African Journal of Ecology, 62,* e13341. https://doi.org/10.1111/aje.13341

Mokake, S. E., Chuyong, G. B., Egbe, E. A., & Njombe, B. (2022). Silvicultural Assessment of Enrichment Planting with Commercial Tree Species after Selective Logging. *Journal of Ecology and The Natural Environment, 14,* 28-43. https://doi.org/10.5897/jene2021.0919

Mokake, S. E., Weyi, B. K., Anyinkeng, N., Ngoh, L. M., Berkeley, O. E., & Andrew, E. E. (2023). Stand Diversity and Carbon Stock of a Tropical Forest in the Deng Deng National Park, Cameroon. *Open Journal of Ecology, 13,* 461-496. https://doi.org/10.4236/oje.2023.137029

Mokany, K., Raison, R. J., & Prokushkin, A. S. (2006). Critical Analysis of Root: Shoot Ratios in Terrestrial Biomes. *Global Change Biology, 12,* 84-96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Mori, S. A., Boom, B. M., de Carvalino, A. M., & dos Santos, T. S. (1983). Ecological Importance of Myrtaceae in an Eastern Brazilian Wet Forest. *Biotropica, 15,* 68-70. https://doi.org/10.2307/2388002

Mueller-Dombois, D., & Ellenberg, H. (1974). *Aims and Methods in Vegetation Ecology.* John Wiley.

Okuda, T., Suzuki, M., Adachi, N., Quah, E. S., Hussein, N. A., & Manokaran, N. (2003). Effect of Selective Logging on Canopy and Stand Structure and Tree Species Composition in a Lowland Dipterocarp Forest in Peninsular Malaysia. *Forest Ecology and Management, 175,* 297-320. https://doi.org/10.1016/s0378-1127(02)00137-8

Pearson, T. R. H., Brown, S., Murray, L., & Sidman, G. (2017). Greenhouse Gas Emissions from Tropical Forest Degradation: An Underestimated Source. *Carbon Balance and Management, 12,* Article No. 3. https://doi.org/10.1186/s13021-017-0072-2

Poorter, L., Bongers, F., Aide, T. M., Almeyda Zambrano, A. M., Balvanera, P., Becknell, J. M. et al. (2016). Biomass Resilience of Neotropical Secondary Forests. *Nature, 530,* 211-214. https://doi.org/10.1038/nature16512

Putz, F. E., Zuidema, P. A., Synnott, T., Peña-Claros, M., Pinard, M. A., Sheil, D. et al. (2012). Sustaining Conservation Values in Selectively Logged Tropical Forests: The Attained and the Attainable. *Conservation Letters, 5,* 296-303. https://doi.org/10.1111/j.1755-263x.2012.00242.x

Rutishauser, E., Hérault, B., Baraloto, C., Blanc, L., Descroix, L., Sotta, E. D. et al. (2015). Rapid Tree Carbon Stock Recovery in Managed Amazonian Forests. *Current Biology, 25,* R787-R788. https://doi.org/10.1016/j.cub.2015.07.034

Shimamoto, C. Y., Botosso, P. C., & Marques, M. C. M. (2014). How Much Carbon Is Sequestered during the Restoration of Tropical Forests? Estimates from Tree Species in the Brazilian Atlantic Forest. *Forest Ecology and Management, 329,* 1-9. https://doi.org/10.1016/j.foreco.2014.06.002

Sierra, C. A., del Valle, J. I., & Restrepo, H. I. (2012). Total Carbon Accumulation in a Tropical Forest Landscape. *Carbon Balance and Management, 7,* Article No. 12. https://doi.org/10.1186/1750-0680-7-12

Suarez, D. R., Rozendaal, D. M. A., De Sy, V., Phillips, O. L., Alvarez-Dávila, E., Anderson-Teixeira, K. et al. (2019). Estimating Aboveground Net Biomass Change for Tropical and Subtropical Forests: Refinement of IPCC Default Rates Using Forest Plot Data. *Global Change Biology, 25,* 3609-3624. https://doi.org/10.1111/gcb.14767

Verburg, R., & van Eijk-Bos, C. (2003). Effects of Selective Logging on Tree Diversity, Composition and Plant Functional Type Patterns in a Bornean Rain Forest. *Journal of Vegetation Science, 14,* 99-110. https://doi.org/10.1111/j.1654-1103.2003.tb02132.x

Vieira, S., de Camargo, P. B., Selhorst, D., da Silva, R., Hutyra, L., Chambers, J. Q. et al. (2004). Forest Structure and Carbon Dynamics in Amazonian Tropical Rain Forests. *Oecologia, 140,* 468-479. https://doi.org/10.1007/s00442-004-1598-z

West, T. A. P., Vidal, E., & Putz, F. E. (2014). Forest Biomass Recovery after Conventional and Reduced-Impact Logging in Amazonian Brazil. *Forest Ecology and Management, 314,* 59-63. https://doi.org/10.1016/j.foreco.2013.11.022

Whittaker, R. J., Willis, K. J., & Field, R. (2001). Scale and Species Richness: Towards a General, Hierarchical Theory of Species Diversity. *Journal of Biogeography, 28,* 453-470. https://doi.org/10.1046/j.1365-2699.2001.00563.x

Yap, S. L., Davies, S. J., & Condit, R. (2016). Dynamic Response of a Philippine Dipterocarp Forest to Typhoon Disturbance. *Journal of Vegetation Science, 27,* 133-143. https://doi.org/10.1111/jvs.12358

Zapfack, L., Noiha, N. V., Dziedjou, K. P. J., Zemagho, L., & Fomete, N. T. (2013). Deforestation and Carbon Stocks in the Surroundings of Lobéké National Park (Cameroon) in the Congo Basin. *Environment and Natural Resources Research, 3,* 78-86. https://doi.org/10.5539/enrr.v3n2p78

Abbreviations

AGB	Above Ground Biomass
ACS	Above ground Carbon Stock
BCS	Below ground Carbon Stock
SOC	Soil Organic Carbon
YAL	Years After Logging

Appendix: 50 Most Common Species

2005							**2011**			
T1		**T2**		**T3**			**T1**	**T2**	**T3**	
Species code	**Frequency**	**Species code**	**Frequency**	**SpCode**	**Frequency**	**SpCode**	**Frequency**	**SpCode**	**Frequency**	**Ranking**
SLOET	616	RINI	302	SLOET	538	RINI	214	SLOET	553	1
RIND	312	MILL	284	RIND	252	MILL	192	MILL	202	2
MILL	267	RIN2	210	MILL	207	MELE	164	DIOSI	152	3
RIN2	216	MELE	196	RIN2	170	RIN2	160	RIN2	150	4
DRYMO	199	DIOSI	166	DRYMO	163	DIOSI	126	DRYW3	120	5
TABR	155	TABR	159	TABR	124	TABR	116	RINI	115	6
DIOSI	148	MUCE	135	DIOSI	121	MUCE	60	TABR	112	7
TRICI	103	DRYW3	85	RINI	86	DRYW3	57	TRICI	90	8
DRY6	100	TRICI	78	DRY6	82	TRICI	54	RINOB	84	9
RINI	98	PENN	59	TRICI	77	PENN	48	RIND	79	10
DIOS2	84	DRYI	48	MIPU	70	DRYI	40	MIPU	71	11
MIPU	82	POSU	46	DRYC	65	MIPU	37	CELTZ	65	12
DRYC	76	MIPU	44	DIOS2	64	POSU	33	DIOS2	59	13
DRYW3	76	ANGY	39	DRYW3	61	ANGY	31	RIN4	54	14
LASIO	73	DIOS2	38	LASIO	59	DIOS2	31	DESBO	53	15
PENN	69	DRY3	38	POSU	54	DRY3	26	DRYTL	38	16
CELTZ	64	DRYMO	37	CELTZ	53	DRYMO	26	DRY6	36	17
POSU	64	CELTP	30	PENN	51	CELTP	24	PENN	32	18
DRYTL	61	PAMA	29	ANGY	45	PAMA	22	DRYMO	31	19
ANGY	53	DRY6	27	DRYTL	45	STRO	22	ANON	29	20
DESBO	48	KEAY	27	MUCE	40	CELTZ	22	MASP	25	21
MUCE	46	RAMA	27	DESBO	40	KEAY	22	ANGY	23	22
PAMA	41	STRO	27	DRIRV	33	MAAC	21	PAMA	22	23
DRIRV	41	CELTZ	24	PAMA	32	PINI	20	MABA	20	24
BAPI	35	MAAC	23	BAPI	30	DIMA	19	BAPI	19	25
RIN4	32	DIMA	21	RIN4	29	DRY6	19	DRYC	19	26
STRO	29	PINI	21	STRO	22	TRIC2	16	POSU	19	27

Continued

TETDI	28	DRYTL	21	CONI	18	RAMA	15	MUCE	18	28
MABA	27	TRIC2	20	RINOB	18	TRHE	15	CELTI	16	29
RINOB	23	SAPW	19	DRYWI	17	DRYTL	14	PTER	15	30
CONI	23	COAF	18	ANON	16	SAPW	13	TRIC2	15	31
MASP	23	TRHE	18	MABA	15	WTET	13	TRHE	15	32
DRYWI	21	MARK	16	TESU	15	MYAR	12	MADI	14	33
MAMO	21	UVAR2	16	TRHE	15	BETE	11	AYOUS	14	34
PAUR2	19	BETE	15	CELTI	14	MARK	11	STRO	11	35
TRHE	18	MYAR	15	TETDI	14	GUA3	11	DRYI	10	36
CELTI	18	WTET	15	DRYI	13	PYCN	10	KEAY	10	37
ANON	17	EUPHI	13	UVARI	13	UVAR2	10	TETDI	9	38
DRYI	17	PYCN	13	MARK	13	SPATH	9	FUEL	9	39
TESU	17	GUA3	12	STST	13	UVARI	9	COMAF	8	40
UVARI	17	UVARI	11	TRIC2	13	EUPHI	8	EUPHI	7	41
ALCONI	15	PAOL	11	DRYSAW	11	FUEL	8	MAMO	7	42
TRIC2	15	TROR	11	ALCONI	11	SAPELI	8	VOAC	7	43
MADI	14	EUPH2	10	ANMA	11	FICI	7	DUMA	6	44
STST	14	SAPELI	10	DIMA	11	NEPA	7	EROB	6	45
DIMA	14	SPATH	9	MASP	11	ANMA	7	MONO	6	46
ANMA	13	BLIG	8	KEAY	10	DIAL	7	BLIG	5	47
DRYLA	12	DIAL	8	MADI	10	BLIG	6	CONI	5	48
DRYSAW	12	DIOSN	8	BETE	10	COAF	6	DRYWI	5	49
DRY3	12	NEPA	8	DRY3	10	DIOSN	6	CELTP	5	50