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Full Length Research Paper

Woody species diversity conservation and carbon sequestration potential of coffee agroforestry systems in the Western Region of Cameroon

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This study sought to assess the contribution of coffee agroforestry systems (CAFS) in conserving tree diversity and carbon stocks in the western region of Cameroon. Inventory was carried out in 52 plots laid out in CAFS and in adjacent secondary forest. Above-ground biomass was estimated using allometric method. A total of 30 species belonging to 19 families were identified in CAFS and 30 species belonging to 15 families in the forest. The Jaccard similarity index between CAFS and forest was 43%. In the CAFS, the average value of Shanon diversity index was 1.61, reflecting a low diversity. The average tree density was 133 stems/ha in CAFS and 345 stems/ha in the forest. The CAFS stored an amount of carbon of 24.28 tC/ha, representing only 10.30% of the average amount of carbon stored by the forest (235.88 tC/ha). In the CAFS, *Elaeis guineensis* was the most dominant species with an important value index of 169.96%. The most efficient species for carbon sequestration were *Triplochiton scleroxylon* with 2.38 tC/tree. These results indicate the need to integrate CAFS as a biodiversity conservation and carbon sequestration land-use system due to the many socio-economic and ecological benefits they provide both in climate change adaptation and mitigation.

Key words: Coffee agroforestry system, diversity, ecosystem services, climate change mitigation, carbon stock.

INTRODUCTION

Global forest cover has drastically decreased from 4128 million ha in 1990 to 3999 million ha in 2015 (FAO, 2016). In tropical regions, extensive conversion of forests and agricultural intensification are typically identified among the most prominent drivers of land-use change and biodiversity loss (Geist and Lambin, 2002). This land-use change is one of the major causes of global climate change (IPCC, 2014). As the impact of climate change is being felt more and more over the years, especially with the perception of small farmers who report lower and / or increased rainfall and shifts in rainy and dry seasons (Ogouwalé, 2006), there is increasing interest to combine

adaptation and mitigation measures (Locatelli et al., 2008; Lasco et al., 2014). Strategies for offsetting greenhouse gas emissions include the implementation of better agricultural practices such as agroforestry (FAO, 2010). Agroforestry systems have received increased attention as potentially cost-effective options for climate change mitigation due to their potential to reduce carbon dioxide (CO_2) concentrations in the atmosphere by increasing carbon stocks in agricultural lands (FAO, 2010; Hergoualc'h et al., 2012; IPCC, 2014). Albrecht and Kandji (2003) estimated that the potential of carbon storage of tropical agroforestry systems range from 12 to 228 tC/ha.

Improving soil fertility and biodiversity conservation are other ecological services provided by agroforestry (Garrity et al., 2010; Atangana et al., 2014) in addition to ensuring food security (Mapongmetsem et al., 2016). Agroforestry combines both food production and environmental protection and are seen as sustainable and therefore eligible for the reduction of emissions from deforestation and degradation (REDD+) mechanism. This incentive mechanism considers conservation and carbon stock in the prospect of payment for environmental services and could be an economic opportunity for farmers (Takimoto et al., 2008; Atangana et al., 2014; Etchiké et al., 2017).

Coffee agriculture represents about 6.5% of world permanent crop and globally, more than 10.5 million hectares of tropical land is under coffee production (FAO, 2019).In many parts of the world, coffee is traditionally cultivated under tree cover, the farmers retaining or introducing useful woody species into their plantations (Dalliere and Dounias, 1999; Perfecto et al., 2005; Correia et al., 2010; Tadesse et al., 2014a; Denu et al., 2016; Koda et al., 2019). These coffee agroforestry systems (CAFS) contribute to the conservation of wood diversity and carbon storage (Häger, 2012; Hergoualc'h et al., 2012; Tadesse, 2014b; De Beenhouwer et al., 2016; Denu et al., 2016; Kodaet al., 2019).The amount of carbon stored in a CAFS varies depending on management intensity. For example in Ethiopia, compared to nearby natural forests, CAFS have been reported to retain 50 to 75% of carbon (Tadesse et al. 2014b; Vanderhaegen et al., 2015; Denu et al., 2016).

Western Cameroon is a volcanic region in which the cultivation of coffee trees is an age-old practice. However, the 1980s was marked by a deep coffee crisis following the fall in world prices (Guétat-Bernard, 2008). To cope with the situation, production systems evolved towards crop diversification in order to multiply sources of income (Kankeu and Kaffo, 2012; Manga et al., 2013). Most of these farmers grow coffee in agroforestry systems with a wide variety of useful trees. But given the fact that coffee is losing value due to constant drops in its price, smallholder coffee farmers remain poor and the tendency is to convert coffee agroforestry farms to other crop farms. There is a need to check for ecological services these CAFS provide so that they could be valued in the context of payment for environmental services and carbon stock sold as CO_2 emission offsets. Several studies have already been carried out on the biodiversity conservation and carbon storage potential of coffee agroforestry systems in Central and South America (Häger, 2012; Schmitt-Harsh et al., 2012; Richards and Mendez, 2014; Goodall et al., 2015; Zaro et al., 2019) and in East Africa (Tadesse et al., 2014a, b; Vanderhaegen et al., 2015; De Beenhouwer et al., 2016; Bukomeko et al., 2019). In Central Africa and in Cameroon in particular, such studies are still very limited (Manga et al., 2013).Thus, this study is very important and timely as it seeks to evaluate the tree diversity and the carbon sequestration potential of coffee agroforestry systems in the western region of Cameroon.

MATERIALS AND METHODS

Study area

The study was carried out in Kekem sub-division found in the Haut-Nkam division, West Region of Cameroon. The sub-division is located between latitudes 5.01° - 5.15°N and longitudes 10.00° - 10.08°E (Figure 1). The climate of Kekem is of the tropical highland type characterised by two seasons namely; the dry season from November to March and the rainy season the rest of the year. The rainfall here is relatively high with about 1800 to 2000 mm of rainfall per year and temperatures range between 20 and 30°C.Haut-Nkam is a transitional zone between the Mbo plains and the mountain chains of west Cameroon. The altitude is between 600 and 1200 m (PNDP, 2013). Naturally, the vegetation cover is mainly made up of forest and savannah grassland. The grasslands are found in plains, while the forest dominates on hill slopes and tops. Agriculture is by far the main economic activity in the study area. It is mostly carried out on extensive mixed cropping systems. Robusta coffee, cocoa and oil palm are the main cash crops.

Data collection

An inventory was carried out in 5 villages. In coffee farms, sample plots were laid out by adapting the method described by Hairiah et al. (2011) with the marking out of rectangular shaped main plots of 2400 m² (40m × 60m) for counting woody trees with a diameter at breast height (dbh) ≥ 30 cm and sub- plots of 800 m² (20m × 40m) for woody trees with a dbh≥ 5 cm. A total of 48 main plots were marked out. Four main control plots of 2400 m² (40m × 60m) were established in adjacent secondary forests for counting woody trees with a diameter at breast height (dbh) ≥ 30 cm and in each plot 2 sub- plots of 200 m² (5m x 40m) were laid out for counting woody trees with a dbh ≥ 5 cm. The choice to count trees of dbh ≥ 5 cm was made based on the allometric equation used for the biomass calculation. Indeed, the equation used (Chave et al., 2014) considers trees with a diameter of at least 5 cm at breast height.

In each plot we measured height and the diameter at breast height of all woody species including coffee trees. The diameters of coffee trees were also measured at breast height. The diameters were measured using a measuring tape and the height with a clinometer. Species identification was made on the basis of discriminating characteristics of species using dichotomous keys of Cameroon flora, Identification Manual of Vivien and Faure (2012) and vernacular names. The botanical nomenclature adopted is that of Lebrun and Stork (1991-1997). Semi-structured interviews with 30 farmers provided information on indigenous knowledge,
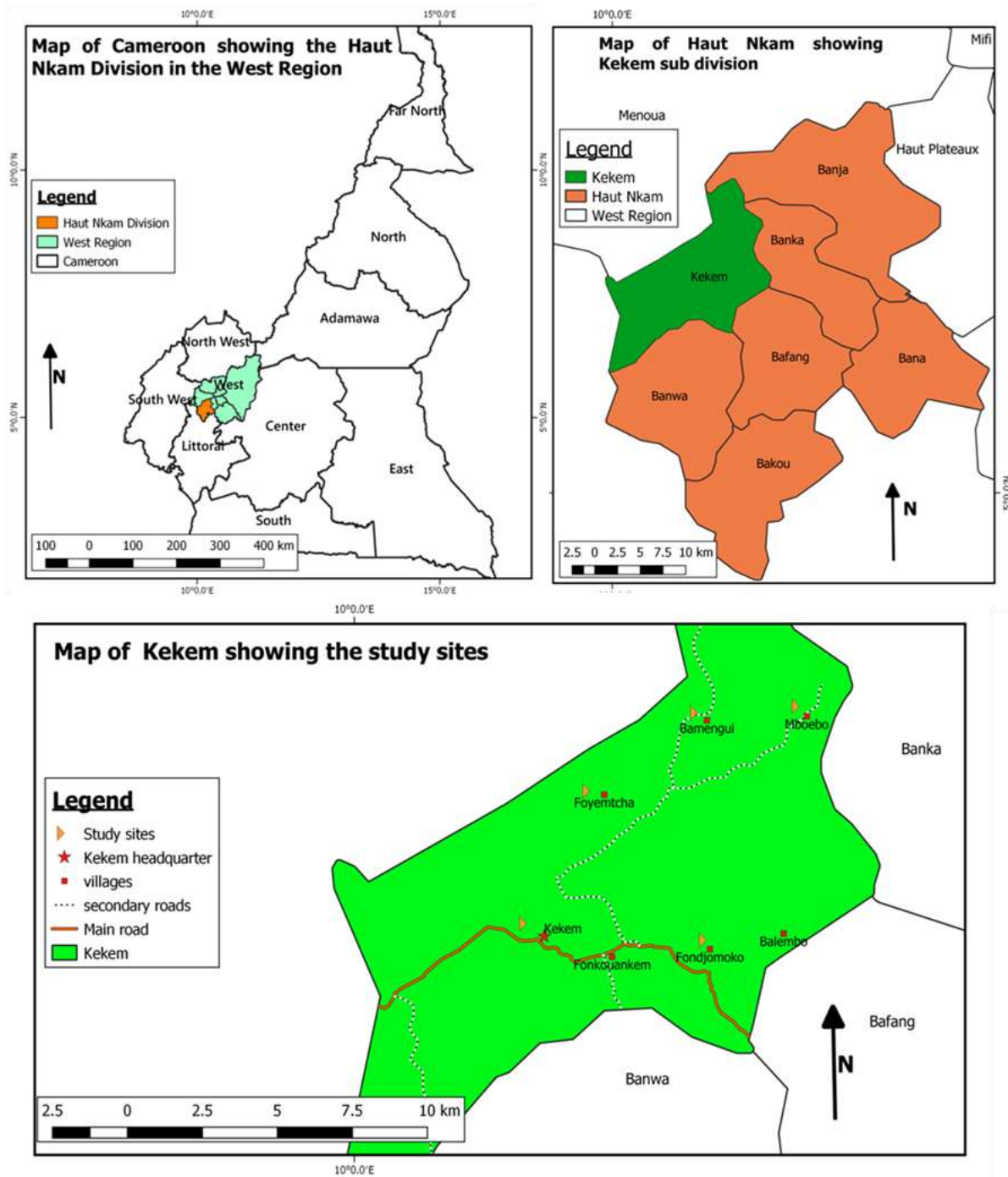
Figure 1. Location of the study area in the western region of Cameroon.

conservation and the introduction of species and their main uses.

Data analysis

Diversity, species richness and floristic composition

The main floristic parameters considered in this study were species richness, the diversity indexes of Shannon and Simpson, Evenness index of Piélou, family importance value index (FIV) and importance value index of species (IVI).

Species richness: This refers to the total number of species that make up a community. To get its values, we need to know the total number of families and species represented in each sub-plot.

Diversity index of Shannon-Weaver (H'): This index helps to measure the probability of interactions between the different

species that constitute the community. This index includes components like the number of species present and the number of individuals within these species.

$$H' = -\sum (ni/N)Log_2 (ni/N)$$

Where: ni is the total number of individuals of the specie i; and N the number of individuals of all the species.

Evenness Index of Pielou (E): It represents the distribution of species within a particular community. This index varies from 0 to 1 and is at its maximum when the species have equal abundances and at its minimum when one species dominates in the community.

$$E = H'/Log_2 S$$

where, S is the total number of species identified and H' the Shannon index.

Simpson diversity index (D'): This is the probability for two individuals selected randomly to belong to different species. The maximum diversity value is represented by 1 and the minimum diversity is represented by 0(Danais, 1982).

$$D' = 1 - D = 1 - \sum (ni/N)^2$$

where: ni is the number of individuals for a particular species; N is the total number of individuals for all species.

Jaccard index: Its measures the similarity between species composition of two sites.

$$J = \frac{C}{A + B - C}$$

Where A is the number of species for site A, B is the number of species for site B and C the number of species site A and B have in common.

To describe the ecological importance of families and species within the total flora, the Family Importance Value index (FIV) (Mori et al., 1983) and the Importance Value Index (IVI) (Curtis and McIntosh, 1950) were calculated.

FIV= Relative diversity + Relative density + Relative dominance

Where: Relative diversity = (number of species in a family / total number of species) x 100
Relative density = (number of trees in a family / total number of trees) x 100
Relative dominance = (basal area of a family / total basal area) x 100
IVI = Relative Frequency + Relative Density + Relative Dominance
Relative frequency = (frequency of a species / sum of frequencies) x 100
Relative density = (density of a species / sum of all densities) x 100
Relative Dominance = (basal area of a species / sum of all basal areas) x 100.

Stand structure parameters

Vegetation structure was determined by parameters such as density, basal area and distribution of individuals by diameter

classes. Density and basal area was estimated using the formula given by Kent and Coker (1992).

Density (D): Density is the number of individuals per hectare. It was calculated by converting the total number of individuals encountered in all plots to equivalent number per hectare, following this formula:

$$D = N/S$$

With D the density (stems ha^{-1}), N the number of stems present on the considered surface and S the area considered (ha).
Basal area (BA) provides information on the area occupied by tree sections at 1.30 m from the ground.

$$BA = \frac{\pi}{4}\sum_{n=1}^{n} (Di^2)$$

Where BA is basal area (m^2 ha^{-1}) and D is diameter (m).
Distribution of individuals by diameter classes: The trees were distributed in the different diameter classes of 10 cm amplitude, following the recommendations of Favrichon et al. (1998).The define classes were as such:(5-15 cm), (15-25 cm), (25-35 cm), (35-45 cm), (45-55 cm), (55-65 cm), (65-75 cm), (75-85 cm) and ≥ 85 cm.

Uses of associated trees

Categories of uses were distinguished according to farmer's point of view about the services provided by associated trees.Information about the status of the trees (planted or conserved) was also found.

Biomass and carbon estimation

Above ground biomass: A non-destructive sampling method was used for the determination of total aboveground biomass (AGB). We used the allometric equation proposed by Chave et al. (2014) which is given by the formula:

AGB = 0.0673× (ρD²H) $^{0.976}$

where, AGB is above ground biomass (in kg), ρ is the specific wood gravity (in g.cm^{-3}), D the tree diameter at breast height (in cm) and H the total tree height (in m).
Because palms trees (*E. guineensis*) do not have secondary growth the only parameter considered for biomass estimation is tree height and the model developed by Aguaron and McPherson (2012) was used.

AGB = 1.282 × (7.7H + 4.5)

Below ground biomass: The estimation of below ground biomass (root biomass) was calculated using the method by IPCC (2006). This method states that the below ground biomass of trees is gotten by multiplying the value of above ground biomass by the coefficient R which is equal to 0.24.

BGB = AGB x R

where, BGB is below ground biomass, AGB is above ground biomass and R is the root/stem ratio.
Carbon stocks were gotten by multiplying the sum of AGB and BGB

Table 1. Species richness and diversity indices per CAFS in different villages and forest.

Sites	Species	Families	Shannon (H')	Simpson (D')	Pielou Evenness (E)
Fonjomonko	7	7	0.48 ± 0.16[c]	0.19 ± 0.05[b]	0.25 ± 0.06[c]
Foyemtcha	16	13	1.72 ± 0.43[b]	0.70 ± 0.23[a]	0.62 ± 0.10[b]
Mboebo	18	15	1.76 ± 0.35[b]	0.70 ± 0.12[a]	0.33 ± 0.07[c]
Kekem center	24	16	1.92 ± 0.48[b]	0.71 ± 0.14[a]	0.35 ± 0.03[c]
Bamengui	19	14	2.16 ± 0.37[b]	0.79 ± 0.20[a]	0.71 ± 0.13[b]
Forest	30	15	3.08 ± 0.39[a]	0.86 ± 0.14[a]	0.91 ± 0.05[a]

On the same column, means bearing the same letter are not significantly different (Newman-Keuls test, 5%).

by the carbon fraction which has a value of 0.47 (IPCC, 2006). It is expressed mathematically as:

$$C = (AGB + BGB) \times 0.47$$

where C is the total carbon stock, AGB is above ground Biomass and BGB is below ground biomass.

Statistical analysis

The Excel spreadsheet Microsoft Office helped to organize the data collected and perform descriptive analyzes for a better characterization of these agroforestry systems. Means value of species richness, diversity indices, densities and carbon stocks were subjected to analysis of variance (ANOVA) using the SPSS software. When the differences were significant between the elements of these coffee agroforestry systems in different villages and forest, we put forward the elements that caused these changes by the test Newman-Keuls.

RESULTS

Tree species composition and diversity

Altogether, out of the 48 plots surveyed in CAFS in five villages, 1066 individuals belonging to 30 species and 19 families were recorded. As for the secondary forest zone, 184 individuals were recorded belonging to 30 species and 15 families. The Shannon diversity indices ranged from 0.48 to 2.16 in CAFS (Table 1) showing low species diversity.

The village where species richness is closest to that of the forest is Kekem center with 24 species, while Fonjomonko is the village with the lowest species richness (7 species). Statistical analysis revealed that there is a significant difference between the Shannon diversity index of the forest and that of CAFS in all the villages and between the villages, there is a significant difference between the Shannon diversity index of Fonjomonko and the other villages (P < 0.001).The Simpson diversity index of Fonjomonko (0.19) was low, showing that there is a higher probability that two trees selected randomly may belong to the same species. There is no significant difference between the Simpson diversity indices of the forest and the other villages, except for Fonjomonko. The Piélou Evenness index

expresses the distribution of individuals within species and thus, the low index in Fonjomonko (0.25) shows that there is clearly one species that dominates the others.

In terms of the number of species in CAFS, the most represented family was Fabaceae with five species, followed by Apocynaceae (4 species), Sterculiaceae, Arecaceae, Rutaceae and Burseraceae with 2 species each.The other 13 families had only onespecies each.The family importance valu es found in CAFS and in the adjacent forest are presented in Table 2. In CAFS, the most important families were Arecaceae, Burseraceae, Fabaceae, Moraceae and Apocynaceae. CAFS and the forest shared in common eleven families. In the secondary forest, Fabaceae occupied the first place in terms of abundance and dominance followed by Moraceae, Meliaceae, Apocynaceae and Burseraceae.

The Importance value indices of species in CAFS are presented in Table 3. *E. guineensis* had the overall highest importance value index in all the villages (169.96%) followed by *Dacryodes edulis* (47.72%), *Persea americana* (11.63%), *Milicia excelsa* (11.49%) and *Albizia zygia* (7.45%). This is quite evident because these species are the most frequent and abundant in the CAFS of the area. Five species had an IVI less than 0.5 (*Podocarpus mannii*, *Citrus lemon*, *Pterocarpus soyauxii*, *Adansonia digitata* and *Picralima nitida*). In the secondary forest, *Milicia excelsa* had the highest importance value index (43.86%) due its high dominance, and abundance, followed by *Pterocarpus soyauxii* (18.6%), *Alstonia boonei* (17.67%), *Piptadeniastrum africanum* (17.65%) and *Lophira alata* (15.64%).

Similarity between coffee agroforestry systems and forest

Jaccard's indices of similarity were calculated to compare species composition between the CAFS of the different villages and forest (Table 4). From the values of the Jaccard index, almost all were below 0.5, implying that the floristic composition of the CAFS in the five villages are not similar to each other. The CAFS in Fonjomonko have the fewest number of species in common with other villages and those in the Kekem center and Mboebo

Table 2. Family importance value (FIV) of families in coffee agroforestry systems and forest.

Family	Coffee agroforestry systems						Forest
	Global	BAM	FON	FOY	KEK	MBO	
Arecaceae	125.31	68.85	197.61	110.95	123.62	125.49	-
Burseraceae	42.77	65.59	21.18	54.23	39.9	32.95	14.18
Fabaceae	23.24	38.67	17.11	19.24	24.79	16.39	94.89
Moraceae	15.43	16.04	14.78	23.1	7.19	16.04	32.25
Apocynaceae	14.31	6.35	-	20.6	17.68	26.9	15.34
Lauraceae	11.17	14.10	-	11.56	13.48	16.71	-
Rutaceae	10.38	10.87	14.82	7.43	11.11	7.67	-
Myrtaceae	9.07	10.52	14.8	8.07	4.61	7.36	-
Clusiaceae	8.03	13.86	-	11.49	7.79	7.04	7.63
Anacardiaceae	7.44	9.46	19.7	-	-	8.03	-
Annonaceae	4.95	5.37	-	6.8	5.09	7.5	-
Ochnaceae	4.83	9.1	-	-	7.66	7.38	12.95
Cecropiaceae	4.11	-	-	11.83	8.75	-	9.53
Caricaceae	3.96	-	-	7.36	4.74	7.69	-
Sterculiaceae	3.60	-	-	-	11.74	6.27	-
Rubiaceae	2.04	10.20	-	-	-	-	10.11
Bombacaceae	1.37	-	-	-	-	6.58	14.79
Podocarpaceae	1.20	-	-	-	6.01	-	11.81
Adoxaceae	1.16	-	-	-	5.83	-	5.83
Combretaceae		-	-	-	-	-	12.15
Malvaceae		-	-	-	-	-	14.74
Meliaceae		-	-	-	-	-	16.10
Urticaceae		-	-	-	-	-	8.59

BAM: Bamengui; FON : Fonjomonko; FOY : Foyemtcha; KEK: Kekem center; MBO: Mboebo.

villages have more species in common (J = 0.62). Concerning the similarity between CAFS and forest, the overall floristic composition of CAFS is different from that of the forest (J= 0.43). Kekem center which was the village with species richness closest to that of the forest wasalso the village which resembles the forest most, with fourteen species in common (J= 0.35). Eighteen species were found in both the CAFS of at least one village and the forest, among which: *Dacryodes edulis, Milicia excelsa, Albizia zygia, Alstonia boonei, Garcinia kola, Albizia ferruginea, Afzelia pachyloba, Triplochiton scleroxylon* and *Podocarpus mannii.* Only 6 species were found in CAFS in all the villages. These were: *Elaeis guineensis, Dacryodes edulis, Milicia excelsa, Albizia zygia, Psidium guajava* and *Citrus reticulata.*

Structure of coffee agroforestry and forest stands

Stem densitiesand basal areas

The CAFS have an average tree density of 133±24 stems/ha for associated trees and 753±142 stems/ha for

the coffee plants. Kekem center has the highest tree density (160 stems/ha) and Fonjomonko the least (109 stems/ha). The forest on its part has an average density of 345.01 ± 28.28 stems/ha (Table 5). This implies that the associated trees density in CAFS is equivalent to 36% of the tree density of the forest. The mean basal area for the CAFS was 15 ± 3 m²/ha, lower than that of the forest (31.09 ± 6.37 m²/ha). This can be explained by the fact that, the trees density in CAFS is lower than in the forest. Fonjomonko is the village where CAFS had the highest basal area (18.32 ± 1.70 m²/ha), followed by Kekem center (15.37 ± 4.77m²/ha) and Mboebo (15.22 ± 3.18m²/ha).

Diameter class distribution

The diameter class distribution of woody vegetation in coffee agroforestry exhibited a tendency towards a bell-curve distribution (Figure 2a). The classes with most abundant individuals were 45-55 cm and 35-45 cm with respectively 27.20 and 26.92% of individuals. Woody vegetation in CAFS has few trees with diameter greater

Table 3. Importance value index (IVI) of species in coffee agroforestry systems and forest.

Species	Coffee agroforestry systems						Forest
	Global	BAM	FON	FOY	KEK	MBO	
Elaeis guineensis	169.96	97.94	272.93	153.66	164.4	160.8	
Dacryodes edulis	47.72	71.43	11.65	62.95	45.95	46.64	5.34
Persea americana	11.63	13.98	-	8.95	15.59	19.61	
Milicia excelsa	11.49	16.42	0.93	22.57	4.69	12.83	43.86
Albizia zygia	7.45	14.12	4.55	6.2	9.39	2.98	7.25
Alstonia boonei	6.77	-	-	8.07	6.38	19.42	17.67
Garcinia kola	6.31	12.68	-	9.41	6.56	2.89	6.14
Albizia ferruginea	4.13	15.95	-	4.7	-	-	7.25
Mangifera indica	3.74	7.28	8.02	-	-	3.42	
Tetrapleura tetraptera	3.60	5.11	-	-	6.57	4.64	7.3
Psidium guajava	3.15	7.8	0.95	3.39	0.87	2.74	
Afzelia pachyloba	3.12	13.48	-	2.14	-	-	8.92
Lophira alata	2.95	6.4	-	-	5.58	2.76	15.64
Myrianthus arboreus	2.95	-	-	7.66	7.09	-	9.62
Citrus reticulata	2.26	1.06	0.97	2.22	4.01	3.06	
Canarium schweinfurthii	1.92	2.91	-	2.22	4.45	-	8.63
Cocos nucifera	1.61	1.41	-	-	1.04	5.61	
Nauclea diderrichii	1.39	6.95	-	-	-	-	8.87
Annona muricata	1.37	1.13	-	1.07	1.76	2.89	-
Carica papaya	1.34	-	-	2.15	0.99	3.54	-
Voacanga thouarsii	1.05	2.63	-	2.64	-	-	-
Voacanga africana	0.93	-	-	-	1.15	3.49	4.33
Cola nitida	0.59	-	-	-	1.78	1.19	-
Triplochiton scleroxylon	0.58	-	-	-	2.89	-	11.23
Unidentified 1	0.51	-	-	-	2.55	-	3.36
Podocarpus mannii	0.45	-	-	-	2.26	-	7.04
Citrus lemon	0.44	1.32	-	-	0.87	-	-
Pterocarpus soyauxii	0.44	-	-	-	2.19	-	18.67
Adansonia digitata	0.30	-	-	-	-	1.49	14.68
Picralima nitida	0.20	-	-	-	0.99	-	-
Piptadeniastrum africanum							17.65
Ceiba pentandra							12.86
Guibourtia tessmannii							11.31
Khaya ivorensis							6.29
Entandrophragma cylindricum							5.31
Unidentified 2							4.33
Unidentified 3							3.05
Unidentified 4							4.66
Unidentified 5							8.31
Entandrophragma candollei							3.29
Podocarpus latifolius							4.03
Musanga cecropioides							8.7

BAM: Bamengui; FON : Fonjomonko; FOY : Foyemtcha; KEK: Kekem center; MBO: Mboebo.

than 85 cm. Small diameter trees represent young growing plants, usually planted by farmers. Larger diameter trees were mostly retained at the time the plantation was established. The same tendency of class diameter distribution was observed in forest with a bell-shape curve (Figure 2b), the classes with most abundant

Table 4. Jaccard indices between the coffee agroforestry systems and forest.

Sites	Jaccard indices					
	Bamengui	**Fonjomonko**	**Foyemtcha**	**Kekem center**	**Mboebo**	**Forest**
Bamengui	1					
Fonjomonko	0.37	1				
Foyemtcha	0.52	0.35	11			
Kekem center	0.48	0.24	0.46	1		
Mboebo	0.48	0.39	0.48	0.62	1	
Forest	0.26	0.09	0.22	0.35	0.23	1
All CAFS	-	-	-	-	-	**0.43**

Table 5. Stem density of trees in coffee agroforestry systems and forest.

Sites	Density (stems/ha)		Basal area (m^2/ha)	
	Associated trees	**Coffee**	**Associated trees**	**Coffee**
Bamengui	127.22 ±19.22	640.56 ± 96.755	13.92 ± 2.30	2.17 ± 0.32
Fonjomonko	109.85 ± 13.49	999.10 ± 67.68	18.32 ± 1.70	3.40 ± 0.23
Foyemtcha	113.23 ± 28.58	731.60 ± 97.91	13.41 ± 2.04	2.49 ± 0.34
Kekem center	160.31 ± 42.58	689.10 ± 112.57	15.37 ± 4. 77	2.34 ± 0.38
Mboebo	157.76 ± 44.6	704.56 ± 111.33	15.22 ± 3.18	2.39 ± 0.38
Forest	345.01 ± 28.2		31.09 ± 6.37	-
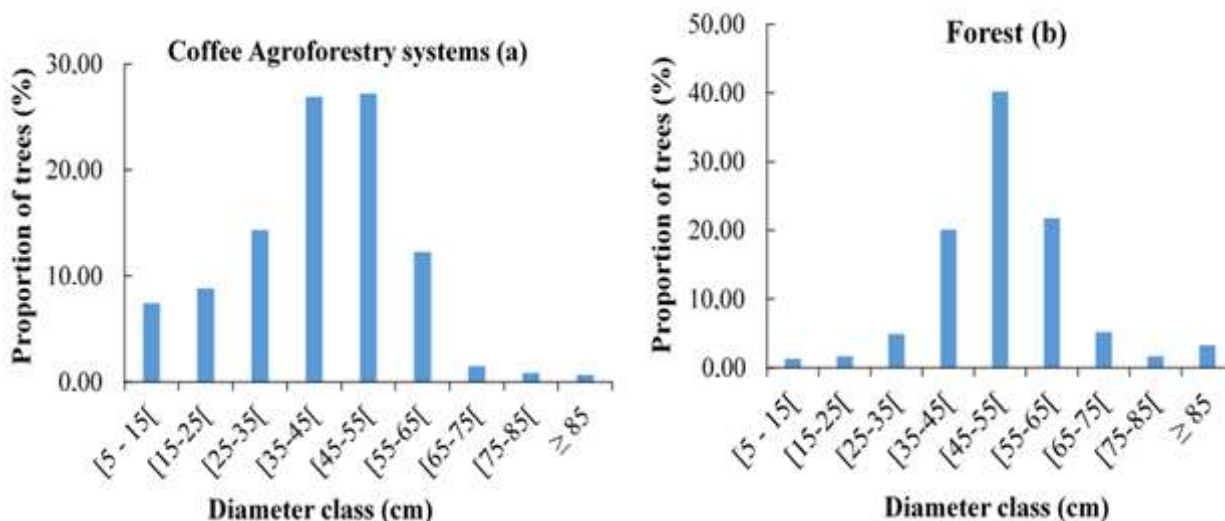
Figure 2. Size class distribution of the trees species in (a) CAFS and in (b) Forest.

individuals being 45-55 cm with 40.22% of individuals.

Uses of associated trees

The conservation or introduction of woody species into CAFS largely responds to the different needs of households. The interviews with farmers showed that about 73% of tree species were planted, while 27% were conserved during plantation establishment. Five uses have been identified for trees associated with coffee. These are:

(i) Fruit production: concerns trees that produce edible

Table 6. Average carbon stock in the coffee agroforestry systems and forest.

Sites	Carbon stocks (tC/ha)	
	Associated trees	Coffee
Bamengui	29.47 ± 4.15	1.05 ± 0.15
Fonjomonko	10.16 ± 1.17	1.64 ± 0.11
Foyemtcha	26.96 ± 6.65	1.20 ± 0.17
Kekem center	24.37 ± 10.23	1.13 ± 0.18
Mboebo	24.18 ± 7.57	1.15 ± 0.18
Forest	235.88 ± 12.15	

fruits which are destined for home consumption or for sale (*Persea americana*, *Dacryodes edulis*, *Citrus reticulata*, *Canarium schweinfurthii*, *Cocos nucifera*, *Carica papaya*, *Mangifera indica*, *Garcinia kola*, *Psydium guajava*, *Citrus lemon*, *Annona muricata* and *Cola nitida*).
(ii) Medicinal: concerns trees whose barks or fruits are used mainly for medicinal purposes (*Alstonia boonei*, *Voacanga africana*, *Picralima nitida* and *Tetrapleura tetraptera*).
(iii) Oil production: specifically of *Elaeis guineensis* whose fruits are used for the production of palm oil which generates considerable income.
(iv) Wood: this comprises trees that are kept in the farms principally to be used as fuel wood or timber (*Milicia excelsa, Lophira alata, Nauclea diderrichii, Triplochiton scleroxylon, Pterocarpus soyauxii, Afzelia pachyloba* and *Podocarpus mannii*).
(v) Shade: for trees which are kept in the farms to shade coffee or because they are too large to be cut down. All the other trees that serve for other purpose but especially tall ones can also serve as shade trees. Some of these shade trees are also leguminous species that contribute to the improvement of soil fertility (*Albizia zygia*, *Albizia ferruginea*, *Afzelia pachyloba*, *Pterocarpus soyauxii* and *Tetrapleura tetraptera*).

Carbon stock in agroforestry systems and forest

Carbon stock in CAFS was on average 24.28± 6.71 tC/ha with the associated trees contributing to 94.8% of this amount (23.03tC/ha) and coffee trees the remaining 5.2% (1.25 tC/ha). The adjacent forest on the other hand, stocked an average of 235.88 ± 12.15tC/ha, which is 9.7 times higher than that of the CAFS (Table 6). From this, we deduce that CAFS stock about 10.30% of the amount of carbon stocked by the forest in this same area. Among the five villages, the carbon stocks of associated trees in the CAFS ranged from 10.16 ± 1.17 tC/ha for Fonjomonkoto 29.47 ± 4.15 tC/ha for Bamengui. At 5% significance level, there is a significant difference between the amount of carbon stocks in the CAFS of Fonjomonko and those of other villages (P = 0.007). In

Fonjomonko the low carbon stock in CAFS is due to the very high abundance of *E. guineensis* which represented 89.6% of individuals counted in this village with an IVI of 272.93%.

Carbon stock allocation by different species

In terms of contribution of species to the total carbon stock, the top five species in the forest were *Milicia excelsa, Lophira alata, Pterocarpus soyauxii, Piptadeniastrum africanum* and *Alstonia boonei.* In the CAFS, the greatest contribution was made by *Milicia excelsa*, *Elaeis guineensis*, *Dacryodes edulis*, *Alstonia boonei* and *Lophira alata* (Figure 3). In the CAFS, *Elaeis guineensis* and *Dacryodes edulis* had a good contribution to carbon storage in general due to their high abundance. They are indeed the two most abundant species with 56.47% and 16.23% of individuals respectively. The three other species (*Milicia excelsa, Alstonia boonei* and *Lophira alata)* have a good contribution to carbon sequestration due to their large size and high wood density, and also because they are among the most efficient species (Table 7).

Carbon sequestration performance was evaluated based on the average amount of carbon stored by a tree of the species. From Table 7, it can be seen that the best performing species were *Triplochiton scleroxylon*, *Milicia excelsa*, *Podocarpus mannii*, *Lophira alata* and *Canarium schweinfurthii*, which are mostly secondary forest species that are conserved at the time of setting up the coffee plantation. Efficient species accumulated high average carbon per tree due to high specific wood densities (*Milicia excelsa* and *Lophira alata*) or relatively large size (*Triplochiton scleroxylon, Podocarpus mannii, Alstonia boonei, Canarium schweinfurthii* and *Mangifera indica*). Majority of non-forest species planted by farmers stored low average amounts of carbon per tree (*Elaies guineensis*, *Persea americana, Citrus reticulata, Psidium guajava, Carica papaya* and *Annona muricata*).

DISCUSSION

Floristic richness and diversity

A total of 30 woody species belonging to 19 families were recorded in the coffee agroforestry systems of Kekem. In the natural forest, 30 species belonging to 15 families were identified. The species richness of CAFS is similar to that of 30 species and 16 families found by Manga et al. (2013) in the western highlands of Cameroon. This similarity can be explained by the fact that these two study areas are ecologically close. However, this richness is lower than that of 44 species found by Dallière and Dounias (1999) in the CAFS in Central region of Cameroon. It is also lower than those found in other parts
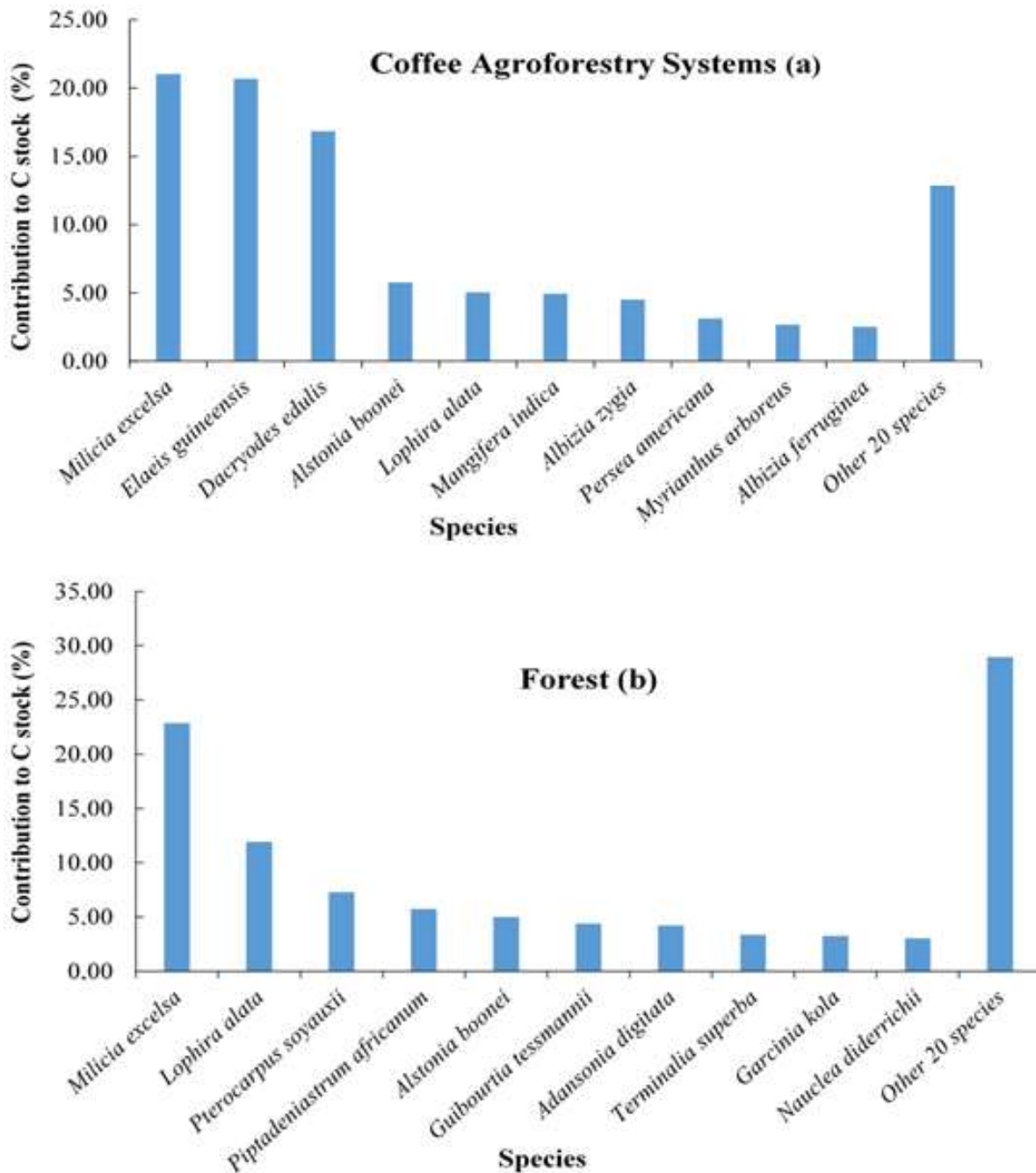
Figure 3. Contribution of species to the total carbon stock in: (a) CAFS and (b) Forest.

of the world: 47 species found by Richard and Mendez (2014), 91 species found by Tadesse et al. (2014a) and 138 species found by Koda et al. (2019) for smallholder coffee systems in El Salvador, Ethiopia and Togo respectively. This difference can be explained by the endogenous knowledge and cultural practices of these peoples and more technological itinerary adopted in establishing these coffee agroforestry systems (Mapongmetsem, 2017). In the study area, farmers

conserve or introduce into their coffee farms, only trees species that are really useful to them and eliminate unnecessary ones, this choice being guided by the socio-economic and ecological benefits of the species.

The Shannon-Weaver diversity index (H') in CAFS ranged from 0.48 to 2.16 with a mean of 1.61, reflecting low diversity. The low diversity was also confirmed by a Simpson's diversity index of 0.62. The low Pielou evenness (0.45) obtained show a low distribution of

Table 7. Carbon sequestration performance of species.

Species	Average diameter (cm)	Number of individuals	Average biomass per tree of the species (kg/tree)	Average carbon per tree of the species (tC/tree)
Triplochiton scleroxylon	89.17	1	2378.2	2.38
Milicia excelsa	55.03	31	1700.13	1.70
Podocarpus mannii	74.20	1	1686.23	1.69
Lophira alata	37.61	11	1143.49	1.14
Canarium schweinfurthii	50.64	5	952.04	0.95
Mangifera indica	51.20	13	917.41	0.92
Alstonia boonei	44.56	21	688.16	0.69
Myrianthus arboreus	44.52	10	669.01	0.67
Albizia ferruginea	36.52	12	527.38	0.53
Afzelia pachyloba	32.80	12	480.68	0.48
Tetrapleura tetraptera	34.18	12	478.72	0.48
Pterocarpus soyauxii	29.14	2	435.62	0.44
Albizia zygia	35.45	26	433.79	0.43
Nauclea diderrichii	34.08	3	354.99	0.35
Unidentified species	33.76	2	317.68	0.32
Cola nitida	30.89	3	313.04	0.31
Adansonia digitata	45.86	1	274.69	0.27
Voacanga thouarsii	30.41	4	267.76	0.27
Dacryodes edulis	30.04	173	243.71	0.24
Voacanga africana	31.05	4	181.16	0.18
Garcinia kola	21.50	25	164.24	0.17
Persea americana	26.13	49	159.43	0.16
Cocos nucifera	26.71	7	107.99	0.11
Picralima nitida	24.52	1	91.84	0.09
Elaeis guineensis	46.86	602	86.06	0.09
Citrus lemon	18.95	2	74.12	0.07
Citrus reticulata	15.16	10	55.16	0.06
Psidium guajava	16.59	11	47.47	0.05
Carica papaya	14.01	6	11.52	0.01
Annona muricata	11.94	6	7.04	0.01

individuals within species due to the fact that *E. guineensis* was the dominant species. The Shannon index of CAFS in the study site was very low compared to the values of 3.5 and 4.06 recorded respectively by Tadesse et al. (2014a) in Ethiopia and Koda et al. (2019) in Togo. This difference can be explained by the fact that associated trees in Kekem are highly selected to leave just a few species that are really useful to farmers. Of the 30 species identified in the natural forest which was the control, 18 were found in agroforestry systems, representing a species conservation rate of 60%. This may be justified by the fact that during the establishment and evolution over time of the coffee plantations, the farmers are able to conserve forest species that have both socio-economic and environmental benefits to coffee and households. However this figure should be put into perspective, because taken separately, the rate of species conservation varies significantly between

villages. In Fonjomonko, CAFS share only 3 species (10%) in common with the natural forest while in Kekem center, they share in common 14 species (46.67%). Among the trees species found in CAFS, four are considered vulnerable (*Afzelia pachyloba, Garcinia kola, Lophira alata, Nauclea diderrichii*) and one is near threatened (*Milicia excelsa*) according to the IUCN Red List (2019). We found that conversion of forests to coffee agroforestry systems resulted in a loss of at least 40% of forest-based woody species. This loss is close to the 34% loss found by Tadesse et al. (2014a) in Ethiopia but is lower than the 54% loss by Mbolo et al. (2016) in cocoa agroforestry systems in central region of Cameroon.

Despite this loss, for income diversification purposes, farmers replace some native forest trees with species that are useful to them. Thus, 12 species that are not found in natural forest were identified in the CAFS. It was

observed that the choice of conserving or introducing trees in the CAFS is guided by their uses, but also by the market opportunities available to farmers. Thus, in order to fill the gaps in coffee production or to keep the inflow of agricultural income constant, these farmers are shaping their farm by prioritizing the conservation/introduction of trees whose fruits or products will be consumed by family or sold. Priority is given to species of high socio-economic value and to those whose planting and regeneration techniques are mastered by farmers. This concerns trees that produce edible fruits and that are usually planted by farmers (*Citrus reticulata, Dacryodes edulis, Elaeis guineensis, Persea americana, Mangifera indica, Garcinia kola, Psydium guajava* and *Annona muricata*). The species useful for wood and shade are those that are most often conserved at the time the plantation is established, and are also species found in the adjacent forest (*Milicia excelsa, Lophira alata, Albizia ferruginea, Nauclea diderrichii, Pterocarpus soyauxii, Albizia zygia, Afzelia pachyloba*).

In addition to shading, four other uses were mentioned by the coffee farmers which were: medicine, wood, fruit production and palm oil production. The latter use is provided by *Elaeis guineensis* which was the most abundant species found in the CAFS in the study area. In the Western Highlands of Cameroon, Manga et al. (2013) found that *Persea americana* was the most abundant species while *E. guineensis* was the least abundant. This difference can be explained by the proximity of the study area to the Littoral region, which is one of the main production basins of oil palm in Cameroon and is an important source of income for smallholders (Ndjogui et al., 2014).

Structure of coffee agroforestry systems and forest

The average tree density found in CAFS was 133 ± 24 stems/ha and was equivalent to about 38.5% of the tree density in the adjacent secondary forest (345 ± 28 stems/ha). The tree density in CAFS is similar to the 108 ± 59 stems/ha recorded by Goodall et al. (2015) in San Ramon in Nicaragua; and is lower than the 207 stems/ha and 246.38 stems/ha recorded by Tadesse et al. (2014a) and Koda et al. (2019) in smallholder coffee systems in southwest Ethiopia and Togo respectively. The basal area of associated trees in CAFS (15 m^2/ha) fell within the range of 11 to 16 m^2/ha found by Manga et al. (2013), but was smaller than those of 54.5 and 27.99 m^2/ha found by Tadesse et al. (2014a) and Koda et al. (2019) respectively. This difference can be explained by much higher stem densities in the study sites of the latter authors than in ours.

In CAFS, size class distribution of stems followed a bell-shaped curve indicating a regeneration deficit with the largest numbers of stems concentrated above 35 cm. This could be due to the selective removal of saplings

by coffee farmers or a non-renewal of big trees. This distribution is similar to that described in coffee agroforestry systems in Highlands of Western Cameroon by Manga et al. (2013), but is different to the J-inverted distribution observed in Guinea (Correia et al., 2010), in Ethiopia (Denu et al., 2016) and in Togo (Koda et al., 2019).

Carbon sequestration potential

The amount of carbon stock in CAFS was about 24.28 tC/ha on average. This value fell within the low end of the range of 12 to 228 tC/ha reported by Albrecht and Kandji (2003) for tropical agroforestry systems, and is similar to the value of 24.4 tC/ha reported in CAFS in El Salvador by Richards and Mendez (2014). However this value is less than the average carbon stock reported for comparable carbon pools in CAFS in other parts of the world. For example, Schmitt-Harsh et al. (2012) found 83.39 tC/ha in western highlands of Guatemala; Goodall et al. (2015) found 49.25 tC/ha in Nicaragua; Denu et al. (2016) and Tadesse et al. (2014b) reported respectively 61.5 tC/ha and 153 tC/ha in southwest Ethiopia; and Zaro et al. (2019) recorded a carbon stock of 75.80 tC/ha in CAFS with rubber trees in southern Brazil. These disparities recorded by several similar studies may be related to the fact that the studies were carried out in different areas with different climatic and ecological conditions and, as such, the wood density, the species as well as the stem densities of trees associated with coffee varied. In the study area the most abundant species with an overall relative abundance of 56.47% and an IVI of 169.96% was *E. guineensis* which, because of its very low wood density do not contribute to carbon sequestration the same way as forest species.

The carbon stock of the natural forest has been estimated at 235.88 tC/ha. The average carbon stock on CAFS represents about 10.30% of the average amount of carbon stored by the adjacent forest. The difference in carbon sequestration between CAFS and forest is due to the high stem density, wood density and diameter of trees found in the forest. In agroforestry systems, the most abundant species was *E. guineensis*. Despite the fact that this species had a very high abundance compared to other species, it had a low performance interms of carbon sequestration, that is, only 0.09 tC/tree.The best performing species were *Triplochyton scleroxylon, Milicia excelsa, Podocarpus mannii, Lophira alata* and *Canarium schweinfurthii.* However these species had low abundance (only 1, 31, 1,11 and 5 individuals respectively).

The 10.30% of carbon stored by CAFS compared to natural forest is smaller than the 75, 62 and 52% reported in Ethiopia by Denu et al. (2016), Tadesse et al. (2014b) and Vanderhaegen et al. (2015) respectively. This great difference is mainly due to the less abundance of carbon

sequestration efficient species in CAFS of the study area. Although CAFS stock less carbon than the forest, they represent one of the most diverse farming systems and agroforestry trees can still store more carbon than other cropping systems (Kirby and Potvin, 2007).

With an average offset price of $3.2 per ton of CO_2 from voluntary carbon markets (Ecosystem Marketplace, 2019), the amount of carbon stored in CAFS in Kekem could enable farmers to earn an additional $294/ha. However, these figures could even be higher if all the carbon pools, particularly litter and soil organic carbon were taken into consideration. These amounts of money may afford an opportunity for coffee farmers to manage such systems for greater carbon sequestration. Thus, payment for environmental services mechanism would promote climate mitigation and adaptation benefits in addition to its socio-economic and ecological benefits if CAFS are integrated into conservation. In fact, the farmers' perception of climate change in the area is very real and in order to adapt to these changes, they are increasingly opting not only for the diversification of crops, but also of cropping systems, the collection and marketing of non-timber forest products in addition to the benefits brought by coffee plants (Mapongmetsem, 2017). This opportunity of payment of carbon credit would encourage the conservation and planting of trees and would reduce the observed tendency of conversion of CAFS to other cropland by farmers in the study area with the drop in coffee prices.

Conclusion

Significant differences were recorded between coffee agroforestry systems and the forest in terms of diversity, tree density and carbon stock. Although tree density is much higher in the forest, CAFS contributed significantly to the conservation of woody species because they share in common 60% of the species with the forest. In CAFS, some forest species were being replaced with non-forest species that are useful and can contribute to income generation and farmers' livelihood. Farmers have mainly oriented their coffee farms towards diversification of production. As a result, the associated trees are mainly introduced/conserved for fruit production, palm oil production and the needed shade for coffee trees. Compared to forests, CAFS contributed little to carbon storage because the more abundant trees were less efficient in terms of carbon storage. However, the amount of carbon stored remains higher than in other non-agroforestry cropping systems. The ecological service linked to carbon sequestration and wood diversity conservation offers a possibility of financial benefits in case of payment for ecosystem services. To farmers, this would then not only raise awareness of climate change and the need for conservation, but would also contribute to the improvement of their livelihood. Farmers should been couraged to plant/conserve more tree species that

are useful but also have good carbon sequestration potential.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Evaluation of forest litter mineralization capacity on the growth of *Irvingia gabonensis* in Ogwashi-Uku Forest Reserve, Delta State, Nigeria

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The study evaluated litter production capacity of three forest plantation foliage litters as potential mineralization sources for the growth of *Irvingiaga bonensis*. Litter production capacity of Bamboo, Teak and Gmelina forest plantations was monitored for 70 days before *Irvingia* seeds were sown in open germination beds containing litters soil samples for vegetative development assessment. Data collected were analyzed using ANOVA and significant means separated with the DMRT. Results showed the mean litter production as Teak (3.65t/ha) >Gmelina (3.60t/ha)> Bamboo (2.67t/ha) and germination percentage was highest for soils of Bamboo plantation. The carbon nitrogen ratio was Gmelina (2.60)> Teak (2.24)> Bamboo (1.90) and bulk density as Gmelina (1.59 g/cm^3) > Teak (1.47 g/cm^3) > Bamboo (1.45 g/cm^3). The plant height, leaf area and leaf to stem ratio were Bamboo >Gmelina> Teak while the collar diameter was highest in Teak forest plantation soils. The study showed soils under the Bamboo forest as the best growth media for *I.* gabonensis, and therefore implied soils under the Bamboo forest as potential natural nursery and forest regeneration materials, especially in the current global deforestation menace that have adversely limited the preponderance of silvical floor litters.

Key words: Soil organic matter, litter production, forest soils, decomposition, vegetative development.

INTRODUCTION

The litter component of forest floor is a major soil structural biota that has strong influence on the nutrient composition characteristics in distinguishing forest soils. This is due to the vital biogeochemical role often demonstrated in the mechanistic transformation of key plant elements in forest floor litters to the soil nutrients (Bassey and Opara, 2015; Krishna and Mohan, 2017).

The resultant soil characteristics are significantly determined by the litter component of the forest floors after decomposition by soil fungi, bacteria and other detritivores (Ibanga, 2006; Read and Lawrence, 2003) interact with the litters to produce organic matters as essential nutrient anchorage for soil micro-organisms to efficiently initiate the decomposition and mineralization processes that confers on the forest ecosystems spatial productive functions (Johnson and Cartley, 2002; Six et al., 2004; Noguez et al., 2008; Liu et al., 2010) that regulate the soil properties of given forest type and

microbial biomass activity. Dechaine et al. (2005) however reported that the physico-chemical environment, litter quality and the composition of the decomposer community regulate litter decomposition rate. More significantly, the leaf litters in forest stands moderate the soil temperature which eventually lowers the oxidation rate of soil organic carbon as well as the transpiration rate, subsequently assisting the bioactivity of the soil micro-organisms which require a wide range of moisture to effectively mineralize into nutrients.

It is on this premise that forests with high species diversity of notably dense leafy canopies represent a variegated source of litter production which may ultimately influence the soil microbial community. Such organic matters varies with tree species (Klein and Dutrow, 2000) and the capacity of the different parts, especially the leaves to photosynthesize in order to create nutrient pools that could become mined by the soil mineralization under favorable environmental conditions. Wu et al. (2012) suggested that the volume of litter falls varies with the composition of the mixed forest, the stand density and anthropogenic activity (Egwunatum et al., 2015),implying that significant differences could occur in the litter quality of a forest stand as nutrient source for the soil under the mixed forest. This therefore underscores the current rate of deforestation as a result of anthropogenic activities (Brunetet al., 2010; Morris, 2010), as a threat to the nutrient pool of the forest soils due to the loss of its preponderant silvical litters for its sustainable enrichment owing to changes in microhabitats and loss of forest biodiversity (Bengtsson et al., 2000; Chaudhary et al., 2016). Brady and Weil (2002) reported that plants on tropical soils recycles approximately 60-80% of minerals, with calcium and phosphorus attaining more than 99% from the soil by the roots of forest trees. This also implies that in addition to the litter concept in the enhancing the forest soil, the root biome plays significant role in the uptake of nutrient from restricted locations in the soil (Speengeren, 2005). Thus to a large extent, especially in the evergreen and secondary forests where there is relatively low leaf shedding and high exploitations respectively, the roots represent potent litter capacity framework for enriching the forest soil. It is these interplay that eventually modify and enrich the forest soil which overtime endangers it as potential fertile soil for agriculture. This therefore confers a significant role on the forest floor as potential input-output system for nutrient regulation via the regular reception of litters at various rates that decompose and mineralize to form edaphic nutrient bridges in forest ecosystems.

Unfortunately, the increasing rate of deforestation particularly for lumbering and collection of minor forest produce has often led to the decline of these forest floor inputs with a commensurate decline in soil nutrient build up in the forest ecosystem. It is against this backdrop that the study was conducted to examine the current level of litter fall and its commensurate nutrient supply to the underlying forest soil under *Tectona grandis*, *Gmelina arborea* and *Bamboo bambusa* forest plantations, as index for choice of soils and site in the growth performance of *Irvingia gabonensis* in the degraded Ogwashi-Uku Forest Reserve.

MATERIALS AND METHODS

Description of study area

The experiment was conducted in the permanent nursery site of the Delta State Ministry of Environment Area field office, beside the Iyi-Ada stream, in the Ogwashi-Uku Forest Reserve. It is located on latitude 6° 25' N and longitude15° 25'E in the lowland rainforest ecological zone of Delta State. The mean temperature is 28°C and annual rainfall averages 1800mm that peaks in July-September (NiMet, 2016). The vegetation is mostly secondary forest of over 10 ha of *T. grandis* and *G. arborea* with naturally occurring *Bambusa* parchments of over 10 ha. The *T. grandis* and *G. arborea* plantations were last regenerated in the year 2002 (MOE, 2015). The topography of the site is undulating with the teak and bamboo vegetation at the top and valley, respectively. The *G. arborea* stand is sandwiched between the *T. grand is* and Bamboo, with Bamboo vegetation closest to the Iyi-Ada stream in the forest reserve. This natural occurring Bamboo vegetation has significantly assisted in abating the observed erosion that is on the increase following the massive deforestation without regeneration as seen on the tract road leading to the stream where sand mining is actively taking place.

Data collection

Plantation litter and soil collection

Two diagonal transect lines of 100m each were taken within 1haof the Teak, Gmelina and Bamboo forest plantation types in the reserve. The two diagonal lines were established in each of the three plantation types that is Teak, Gmelina and Bamboo to enable the location of 1m × 1m quadrants as permanent litter sampling points. These litter sampling points were at 20, 40, 60, 80 and 100m that is at 20m intervals along the established diagonal lines. This gave a total of 5litter sampling points per line transect and 10 L sampling points per plantation type which translated to 5 grab litter sampling points per plantation type.

Litter samples were carefully harvested with the hand garden fork from each quadrant every forth night for 10 weeks at the rate of5 and 10 L samples per transect line and plantation type respectively which translated to five grab samples per forest plantation type. Experimental soils of approximately 1.50m³ were obtained from a depth of 0.30m in the established permanent litter sampling quadrants at the end of the 10 weeks litter collection from each of the three   forest plantation types for use in the screen house experiment. The soil auger was used to collect grab samples of soil from the sampling quadrants in each forest plantation types at a depth of 0-30cm for laboratory analysis.

Germination trials

Three open germination beds measuring 150cm × 50cm × 30cm were prepared within the Teak, Gmelina and bamboo forest plantation type, taking the need for adequate sunlight into consideration. The beds were deliberately and carefully established in each plantation type with a view to maintaining the same nutrient

Table 1. Litter production capacity in the different forest plantations (t/ha, dry weight).

Period (Weeks)	Forest plantation type		
	Bamboo	Teak	Gmelina
2	2.57[b]	3.14[b]	4.12[a]
4	2.21[b]	4.10[a]	3.69[a]
6	2.65[b]	3.63[a]	3.58[a]
8	2.85[b]	4.05[a]	3.53[b]
10	3.05[a]	3.18[a]	3.07[a]
Mean	2.67	3.65	3.60

Means with the same superscript on the same row are not significantly different (P < 0.05).

soil and litter source. They were established in relatively open spaces between standing trees within each plantation type and not directly under tree canopy. Sixty seeds of *Irvingia gabonesis,* which were obtained from a local market in Kwale, were planted out on each germination bed using an enspacement of 7.5 cm✗ 2.5 cm at the rate of 20 seeds per bed. These were then watered uniformly by sprinkling with an average of 8 L per bed/week to allow for consistent wetness and ensure that litter deposits were equally aided in the process of decomposition for mineralization of nutrients. These were monitored for emergence every week for a period of 6 weeks after which 10 germinated seedlings were selectively pricked from the germination beds of each plantation type and transplanted in 30 polypots already recharged with the experimental grab soil samples of forest plantation types of 10 replicates each in the Presidential Initiative on Afforestation screen house of the Ministry of Environment, Ogwashi Uku These were further monitored for over a period for growth variables of height, leaf area, collar diameter, and leaf-stem ratio.

Litter estimation and soil analysis

The harvested litter samples were oven dried at a temperature of 80°C until a constant weight was attained. The weight of litter per grab sample of the quadrant was taken and averaged as litter production in each forest plantation type. It was in view of ensuring good representative samples of litters during harvest that a minimum of two diagonal transect lines were established per plantation type. This resulted in 10 L sampling points/quadrants measuring 10^4cm^2 to give approximately 10% sampling size per hectare for each plantation type.

The soil samples were analyzed for bulk density, porosity, pH, organic carbon and matter. Bulk density was determined by oven-drying the soil samples to constant weight at 105°C and the bulk density derived as described by Klute (1986). Porosity was inferred from the bulk density. The pH was measured in 1:2.5 soils: water suspension as described by Dane et al. (2002). Organic carbon was determined using the Walkley and Black (1934) wet oxidation method as modified by Nelson and Sommers (1986) and the organic matter was computed by multiplying organic carbon the van Bermelen's factor of 1.725. Exchangeable cations (K^+, Ca^{2+}, Mg^{2+} and Na^+) were extracted with 1M NH_4OAc and the amounts in extracts were then determined using atomic absorption spectrophotometer (Thomas, 1982). Total nitrogen was assessed using the Kjeldahl nitrogen analysis method (Jackson, 1958). Exchangeable acidity was measured from 0.1M KCI extract and titrated with 0.1M NaOH (Juo, 1979). The effective cation exchange capacity was taken as the sum total of exchangeable cations and

exchangeable acidity. Standard soil sample as prescribed for the various parameters. The data collected were subjected to analysis of variance (ANOVA) and significant means separated using the Duncan multiple range test (DMRT) at 5% probability levels. Inferential statistics (correlation and regression) was employed to analyze the data where appropriate.

RESULTS

Litter production capacity

The average litter production was higher in the Teak and Gmelina than the Bamboo forest plantation (Table 1). It ranged from 2.21t/ha in the Bamboo plantation to 4.12t/ha in the Gmelina plantation. However, within the forest plantation types, itranged from 2.21-3.05 t/ha to 3.07-4.12 and 3.14-4.10t/ha for the Bamboo, Gmelina and Teak respectively. The mean litter fall capacity was highest for the teak (3.65t/ha) and least for bamboo (2.67 t/ha).There was no significant difference in the mean litter fall and production among the three forest types at the tenth week. Nonetheless, there were significant differences between the Teak and Gmelina, Bamboo and Teak as well as Teak and Bamboo at second, sixth and eighth weeks of litter harvests respectively.

Physico-chemical properties of soils under different forest plantation

The physico-chemical properties of the soils of the 3 subgroup (Bamboo, Teak and Gmelina plantation types) are summarized in Table 2. The bulk densities of the soils under the three plantations varied significantly (Table 2). The highest soil organic matter (3.02%) was recorded in the Bamboo plantation which differed significantly from the Teak and Gmelina plantations that were statistically at par. With respect to the organic carbon, the trend was similar to that of organic matter as the Bamboo plantation showed the highest (1.75%) while the Gmelina (1.66%)

Table 2. Physical and chemical properties of soils under different forest plantation.

Parameter	Forest plantation type		
	Bamboo	Teak	Gmelina
Bulk density (g/cm^3)	1.45^b	1.47^b	1.59^a
Porosity (%)	44.66^a	44.40^b	39.88^c
Moisture content (%)	27.32^a	23.30^b	21.28^c
Organic carbon (%)	1.75^a	1.70^b	1.66^b
Organic matter (%)	3.02	2.93^b	2.86^b
Total nitrogen (%)	0.92^a	0.76^b	0.64^c
Carbon-nitrogen ratio	1.90^c	2.24^b	2.60^a
pH (pH $_{(KCl)}$- pH $_{(H2O)}$)	5.94^a	5.80^b	5.69^c
Exchange cation (Meq/100g soil)	8.06^a	5.50^b	5.05^c
Exchangeable acidity (Meq/100g soil)	3.44^a	1.34^b	1.29^b

Means with the same superscript on the same row are not significantly different (P < 0.05).
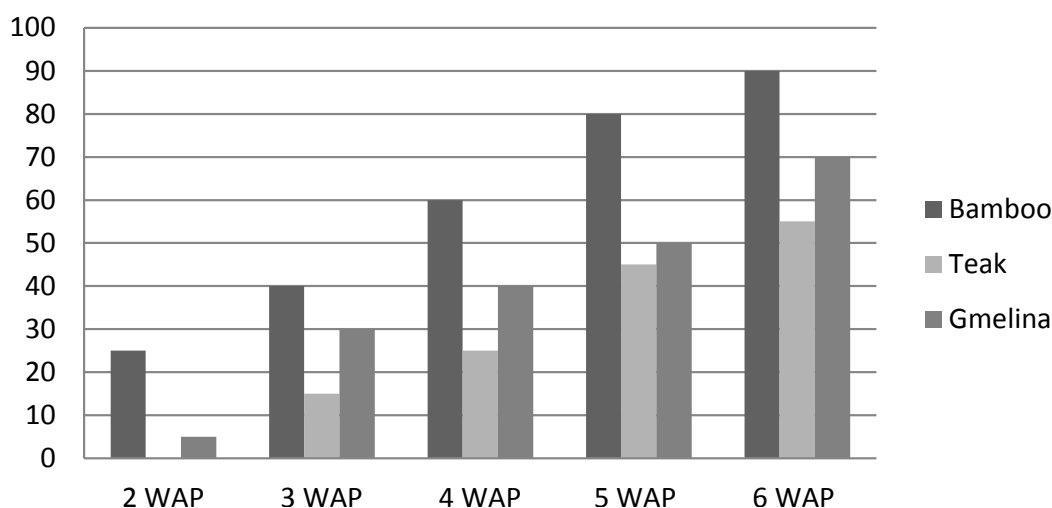
Figure 1. Germination percentage of Irvingina under different plantation soils.

had the least. The pH difference, (pH $_{(KCl)}$ – pH $_{(H2O)}$), was positive for the three plantation forest soil types although were statistically not at par. However, the pH was highest in the bamboo forest plantation forest soil while the least pH of 5.69 was recorded by the Gmelina plantation. The soil physico-chemical properties were significantly correlated with each other. The correlation analyses of the various soil physical and chemical properties in the three plantation types are shown (Table 3). With respect to the Bamboo plantation soil, the organic matter was positively correlated with the bulk density (r = 0.919). This showed the contribution of organic matter to bulk density. The same result was recorded in the Gmelina (r = 0.944) and the Teak (r = 0.998) forest plantation soils. The pH showed negative significant correlation with organic carbon (r = -0.404) and CEC (r = -0.667) in the Gmelina plantation forest soils whereas in the bamboo forest soil

pH showed positive correlation with organic carbon (r =1.903) and CEC (r = 1.685).

Germination trial of *I. gabonensis*

The germination percentage of Irvingia under the various forest plantation soils are shown in Figure 1. At two weeks after planting, the Bamboo forest soils recorded a germination percentage of 25% while the Gmelina forest soil was 5%. There was no germination in the Teak plantation forest soil. However, at three weeks after planting it was Bamboo soils (40%) >Gmelina soil (30%) > Teak soils (15%). The highest (90%) and least (55%) germination percentages were attained at 6 weeks after planting with the Bamboo and teak forest soils respectively.

Table 3. Pearson product moment correlation coefficient of the three forest soils.

Correlated variable	Bamboo	Teak	Gmelina
Bulk density vs. porosity	0.8850	0.9982	0.8205
Bulk density vs. organic carbon	0.9980	0.3973^{ns}	0.9720
Bulk density vs. organic matter	0.9190	0.9998	0.9787
pH vs. Organic carbon	0.9030	0.9834	-0.4040
pH vs. Cation exchange capacity (CEC)	0.6850	0.9578	-0.6667

Table 4. Vegetative development of *I. gabonensis* seedlings under forest plantation soils.

	Forest plantation type		
Growth variable	Bamboo	Teak	Gmelina
Height (cm)	53.10 ± 3.82^a	28.40 ± 2.28^c	48.20 ± 2.17^b
Leaf Area (cm^2)	47.19 ± 1.04^a	10.80 ± 0.23^c	30.19 ± 1.28^b
Collar Diameter (cm)	$3.05 \times 10^{-1} \pm 0.44^{bc}$	$3.61 \times 10^{-1} \pm 0.48^a$	$3.23 \times 10^{-1} \pm 1.31^b$
Leaf-stem ratio	0.43^a	0.17^c	0.33^b

Means ± SD with the same superscript on the same row are not significantly different (P < 0.05).

The height of *I. gabonensis* seedlings varied significantly among the three plantation forest soils (Table 4). Plant height under the Bamboo litter forest soil, recorded a height of 53.10 ±3.82cm that significantly differed from the Gmelina (48.20 ± 2.17cm) and Teak (28.40 ± 2.28cm). Hence, it recorded the highest moisture content (27.32%) and the least by Gmelina forest soil (21.28%) with a corresponding high bulk density of 1.59g/cm$^{3.}$ There was significant difference among the leaf areas of the different forest plantation soils. The leaf area showed similar trend with the plant height and the bamboo forest soil recorded the highest mean area of 47.19 ±1.04 cm^2 while the Teak (10.80 ± 0.23 cm^2) recorded the least leaf area. The leaf-stem ratio which is a measure of the change in botanical composition was highest in the Bamboo plantation forest soil (0.43) and least in the Teak forest plantation soil (0.17).

DISCUSSION

The mean litter production was Gmelina (3.65 t/ha) > Teak (3.60 t/ha) > Bamboo (2.67t/ha)was quite low compared to the estimated litter fall of 7.50 -7.80t/ha in the Sakponba Forest reserve (Onweluzo E, 1970) and 5.60-7.30t/ha for the Gambari forest reserve (Ola-Adams and Egunjobi, 1992). The low litter fall in the Teak and Gmelina plantations could be due to the high timber and fuel-wood extraction rates in the Ogwashi-Uku forest reserve as it was established for poles and timber, to forestall the accelerated rate of deforestation and fragmentation of its status as protected area (FORMECU, 2000; Onojeghuo and Onojeghuo, 2015). However, with

respect to the individual number of leaves per quadrat at the various points on the transect lines the Bamboo recorded a remarkably higher quantity, but for the larger leaf sizes of the Teak and Gmelina in comparison with that of Bamboo. This to a large extent shows that while tree species could have high litter fall capacity, the size of leaf could also account for its proportionate contribution to the soil organic matter and nutrient status in a given period of time. This finding agrees with Indriyanto (2009) that litter produced by a forest is related to different amount and composition based on the structure and the species diversity of the plant. Notwithstanding, the nutrient mining capacity could also vary with the available environmental conditions that can enhance or retard the decomposition depending on the interplay of critical elements particularly in presence of oxygen and nitrogen.

The rooting structure that actually proliferate the upper 0-30cm as well as its slower decomposition and infusion may have accounted for the favorably low bulk density of the bamboo plantation soil because of the nature of the glossy leaf surface and structure respectively. Hence, unlike the Teak and Gmelina, the bamboo surface offers additional resistance to decomposing organisms which invariably increases the phytocycling process. This delay commensurately ensures that nutrients are mined from the litters at a steadier rate and readily available state that make for retention in soil. The Teak and Gmelina could have faster decomposition rates that lead to loss of nutrient through leaching. There was however no significant difference between the bulk densities of the Teak and Bamboo. This agrees with Johnson and Curtis (2001) who stated carbon losses may result from leaching and soil erosion.

The three forest soil types are relatively acidic in nature and are therefore fertile since the availability of nutrients for plants is influenced by the soil pH (Zhao et al., 2012). However, the pH was highest in the bamboo forest plantation forest soil which could be as a result of the increasing carbon potentials of the soil due to steady litter mineralization rate which may have accounted for the acidic accumulation in comparison to that of the Teak and Gmelina. The high mineralization rate could have led to its prompt leaching downward from the upper horizon. The soil organic matter content of the three plantations were quite high (≥ 2.50%) according to classification of Adepetu (1986). This may not be unrelated with the fact that all the soil samples were taken from the same soil depth. However, the highest soil organic matter of the bamboo plantation may not be unrelated with the slower phytocycling potential of the needle leaf shape structure which leaves behind much of the leaf materials in the soil as organic matters.

Furthermore the rate of litter deposition varies widely among species in identical ecological situations (Wardle et al., 1997; Perez-Harguindeguy et al., 2000). On the other hand, the Teak and Gmelina did not differ significantly as the leaves have almost similar leaf surface quality. Hence, the results are quite suggestive of the decomposition rate of these veins and other leaf parts in the process of phytocycling which could be deemed lower in the Bamboo than in the Teak and Gmelina plantations.

The lack of significant difference between the organic carbon of the Teak and Gmelina plantations agrees with the finding of Wang et al (2013) which indicated that bamboo forest ecosystem through its high photosynthetic mechanism turns more carbon dioxide (CO_2) into organic carbon which are stored in leaf structures that eventually become litter components of the forest floor. The higher organic carbon content of Bamboo soils could be due to the presence of dense fine root on the top layer of the soil as reported by Paudel and Sal (2003).

Furthermore, the leaf-shedding potential of bamboo is reported to be quite high because its leaves usually fall at earlier age of between 12-18 months (Haettenschweiler et al., 2011) which could yield an above ground litter value of 4.1-7.2tons/ha in 2 years (Wang et al., 2013). Although the Teak and Gmelina have broad leaves which could have contributed to the organic matter and carbon contents of each plantation, the capacity to restrict oxygen diffusion into the soil particularly when wet (or green) could have equally limited the phytocycling rates leading to a commensurate decline in nutrient infusion into the forest soil.

Gmelina and Teak plantation forest soils in comparison with the Bamboo forest soil recorded the least C/N ratio which depicted the high mineralization rate of the bamboo forest litters. This finding agrees with Mafongoya et al. (1998) which suggest that litter materials with high N and low carbon-nitrogen ratios mineralize quicker than those with low N and higher C/N ratio. Furthermore, the

mean C/N of each forest plantation type is also suggestive of the dominant active microbial biomass. High C/N ratio indicates fungal dominance of a microbial community whereas a low ratio suggests the prevalence of bacteria (Anderson and Domsch, 1989) and hence could be extrapolated that the microbial community in the T. grandis and G. arborea forest plantation soils are likely dominated by fungi. This may have accounted for the poor mineralization potentials and low organic materials recorded.

The early and high germination percentages recorded in the bamboo forest soils may be related with its high moisture content and improved porosity which is critical to the decomposition and mineralization processes. The high root proliferation capacity of Bamboo may have accounted for a constant moisture content that facilitated the advanced germination, enabling the bathing of the protoplasmic mass of the Irvingia seeds in the germination beds under the bamboo forest plantation, when compared with the tap-rooted T. grandis and G. arborea forest plantations that tended to pull water from the soil but cannot retain the same in the upper root biome due to the absence of specialized root structure typical of the bamboo forest. This finding is in line with Pandel and Sah (2003) that reported that the presence of dense fine roots on top layer of soil and higher organic carbon content results in high water holding capacity. Improved porosity observed in bamboo may have facilitated respiratory activities in germinating embryos.

The highest plant height recorded under the Bamboo litter forest soil may not be unrelated with the favorable bulk density of the bamboo forest soil due to its characteristic rooting system that often permeates the root biome and thereby increasing aeration and enhancing the macro-pores spaces for more water retention and release. The capacity of Bamboo not only to grow in relatively poor soil but to equally and efficiently make use of the available nutrients to build up relatively fertile soil around the clumps (Hairiahet al., 2006) could have contributed to the positive effect of the forest type on the soil.

The highest leaf-stem ratio which is a measure of the change in botanical composition recorded in the Bamboo plantation forest soil is an indication that the level of photosynthates accumulation is highest in the bamboo forest soil which may be connected with the relationship between the nutrient bioavailability. The significantly higher growth performance recorded in soil with higher total organic carbon is not unusual since soil organic matter governs soil physical and chemical properties, ensures abundance of the concentration of essential nutrients and provides favorable conditions for plant survival, development (Horwath, 2005)

Conclusion

The litter production capacity of the three evaluated forest

plantations showed that the Teak and Gmelina were predominantly higher than the Bamboo forest. However, this did not translate into commensurate nutrient richer soils in the *T. grandis* and *G. arborea* forest plantations, perhaps, due to the faster decomposition rate of these forests unlike the Bamboo forest plantation. This may have accounted for the significant positive effects on the germination trial and vegetative development of *I. gabonensis* by the Bamboo forest plantation soils as indicated by the highest germination rate, plant height, leaf area and the leaf-stem ratio which are critical tree growth indicators. This therefore revealed that the forest soils from the Bamboo plantation represent potential nutrient sources for the growth of Irvingia especially in the deforested soil resource depletion crisis in the Ogwashi-Uku Forest Reserve. The result therefore offer significant clue as to its usefulness as edaphic bridge in various *ex-situ* nursery and forest regeneration activities for the development of *Irvingia* as well as other related indigenous forest tree species that have crucial nursery to establishment challenges.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Studies of the wood of some Nigerian alkaloid-rich *Strychnos* species

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The wood of three Nigerian species of *Strychnos* Linn. growing in different ecological zones was studied. The transverse, transverse longitudinal and radial longitudinal sections of the wood were made with sliding sledge microtome. The wood was macerated to measure its fiber and vessel dimensions. The wood was diffusing porous and intraxylary phloem occurred in the three species. Interxylary phloem in discontinuous ring occurred in the xylem cylinder of *Strychnos innocua* Del. and *Strychnos usambarensis* Gilg. Parenchyma was paratracheal and formed aliform to confluent patterns in *S. spinosa* Lam. but scanty in *S. innocua* and *S. usambarensis.* Vessel elements occurred singly and in radial and tangential multiples of two to four. The fiber lumen dimension of *S. spinosa* had the least value while its fiber cell wall thickness also had the greatest value. In *S. spinosa,* alkaloids and sterols were detected in the leaves and stem extracts. Alkaloids were found in the leaves, stem bark and fruits of *S. usambarensis.* The micro morphological features in each species were useful in making them adapt to the climatic conditions of the ecological zones where they grow.

Key words: Interxylary phloem, Intraxylary phloem, *Strychnos spinosa, Strychnos innocua, Strychnos usambarensis.*

INTRODUCTION

Strychnos Linn. belongs to the family Loganiaceae and has been variously circumscribed by different authors. It is the most specious genus of the family with about 200 species and is pantropically distributed (Krukoff and Munachino, 1942; Leeuwenberg and Leenhout, 1980). Frasier (2008) stated that the family was first suggested by Robert (1814) but validly published by Von Marius (1827). Some species in the genus produce alkaloids like strychnine and also have a history of being used in folk medicine to treat fever and malaria (Bisset, 1970) and other conditions. Interest in the genus has been ongoing

for a long time because of its alkaloid rich content. Some studies have been done in the species from Africa (Adebowale et al., 2009, 2012; Oduoye and Ogundipe, 2013). According to Angenot (1988), indole alkaloids are the most active ingredients of *Strychnos* and more of the alkaloids are produced in the stem bark and roots than in the leaves (Quetin-Leclercq et al., 1990).

Although Metcalfe and Chalk (1989), Mennaga (1980) and Dayal et al. (1984) examined the wood of some Loganiaceae, Carlquist (1984) and Frasier (2008) opined that investigation into various aspects of the wood of the

genus should be made. Carlquist (1984) reiterated that several phylogenists have shown interest in delineating natural relationships and plausible groupings among dicotyledons. He also stated that wood anatomy appears to offer some clues about affinity among sympetalous families of dicotyledons. According to Stace (1991), a good taxonomic classification relies on a wide range of characters obtained from morphology, systematic anatomy, chemical taxonomy, cytology and phylogenetics. None of these characters (like anatomical character) can on its own form the basis of classification but when used in synergy, a good taxonomic classification can be achieved. There is no literature that compared the wood of these three species of *Strychnos*. This prompted the present authors to examine these woods of Nigerian species of *Strychnos* from sections Brevitubae, Densiflorae and Spinosae.

MATERIALS AND METHODS

Fresh samples of the wood of *Strychnos innocua* were collected from Rigasa village at the outskirts of Kaduna city, *S. spinosa* was collected from Kuje village at the outskirts of Abuja city and *Strychnos usambarensis* from Ohebe-Dim at the outskirts of Nsukka. Ten stands of each species were randomly collected from their natural regions of provenance in Nigeria. The stem and root of freshly collected samples were cut into small pieces about 2 cm cubes and stored in labeled bottles containing FAA in the Anatomy Laboratory of the Department of Plant Science and Biotechnology, University of Nigeria Nsukka. Three dimensional structures of the stem (transverse section, transverse longitudinal section and radial longitudinal sections) measuring 5-10 um thick were made using a Reichert sledge microtome and stored in well labeled petri dishes containing 70% ethyl alcohol.

Wood of the species of *Strychnos* were split into chips measuring 2 mm in thickness and put into well labeled long test tubes. The chips were macerated with Jane's method (Oladele, 1991).The macerated chips were transferred into well-labeled specimen bottles and stained with crystal blue and safranine before mounting on slides with Canada balsam and covering with cover slips. The fiber dimensions, the vessel element length and the diameter taken at the widest point were measured and recorded. The cut sections of the stem and root stained with safranine and counter stained with fast green according to Sass's method (Oladele, 1991) were mounted with Canada balsam and left on the laboratory bench to dry for 3-4 days. They were then examined under a Zeiss light microscope.

RESULTS

Phytochemical constituents of *Strychnos*

In *S. spinosa,* Philippe et al. (2005) isolated two alkaloids namely saringo sterol and 2,4-hydroperoxy-24-vinyl cholestorel and these showed anti-trypanosomal activity while Rajesh et al. (2009) detected four sterols from the leaf extract of *S. spinosa*. According to Morah (2011) and Oguakwa et al. (1980), the stem and leaf extract of *S. spinosa* collected from different locations in Nigeria

yielded some alkaloids. However, Kingsley and Lofgreen (1942), working with stem and leaf extracts grown in Florida, found no alkaloids from the samples they analysed.

Corsaro et al. (1995) isolated polysaccharides from the seeds of *S. innocua* while Bello et al. (2008) reported the presence of trypsin inhibitor that caused diminished growth in rats, chicken and other experimental animals when eaten raw from the fruit juice and seed of *S. innocua.* Corsaro et al. (1995) also reported the presence of sterols, and fatty acids in the oil of the seed.

Coprasse and Angenot (1982) isolated iso strychnopentamine and dihydro usambarensine which showed strong activity against *Plasmodium falcipariun in vitro*. Federick et al. (2002) also isolated strychnopentamine from the leaves of S. usambarensis and it exhibited antiplasmodial activity *in vitro* against *P. falciparum* that is sensitive and resistant to chloroquine. Cruz (2008) reported that combination of curare alkaloids from the leaves of *S. usambarensis* with anaesthetic material, allowed for the use of less of the latter thereby, reducing the risk inherent in the use of the normal dose of anaesthesia.

Philippe et al. (2005) isolated tertiary and quaternary alkaloids as well as anydronium bases from the root bark of *S. usambarensis*. Federick et al. (1998) also isolated alkaloids from the stem bark of *S. usambarensis*. The fruits of *S. usambarensis* which look like cherries and have an attractive yellow colour when ripe have caused poisoning in children in Africa. This alkaloid has never been isolated from any member of Loganiaceae but has been earlier identified in *Ochrosia* (Apocynacae) by Angenot (1988).

Transverse section of stem

S. spinosa has more than 70% of solitary vessels, less than 29% are in twos or more. *S. innocua* has about 50% vessels occurring singly while the other 50% occur in radial or tangential patterns of 2-3(4). *S. usambarensis* has almost 60% of vessels in singles while the vessels in multiples are in radial patterns.

Parenchyma is paratracheal and forms aliform to confluent pattern in *S. spinosa*. In *S. innocua* and *S. usambarensis* parenchyma is apotracheal to scanty. Interxylary phloem occurs in discontinuous ring right round the xylem cylinder of *S. innocua* and *S. usambarensis* but was not observed in *S. spinosa*. Intraxylary phloem was present in the three species (Figure 1a to c). Fibers in *S. spinosa* have very thick walls.

Transverse longitudinal section

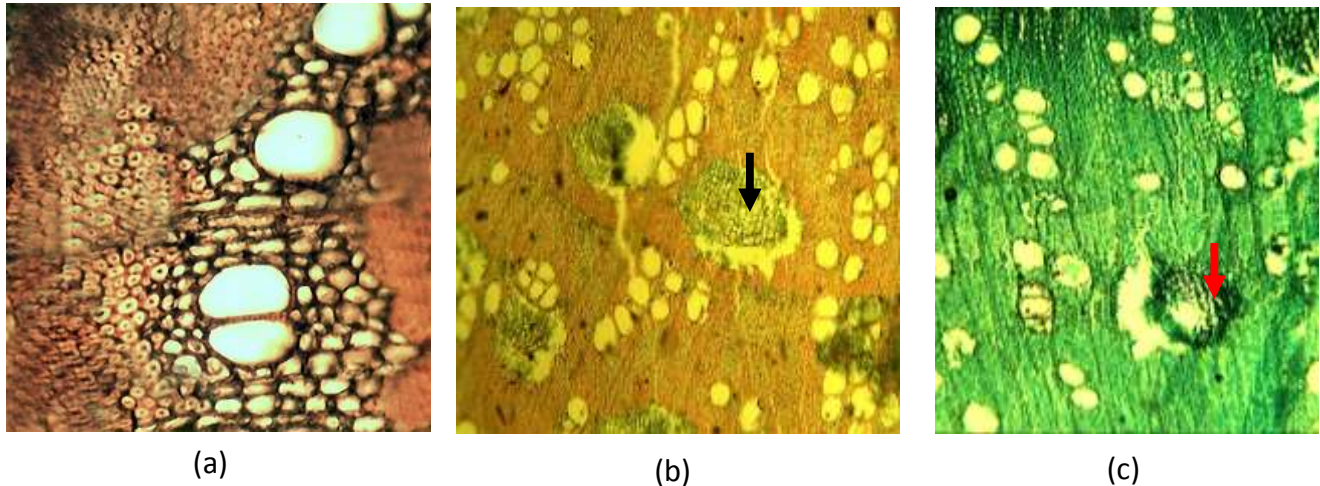Rays are heterogeneous, having uni and multiseriate

Figure 1. (a) TS stem of *S. spinosa* x100, (b) TS stem of *S. innocua* showing interxylary phloemx40, (c) TS stem of *S. usambarensis* showing interxylary phloemx40.
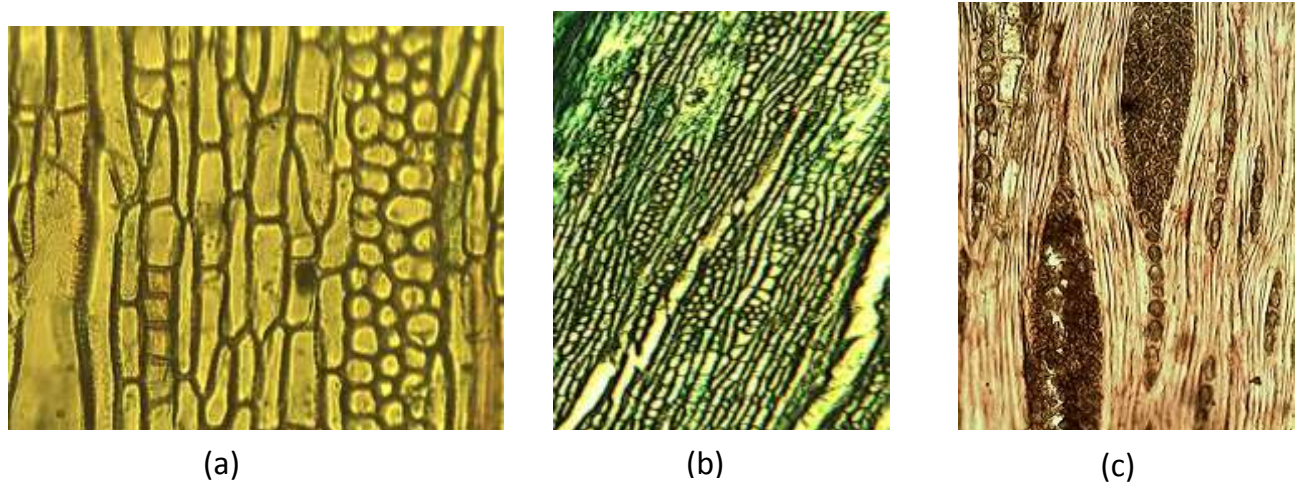

Figure 2. (a) TLS stem of S. spinosa x200, (b) TLS stem of S. innocua x40, (c) TLS stem of *S. usambarensis* x100.

types. Multiseriate rays are more abundant in *S. usambarensis* with some rays being more than four cells wide while in *S. innocua*, the rays are mostly 1-3 seriate and are short (Figure 2a to c). Rays are irregularly storied in *S. spinosa* and *S. innocua.*

Radial longitudinal section

The rays are heterocellular having both upright and procumbent types in the three species (Figure 3a to c). The fiber lumen diameter (FLD) of *S. spinosa* had the least value (Table 1). On the other hand, the fiber cell wall thickness (FCWT) of *S. spinosa* had the greatest value while the dimensions of that of *S. usambarensis*

had the least value (Figure 4a to c). The vessel walls of the three species have simple reticulate pitting (Table 1, Figure 5a to c).

DISCUSSION

The possession of vessels in radial and tangential directions occurring together with solitary vessels is a feature common to members of Loganiaceae (Krukoff and Munachino, 1942; Mennega, 1980; Dayal et al., 1984; Metcalfe and Chalk, 1989; Moya et al., 2017). Also the possession of vessels that are round in transaction is a feature of Loganiaceae (Carlquist, 1984; Metcalfe and Chalk, 1989). The presence of up to 50% of vessels in
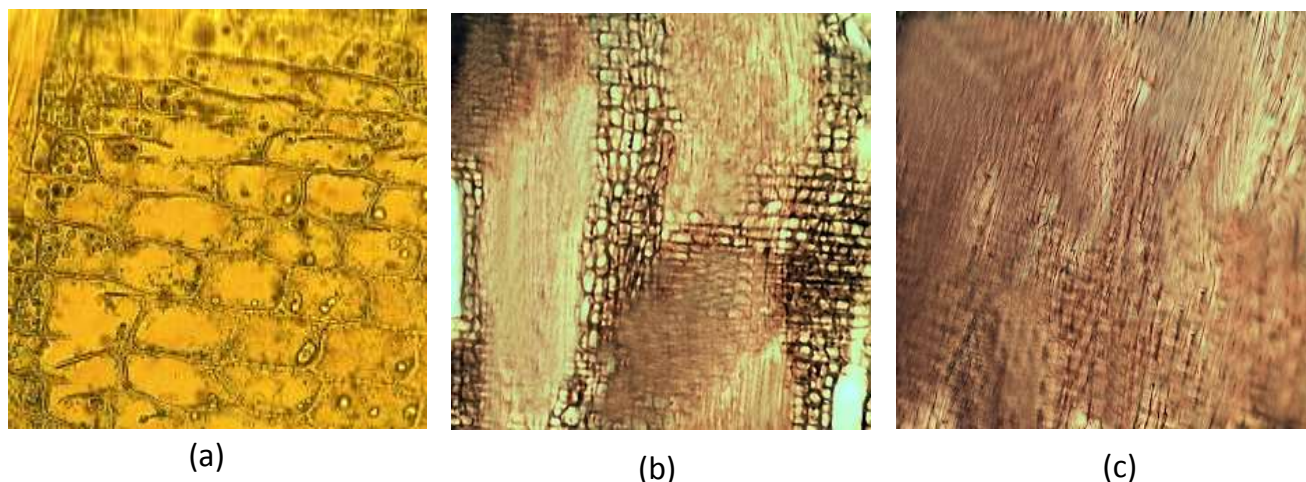
Figure 3. (a) RLS stem of *S. spinosa* x200, (b) RLS stem of *S. innocua* x100, © RLS stem of *S. usambarensis* x100.

Table 1. Vessel and fiber dimensions of stem of *S. spinosa, S. innocua* and *S. usambarensis.*

Name of Plant	VL (mm)	VD (mm)	FL (mm)	FCWT (mm)	FLD (mm)
S. spinosa	0.456±0.22[b]	0.133±0.04[b]	2.45±0.31[b]	0.014±0.00[b]	0.028±0.01[b]
S. innocua	0.396±0.16[a]	0.107±0.01[a]	1.773±0.11[a]	0.0133±0.00[b]	0.0017±0.0001[a]
S. usambarensis	0.453±0.18[b]	0.145±0.03[c]	1.88±0.001[a]	0.002±0.00[a]	0.002±0.00[a]

VL- Vessel length, VD- Vessel diameter, FL- Fiber length, FCWT- Fiber cell wall thickness and FLD Fiber lumen diameter.
Means followed by different alphabets vertically are significantly different at $p<0.05$. Means ± standard deviation of three replicates.
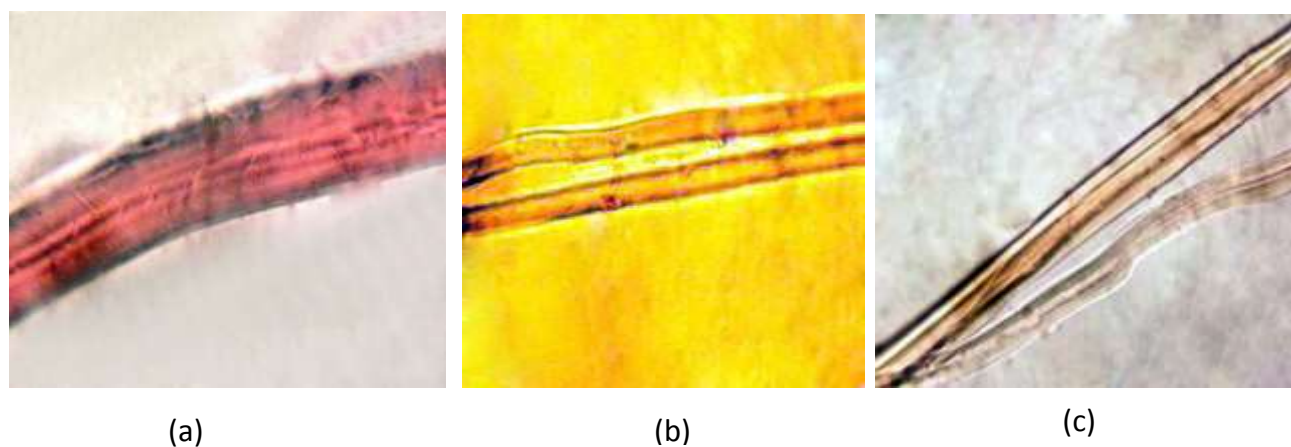
Figure 4. (a) Fiber stem of *S. spinosa* x400, (b) Fiber stem of *S. innocua* x400, (c) Fiber stem of *S. usambarensis* x400.

radial chains suggests a feature that can help to enhance better conductivity of fluid. Evert (2006) stated that multiple vessels assist the plant in circumventing embolism if it occurs and ensures efficient flow of fluid through nearby vessels. *S. innocua* grows in a drier ecological region and will be faced with the challenge of conserving water and will probably be at an advantage with multiple vessels. Moya et al. (2017) in their study of *S. bredemeyeri* from Costa Rico also observed the occurrence of solitary vessels and those in radial and
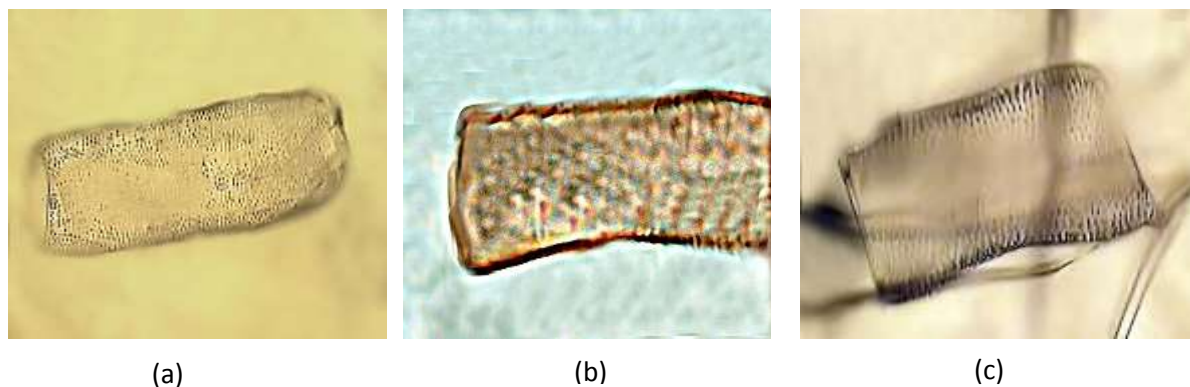
Figure 5. (a)Vessel of stem of *S. spinosa* x100, (b) Vessel of stem of *S. innocua* x100, (c) Vessel of stem of *S. usambarensis* x100.

diagonal multiples.

The length of vessel elements in *S. innocua* that grows predominantly in drier parts (Sudan savanna) is shorter than that of *S. spinosa* and *S. usambarensis* that grow in Guinea savanna and Derived savanna respectively. According to Ekwutoziem (2015), shorter vessels are associated with drier habitats and longer vessels with wetter ones. The diameter of vessels of *S. innocua* growing in the drier ecological zone of Sudan savanna is smaller than those of *S. spinosa* in Guinea savanna and *S. usambarensis* in derived savanna. According to Ekwutoziem (2015) plants in the arid regions tend to have smaller vessel diameter and are also less vulnerable to cavitations. Sperry (2003) observed that wider conduits are more vulnerable to cavitation than smaller ones and are thus more exposed to embolism of vessels.

Rays of varying width can help to delimit the different species. *S. innocua* has rays with 1-3 seriate, while *S. usambarensis* has rays wider than 4- seriate. Moya et al. (2017) observed rays that were 2- to many celled wide being mixed up with few uniseriate rays in *S. bredemeyeri* that they studied. According to Evert (2006), the possession of wide rays is equally of importance in strengthening a plant.

The possession of intraxylary phloem in the three species is a diagnostic feature for family Loganiaceae and other families in the order Gentianales (Metcalfe and Chalk, 1989; Frasier, 2008). Carlquist (2013) also stated that interxylary phloem occurs in only a relatively small number of families and consisted of strands of sieve tubes, and companion cells embedded within the secondary xylem. *S. spinosa* lacks interxylary phloem while *S. innocua* and *S. usambarensis* possess it. Moya et al. (2017) noted that the possession of interxylary phloem is restricted to small number of dicotyledonous taxa and mentioned that it has been reported in many species of *Strychnos*.   This is the first time the possession of interxylary phloem is being reported in *S. innocua* and *S. usambarensis*. Moya et al. (2017) observed

that the development of interxylary phloem occurred at a later age in *S. bredemeyeri*. It was not found in the juvenile wood of that species. They suggested that further work should be done at different developmental ages of those species currently reported in literature that lack this feature. Mennega (1980) however noted that within a genus, some species may have this feature and others lack it with no clear difference in habit or size of plant.

Axial parenchyma is scanty in *S. innocua* and *S. usambarensis*. This confirms the earlier submission of Carlquist (1984); Metcalfe and Chalk (1989) on the possession of scanty axial parenchyma in Loganiaceae. Fibers of *S. spinosa* have very thick walls and this feature is important in performing, mechanical functions. Moya et al. (2017) reported that thick walled fiber is a characteristic of genus *Strychnos*. Herendeen and Miller (2000) reported that the thickness of fiber cell wall is closely related to density, stating that the thicker the fiber cell wall, the higher the density. The possession of thick walled fiber could be used to support the use of traditional folks of the wood of *S. spinosa* in construction of poles, agricultural and other tool handles (ICRAF, 2000). The possession of thick walled fibers of *S. spinosa* is been reported for the first time. Some of the features possessed by the species are of great importance in making the plants adapt to the climatic conditions of the ecological zones where they grow. This study is a part of the ongoing studies on the African *Strychnos*. DNA studies in all the members of the genus to better separate them into sections and also elucidate their phylogeny are desirable.

In conclusion, the *Strycnos* species studied possess alkaloids and other phytochemicals. The presence of interxylary phloem which is suggested to have physiological function is reported for the first time in *S. innocua* and *S. usambarensis*. The fiber cell wall thickness of *S. spinosa* which is greater than that of *S. innocua* and *S. usambarensis* is also reported for the first

time. Fiber cell wall thickness is associated with mechanical function of the plant and explains the use of the wood by farmers in making farm implements.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Patula pine (*Pinus patula*) cones opening under different treatments for rapid seed extraction in Londiani, Kenya

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Seed extraction from pines is challenging to the forestry sector globally. This is usually contributed by the pine cone anatomy that opens through a function of temperature and humidity which varies widely in the pine growing regions of the world and the *Pinus* species as observed in previous works done on *Pinus roxburghii*, *Pinus halepensis*, *Pinus wallichiana*, *Pinus pinaster*, *Pinus radiata*, and *Pinus sylvestris*. This study sought to reduce the extraction time and improve the extraction efficiency of *Pinus patula* seed in Kenya. The experimental design used was two factorial design with replicates of twenty cones randomly picked per treatment. Data analysis was analyzed through ANOVA with a P-value of 0.05. We present evidence that soaking does not influence the opening of cones and seed yield for the optimum temperature which the study determined to be 65°C. We also present evidence that, for rapid seed extraction, the temperature 65°C with an exposure period of between 4 and 24 h is significantly effective. This study presents a new understanding of rapid seed extraction, which contributes to one of the Kenya Forestry Research Institute's strategic objectives of generating technologies for enhanced production of superior germplasm for priority tree species.

Key words: Soaking effects, temperature treatments, seed yield.

INTRODUCTION

Seed extraction from pines globally is challenging to the forestry sector (Bhat et al., 2017; Reyes and Casal, 2001) with most countries using the conventional methods for seed extraction from cones, which entails drying in beds to facilitate seed release. This weather-dependent process is particularly slower and less efficient in moist; cool temperate climates as an increase in the atmospheric humidity may cause a reclosing of the cones (Willan, 1984). In moist conditions, this method is not very reliable. However, it is the most economical, convenient, and effective method of seed extraction for many cone-bearing species (Bhat et al., 2017; Ghildiyal et al., 2008). This is due to the fact that the process in most countries is based on natural sun drying in canvas or drying beds to facilitate the release of seeds (Bhat et al., 2017; Wyse et al., 2019).

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The major preferred species used in commercial plantation forestry are Eucalypts, Cypress, and Pines (Essl et al., 2011; Ngugi et al., 2000). Sustainable plantation forest production demands a continuous supply of high-quality seeds for the production of seedlings in the nursery or for direct sowing (Ridder, 2007). Previous studies have reported that pine cones open to release seed through a combination of factors (temperature and humidity) which varies widely in the pine growing regions of the world (Aniszewska et al., 2020b; Essl et al., 2011; Wyse et al., 2019). Another factor affecting the pine cone opening is the presence of resin with serotinous cones occurring in many species (Wyse et al., 2019). In these species, cone scales remain closed due to sealing with resin, which requires high temperatures for resins to melt and cones to open (Perry and Lotan, 1977; Wyse et al., 2019).

Patula pine (*Pinus patula*) is a straight bole tree with its origin from Mexico (Perry, 1992). It is has a wide distribution range including Southern and East Africa where it is commercially planted (Dvorak et al., 2012; Essl et al., 2011). In Kenya, *P. patula* represents 27% of plantation species among others such as *Cupressus lusitanica* and Eucalyptus species (Ngugi et al., 2000). It has been grown for industrial production for pulpwood and sawn wood which therefore exerts a high demand for seed extraction. There are scanty works of literature on *Pinus patula* seed extraction efficiency with most studies focusing on other pine species (Ayari and Khouja, 2014; Bilir et al., 2008; Reyes and Casal, 2001; Singh et al., 2017; Wyse et al., 2019). Earlier work by Calvo and Nu (2000) has also revealed that the primary factor for seed release in Aleppo and Scots pines is the degree of cone opening, with few studies on other pine species. Many factors have been attributed to poor cone opening such as early harvesting, fungal attacks, insect damage and case hardening during storage with little data on soaking and temperature effects which mimic field conditions (Ayari et al., 2011, 2012; Ayari and Khouja, 2014; Bramlett, 1977). The lack of understanding of these effects has led to a combined reduction of available *P. patula* seeds.

The case of Kenya is marked by *P. patula* being one of the commercial species in the country. Kenya Forestry Research Institute (KEFRI), Londiani centre is the source of pine seed for the country (Albrecht, 1993). The major challenge faced by KEFRI is the prolonged extraction periods, thereby delaying the availability of the seed. Thus, there is need to reduce the extraction time and improve extraction yield in terms of quantity and quality. This paper sought to determine the effect of varying temperatures on *P. patula* cone opening for seed extraction, with specific objectives being: (i) to determine effect of soaking on cone opening, (ii) to determine the effect of various temperatures on percent opening of cones and (iii) to assess the combined effects of soaking and temperature treatments on cone opening and seed yield.

MATERIALS AND METHODS

Mature *P. patula* cones samples were randomly collected from a wider general collection batch whose sources were an assortment of seed stands and orchards. The cones were closed at the time of collection. The cones were packed in gunny bags and then brought to the KEFRI Rift Valley Eco-Region Research Programme – laboratory in Londiani, positioned between 35.607270°E longitude and 0.155520°S latitude.

Londiani area is cool and moist in most part of the year and is at an elevation of 2,308 masl with an average temperature of 15.7°C. The average temperatures around the forest reserve are between a minimum of 8.6°C and a maximum of 23.31°C. The area has two rainy seasons, long rains occurring in the months of March to May with an average rainfall of 750 mm for the three months, and short rains in October to December with average rainfall for the three months of 423 mm. The driest months are January to February and August to September. This study was conducted in March 2020, which is the peak cone production season for Patula pine (Albrecht, 1993).

Experimental design

The cones collected were assessed for maturity, defects (already opened at least once and closed; immature and pests damage). This was a factorial experimental design with temperature and soaking conditions as factors and exposure periods as levels. Twenty replicates were used for each treatment. Cones were exposed to soaking in hot and cold water for varying periods (10 min and 24 h) to simulate the varying humidity effects (Aniszewska, 2013). The design is as represented in Table 1. Cones in each treatment group were labeled and measured for length (cm), diameter (cm), and weight (g). Cones were then soaked in hot (100°C) and room temperature (25°C) water for different durations: 10 min and 24 h. The cones were placed in labeled glass Petri dishes with sufficient space to prevent contamination of seeds from one cone to another.

The cones were subjected to artificial heating for seed extraction at eight temperature conditions: 30, 40, 50, 65, 70, 75 and 85°C (Schmidt, 2000) and DB (drying bed conditions to simulate the current practice for seed extraction; 44.8±6.00°C) at three exposure times (4, 24, and 48 h) together with the control (no soaking). The soaked and not soaked cones were then subjected to oven (YAMATO DS411) temperatures of 30, 40, 50, 65, 70, 75 and 85°C (Schmidt, 2000) and DB (natural sun drying conditions in a drying bed). The extraction exposure times varied for set temperatures: 48 h for lower temperatures (30 and 40°C and DB); 24 h for 50 and 65°C: and 4 h for higher temperature (70, 75 and 85°C). This was modified according to a previous study by Aniszewska et al. (2019), which showed that longer exposure durations at higher temperatures reduced seed vigor. Petri dishes with cones were removed immediately at the end of the exposure times from the oven and drying bed. Seeds were then extracted from cones in each Petri dish by tapping gently for 15 times on a flat wooden bench and counted. Length (cm) of the part of the cone that had opened was measured as well as cone weight (g).

Data analysis

The data were tabulated in a data-sheet in MS excel and analyzed for: effect of soaking on percent opening and seed yield; effects of temperature on percent opening and seed yield and combined

Table 1. Experimental design.

S/N	Treatment	Sample size
1	No soaking, drying bed, 48 h	20
2	No soaking, oven 30ºC, 48 h	20
3	No soaking, oven 40ºC, 48 h	20
4	No soaking, oven 50ºC, 24 h	20
5	No soaking, oven 65ºC, 24 h	40
6	No soaking, oven 70ºC, 4 h	20
7	No soaking, oven 75ºC, 4 h	20
8	No soaking, oven 85ºC, 4 h	20
9	Soaking in cold water for 10 min, Drying bed, 48 h	20
10	Soaking in cold water for 10 min, oven 30ºC, 48 h	20
11	Soaking in cold water for 10 min, oven 40ºC, 48 h.	20
12	Soaking in cold water for 10 min, oven 50ºC, 24 h	20
13	Soaking in cold water for 10 min, oven 65ºC, 24 h	20
14	Soaking in cold water for 24 h, oven 65ºC, 24 h	20
15	Soaking in cold water for 24 h, oven 70ºC, 4 h	20
16	Soaking in cold water for 24 h, oven 75ºC, 4 h	20
17	Soaking in cold water for 24 h, oven 85ºC, 4 h	20
18	Soaking in hot water 24 h oven 65º 24 h	20
19	Soaking in hot water 24 h, oven 70º 4 h	20
20	Soaking in hot water 24 h, oven 75º 4 h.	20
21	Soaking in hot water 24 h, oven 85º 4 h.	20

Figure 1. *P. patula* cones showing stages of cone opening.

effects of soaking and temperature on percent opening and seed yield done with RStudio Version 1.2.1335. Post hoc analysis (Tukey's HSD) was used to determine difference in means (95% CI) in the two-way ANOVA with soaking, the exposure time for soaking, temperatures and exposure times for temperatures as factors and percent opening and seed yield as variables.

RESULTS AND DISCUSSION

The conventional practice in Kenya for extracting seeds from cones of *P. patula* consists of drying cones in the sun. The process (DB) takes about two weeks for complete seed extraction. This paper's results from the DB conditions were attributed to the diurnal temperature variation of 44.8±6.00°C.

Cones were observed to open from the widest part of the cone to the top section (Figure 1). This was in agreement with previous studies on other pine species that show, longer scales were located in the middle to the top part of the cone (Aniszewska, 2010). These studies
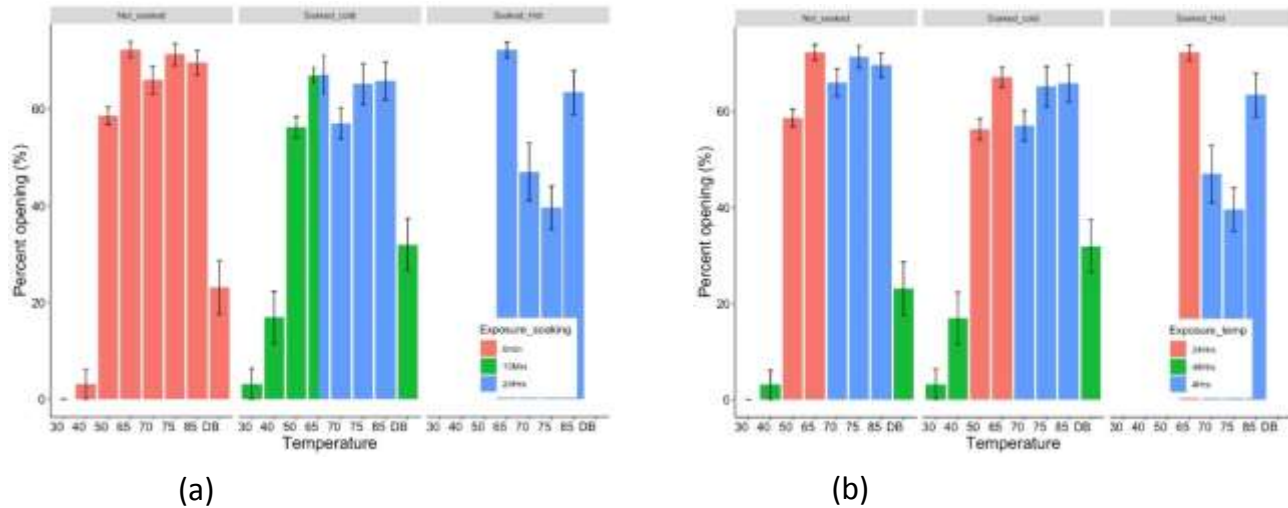
Figure 2. *P. patula* cones percent opening based on exposure times to soaking in hot and cold water (a) and percent opening based on oven exposure at different temperature regimes (b).

noted that the longer scales had higher deflection compared to scales at the base (short), which attributes to the base part of the cone not to open (Wyse et al., 2019; Aniszewska, 2010; Reyes and Casal, 2001).

The results of this study showed that soaking (50.2±1.69) or not soaking (48.5±2.36) of cones did not have a significant effect (p>0.05) on the percent opening of the cones from the temperature treatments. This study observed that when soaking temperature treatments are isolated (soaking in room temperature water and soaking in hot water) for their effects on percent opening of the cone, and there were significant differences (p<0.05) (Figure 2b). Soaking in hot water significantly influenced the cone opening with the highest mean percent opening (55.5±2.62%) (p<0.05). This study observed that 65°C had highest percent opening of cones after soaking in hot water (72.2 ±1.62%), soaking in cold water (67.1±2.11%) and for cones subjected to no soaking (75.0±3.01%) (Figure 2b). Soaking of cones in either hot or cold water increases the moisture content of the cone, which impedes the quick opening of the cones. This finding agrees with earlier work by Wyse et al. (2019) and Ghildiyal et al. (2008) and who reported that moisture content is a factor for cone opening.

The variations in cone opening based on different temperatures were noted to be similar to previous studies on other pine species (Wyse et al., 2019; Bilir et al., 2008; Iwaizumi et al., 2008). Within our study, cones opening subject to the temperatures of 30 and 40°C were observed to be few, with many remaining closed. There are studies that suggested more reasons for variation in cone opening such as cone morphology, degrees of asymmetry, differences in scale tension, the effect of environment on bonding strength and genetic differences in bonding agent (Aniszewska et al., 2020a; Perry and Lotan, 1977). The reasons need further investigation

focusing on *P. patula* cones, though, this study agrees with previous findings on other pines that also observed temperature being a key factor for cone opening (Bhat et al., 2017; Ghildiyal et al., 2008). During the study, it was observed that at temperatures from 50 to 85°C the number of cones opening ranged from 95 to 100% per temperature treatment. The number of cones opening decreased with reducing temperature: DB (63%), 40°C (20%), and 30°C (2.5%) under 48 h exposure. This finding suggests the need for longer exposure for these temperatures, which agrees with observations from other studies (Bhat et al., 2017; Singh et al., 2017). At exposures of 4 and 24 h, 65°C was the most effective temperature for cone opening, with the results having no significant differences (p<0.05) in percent opening between 4 and 24 h (Figure 2b).

The least mean seed yield (43.3±4.50) was observed from cones soaked in hot water. This implies that soaking in hot water causes additional moisture to be absorbed by the cones thereby requiring a higher exposure for the cones to lose the additional moisture. Earlier studies show high temperature melts resin in the cone (Perry and Lotan, 1977; Wyse et al., 2019), thus with melted resin, the cone imbibes more moisture hence not suitable for rapid seed extraction (Figure 3a and b). Percentage opening of pine cones was observed to have a significant influence on the seed release for all the temperature treatments except for the 50°C treatment (p >0.05) (Figure 3a and b). An analysis by temperature and treatment from this study observed cones not exposed to the soaking treatment yielded the highest number of seeds (86.5±4.94) at temperature 65°C (Figure 3a, b). Further analysis by temperature treatment still observed 65°C having a mean seed yield of 75.9±3.41.

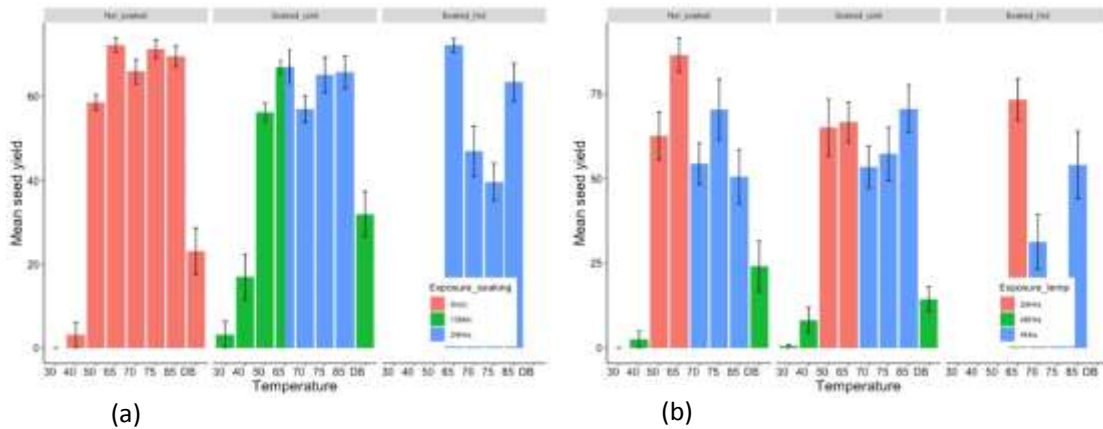The overall combined effects of soaking water temperatures, soaking exposure, oven temperatures, and

(a)   (b)

Figure 3. *P. patula* cones mean cumulative seed yield based on exposure times to soaking in hot and cold water (a) and mean cumulative seed yield based on oven exposure at different temperature regimes (b).
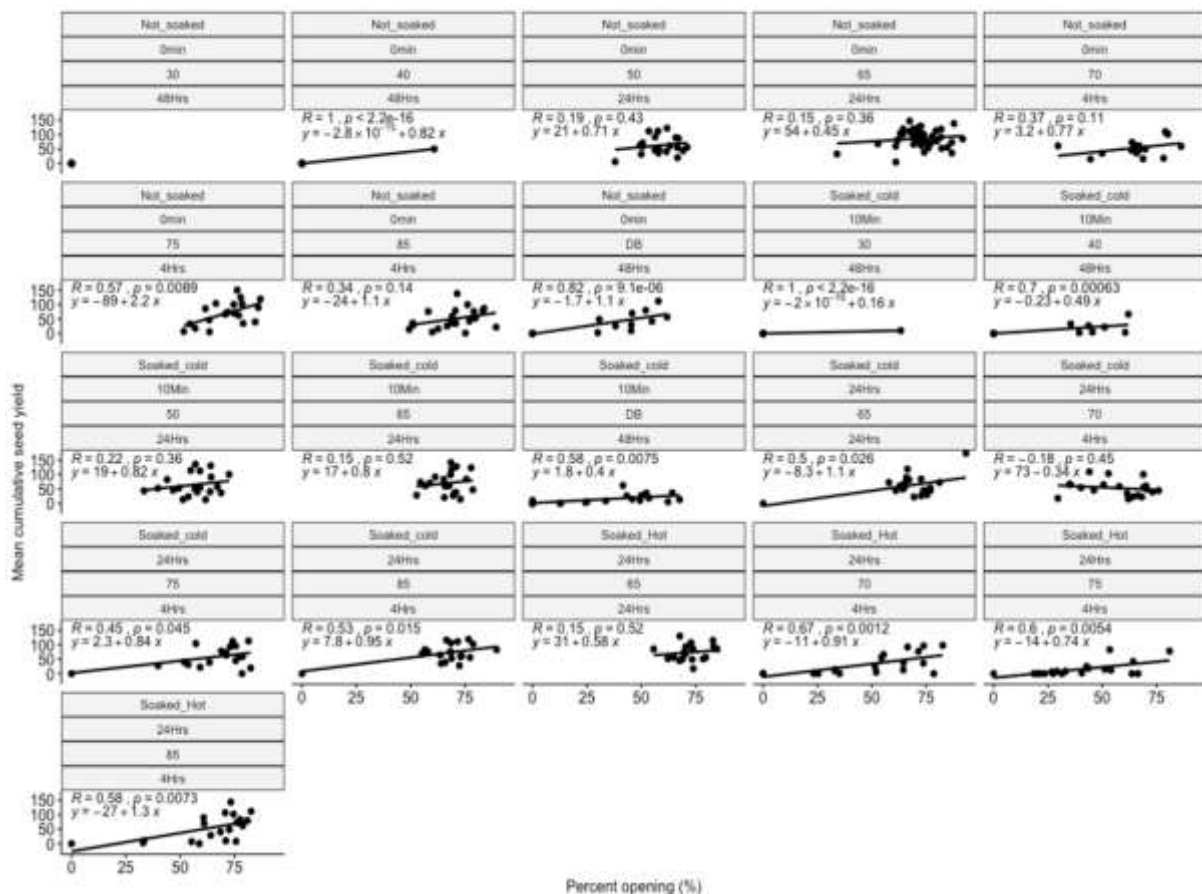
Figure 4. Correlations of combined effects of soaking and temperature exposure on *P. patula* cones percent opening and seed yield.

oven exposure time established that 65°C is the best performing temperature for rapid seed extraction. The results showed a positive correlation between percent opening and seed yield under the different treatments except for 24 h soaking in cold water and oven exposure of 4 h at 70°C (Figure 4). Higher temperatures (>75°C)

are known to be less suitable due to the possibility of greater damage to seeds when exposed to this temperature (Calvo and Nu, 2000). This identifies the need to study seed viability when the extraction is carried out at higher temperatures.

Artificial heating for drying of cones at controlled temperatures requires expensive equipment and installations, which are seasonally used. This makes their unit cost exceptionally high. A very careful appraisal must, therefore, be made of the capital cost before establishing a large permanent kiln (FAO, 1985). There is, however, the scope for adapting the best procedure found in this study to many nursery conditions. There was a significant increase in the number of seeds extraction on cumulative percent basis as the temperature was increased from 50 to 65°C. The opening mechanism of *Pinus patula* cones scales under oven and drying beds conditions is related to temperature and moisture differences. The present investigation on *P. patula* indicated that seed extraction temperatures exert a significant influence on the number of seeds extracted on a cumulative basis. The authors, therefore, recommend the use of artificial heating of cones at 65°C for 4 to 24 h for the rapid extraction of *P. patula* seeds.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

An analytical assessment of forest cover changes over the last 30 Years in the semi-deciduous forest zone of Togo

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Understanding dynamics of forest cover is important to monitor change in forest area. The objective of the present study is to develop an approach for assessing forest cover changes in landscapes with high spatial complexity and temporal variation that can allow the generation of robust monitoring information. The forest-cover change maps were produced using time-series of Landsat images, high resolution images from Google Earth, free software R and QGIS. A complete map of forest cover change at 30 m spatial resolution was produced over 603'972 ha. The result was validated by photo-interpretation of 5000 randomly sampled points and on the basis of high-resolution images available in Google Earth (Quickbird) for the year 2018 and Landsat satellite images for the year 2018, 1991 and 2003. The estimated overall accuracy of the forest cover change map is 88.7%. In the study area, the forest area was estimated at 246'915 ha in 1991, 232'741 ha in 2003 and 230'390 ha in 2018. The gross forest loss has increased from 182.5 ha/year in the first period 1991-2003 to 187.47 ha/year in the second period 2003-2018. The corresponding net annual forest loss (incl. regeneration) rates are 0.5% in the first period and 0.1% in the second period. The decrease of the net annual forest loss rate in the second period is attributed to an increase in forest regeneration. This study can be considered as a reproducible approach to map forest-cover change and can support policy approaches towards reducing emissions from deforestation and degradation (REDD+).

Key words: Forest loss, forest gain, multi-date, Landsat, random forest, Togo.

INTRODUCTION

Changes in forest cover affect important ecosystem services, including biodiversity, climate regulation and carbon storage (Achard et al., 2002; Foley et al., 2005). Forest cover change in the tropics is recognized by the international climate change community to be a major contributor to anthropogenic GHG emissions. Most of the net flux of carbon into the atmosphere due to land-cover changes is attributable to deforestation in the tropics, with

a smaller fraction attributable to forest degradation (Houghton, 2012). As a consequence, a mechanism for Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+) has been developed under the United Nations Framework Convention on Climate Change (UNFCCC). REDD+ aims at rewarding developing nations for slowing down deforestation and forest degradation, which is considered a cost effective way to mitigate anthropogenic greenhouse gas emissions, through a compensation mechanism (UNFCCC, 2010). Mapping forest cover change is a key issue for REDD+ program. Despite well established guidelines provided by the international scientific community (GFOI, 2016); Houghton et al. (2010) showed that "REDD+ program, often lack the institutional investment and scientific capacity to begin implementation of a program that can make use of the global observational record". In order to get access to REDD+ result-based payments, countries require a national forest monitoring system for measuring forest cover and carbon stock changes in forests in an accurate and consistent way, and comparing them to a counterfactual reference level based on historic forest cover changes (UNFCCC, 2015).

In Togo, several factors contribute to the reduction of forest cover. Main drivers of forest degradation and deforestation are traditional slash and burn agriculture, pasture extension, charcoal production, illegal logging and mining activities, with adverse consequences for local climate, soil degradation, livelihoods, biodiversity conservation and GHG emissions (MERF, 2013). The forests of Togo's sub-humid mountainous area constitute the domain of the semi-deciduous dense forests (Ern, 1979), which are now very degraded and disappearing. Several previous studies (Adjonou et al., 2009; Adjossou, 2004; Adjossou and Kokou, 2004) have shown that forests in the sub-humid mountainous area are very fragmented and have practically been reduced to hard-to-reach areas and along rivers. This fact highlights a research question: (1) what forest cover changes can be observed in the study area over the last decades?

Togo, as many tropical countries, has recently joined the REDD+ mechanism with the ambition of creating a new incentive system to reduce forest loss and to restore the integrity of degraded forests (MERF, 2013). In 2012, the global deforestation map produced by the University of Maryland (Hansen et al., 2013) attracted great attention from scientists. However, (Tropek et al., 2014) have shown that this map overestimates forest cover and underestimates the rate of deforestation at local level. Monitoring the evolution of forest cover by remote sensing in forests of Togo's sub-humid mountainous area is a challenge because of the effect of the relief, gradual changes of degradation and regeneration, different forest types that mix up with fallows and secondary forests growing on agricultural land, high temporal dynamic of clearing and regrowth and relatively low net changes of forest cover. This fact highlights the second research question: How can forest cover changes be mapped consistently, in areas with high diversity of forest types, high forest dynamics and low rates of net change?

In the context of REDD+ in Togo, previous work on forest cover mapping has provided valuable insight into vegetation status and different maps were produced. Indeed, German cooperation financed the production of the land use map using RapidEye satellite images in the context of the national inventory in 2014. This mapping exercise was based on automated segmentation and of RapidEye images acquired in 2013/2014 and visual classification of the resulting segments. Then in 2016, the World Bank funded the interpretation of aerial photos taken between 1976 and 1985 using the same methodological approach. To what extent the resulting figures are comparable with the RapidEye map is uncertain and difficult to validate as the aerial images were not co-registered with the RapidEye images. Despite the production of forest cover maps for different dates, further improvements in classification methods for forest cover change are necessary in order to provide accurate and consistent estimates of forest cover change at national and subnational levels. The general objective of the present study is to develop an approach for assessing forest cover changes in landscapes with high spatial complexity and temporal variation, that can consistently be applied for repeated assessments and thus allows the generation of robust monitoring information as for example required for the reporting of changes in forest carbon stocks in the framework of REDD+. The specific objectives are to map and to quantify forest cover changes in different forest landscapes of semi-deciduous forest zone of Togo for the periods 1991-2003 and 2003-2018.

MATERIALS AND METHODS

Study area

The study area corresponds to Togo's forest's zone "ecological zone IV" and is located in the southern part of the Atakora Mountains, south-west of Togo, on the border between Togo and Ghana in the region called Togo Mountains or Togo highlands. The study area extends between the latitudes 6° 15 and 8° 20 N and the longitudes 0° 30 and 1° E, and covers an area of 603'972 hectares (Figure 1). The climate prevailing in this area is a Guinean mountain climate characterized by a long rainy season (8-10 months). The mean annual temperatures range from 21 to 25°C and the total annual rainfall ranges vary from 1400 to 1700 mm. This zone contributes significantly to species richness in Togo (Adjossou, 2009). It is the current domain of semi-deciduous forests. The study area shows a strong topographic heterogeneity. The average altitude is 800 m, with peaks at Djogadjeto (972 m) and Liva (950 m). It has a successions of plateaus (plateau of Kloto, Kouma, Danyi, Akposso, Akebou and Adele), where hills along with their
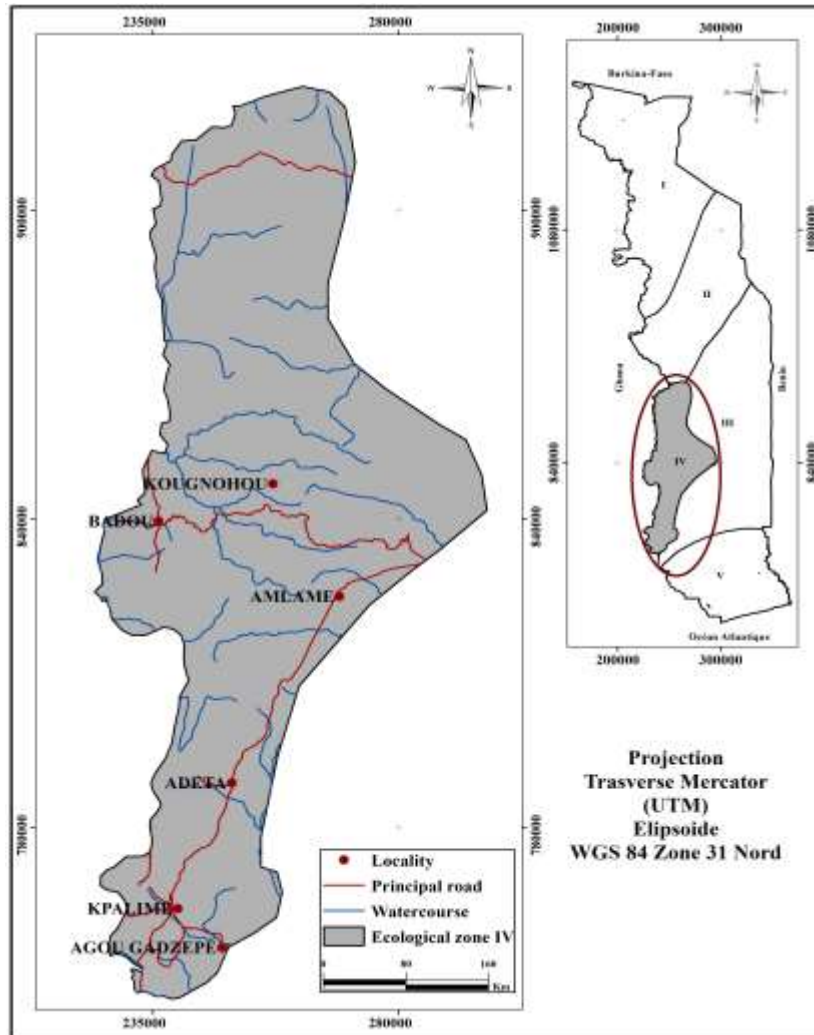
Figure 1. Study area Ecological zone IV.

valleys and caves are common. Landforms are diverse and complex. The main geologic component is of the late Precambrian: Togo and Buem quartzites phyllites, shales and sandstones were largely folded and metamorphosed during the Cambrian Pan-African Orogeny (Hall and Swaine, 1976). A network of complex secondary rivers covers the area with three catchment areas: the basin of the lake Volta in the west of the Mounts and basins of the Mono River and Zio River in the east of the Mounts. Population distribution and land management varies across the area with implications for forest cover changes (Figure 1). The research methodology was based on the following steps:

(i) Acquisition, pre-processing, and stacking of Landsat images.
(ii) Collecting a representative set of training plots for different crown cover densities observed in the region.
(iii) Forest/non-forest classification of reference maps based on training plots using RandomForest.
(iv) Forest/non-forest classification of Landsat time series based on reference maps, again using RandomForest.
(v) Cleaning of time-series using majority filters.
(vi) Accuracy assessment of resulting maps using a set of independent validation plots. These steps are outlined in Figure 3.

Landsat image collection and pre-processing

Landsat-type data has been proven useful for national-scale land cover and land cover change assessments for minimal mapping units (MMU's) of about 1 ha (Achard et al., 2014). A number of other national or regional forest cover change maps have been produced based on the analysis of full coverage of Landsat data (Achard et al., 2014; Grinand et al., 2013; Hansen et al., 2013). The study area is covered by two WRS2 scenes with path 193 and rows 054 and 055. Landsat surface reflectance data at the end of the dry period (Jan - Feb) with less than 10% cloud cover were downloaded from the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) portal (https://earthexplorer.usgs.gov/) at full spatial and spectral resolution (30 x 30 m resolution). The data selected was for the end of dry season as forests can then be best distinguished from other types of vegetation and classification tends to be more accurate than during the wet season (Liu et al., 2015). Furthermore, the availability of cloud-free images is limited in wet season in comparison to dry season.

The final dataset obtained consists of a series of 15 geometrically and radiometrically corrected images from the satellites Landsat

Figure 2. Examples of visual interpretation of training plots (30x30m) for crown cover using QGIS and QuickBird/GoogleEarth images 2018. 1/9 means that 1 of the 9 cells are covered by tree crowns and corresponds to a crown cover of 11%.

4 and 5, Landsat 7 and 8, covering a period of 32 years (Table 1). According to Gutman et al. (2008) these data have satisfactory radiometric and geometric qualities for performing land-use change analysis and in particular the historical analysis of deforestation. Due to a sensor failure (Scan Line Corrector or SLC) since 2003, the Landsat 7 images of the years 2005 to 2013 have high rates of missing data (leaf stripping) even if it has good geometric and radiometric qualities (Barsi et al., 2007). For each date, the six spectral bands B, G, R, NIR, SWIR1 and SWIR2 of the Landsat images of scenes p193r054 and p193r055 were mosaicked and projected to the coordinate reference system WGS 84 - UTM 31. All data manipulation and analysis of satellite images was done using the R environment for statistical computing (R Core Team, 2013) using the R-packages "raster" (Hijmans, 2019).

Classification of land covers change

Collection of tree cover training plots data

Accurate training plot data are essential for RandomForest classification. Several studies have shown that non-parametric machine learning algorithms, such as RandomForests, need a larger number of training data to attain optimal results (Potapov et al., 2012; Schneider, 2012). For obtaining a balanced set of training plots, the study followed a two-level sampling strategy. A random sample of 500 training plots was first selected and used them for the creation of an initial tree cover map. Based on this initial map a final sample of 5'402 training plots was drawn, stratified according to the tree cover observed in the initial map. The forest cover training plots were defined on the basis of the Landsat pixels (30 m × 30 m) and interpretation was done in QGIS based on high-resolution images of the year 2018 available in Google Earth (Quickbird). Based on a grid subdividing the training plots into nine cells, each training plot was assigned one of ten tree cover classes from 0 to 100% by counting the cells covered by tree crowns. These training plots served as the basis for the production of 2018 tree cover map. An example of visual interpretation of training plot is presented in Figure 2.

Classification with RandomForest

The RandomForest algorithm, developed by Breiman (2001), was selected for its good predictive capabilities for land-use

classifications (Gislason et al., 2006) and time series analysis (Schneider, 2012). Several authors have shown that forest cover classifications with RandomForest outperform classifications with other types of algorithms such as maximum likelihood classification (Gislason et al., 2006; Schneider, 2012). RandomForest is a non-parametric supervised classification algorithm that combines the decision tree algorithm and an aggregation technique. The algorithm randomly selects a sample of observations and a sample of variables many times to produce a number of small classification trees (Breiman, 2001). "These small trees are then aggregated and a majority vote rule is applied to determine the final category" (Breiman, 2001). For this study the RandomForest implementation provided by the R-package "RandomForest" was used (Liaw and Wiener, 2002).

In order to improve the discrimination of different densities of tree cover, six indices derived from the spectral bands of the satellite images were calculated (1) the normalized vegetation index (NDVI) calculated as:

$$NDVI= (NIR-red)/(NIR+red) \tag{1}$$

where red and NIR stand for the spectral reflectance measurements acquired in the red (visible) and near-infrared regions, respectively (Rouse et al., 1974); (2) the enhanced vegetation index (EVI) is computed following this equation:

$$EVI = 2.5 \times (NIR-red)/(NIR+C1\times red - C2 \times blue + L) \tag{2}$$ (Liu and Huete, 1995)

where NIR/red/blue are atmospherically-corrected, L is the canopy background adjustment that addresses non-linear, differential NIR and red radiant transfer through a canopy, and C1, C2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. The coefficients adopted in Landsat are; L=1, C1 = 6, C2 = 7.5; (3) the Normalized Difference Moisture Index (NDMI) is calculated with the following equation:

$$NDMI=(NIR−MIR)/(NIR+MIR) \tag{3}$$ (Jin and Sader, 2006)

where MIR is the middle infrared; (4) the Soil Adjusted Vegetation Index (SAVI) is calculated as:
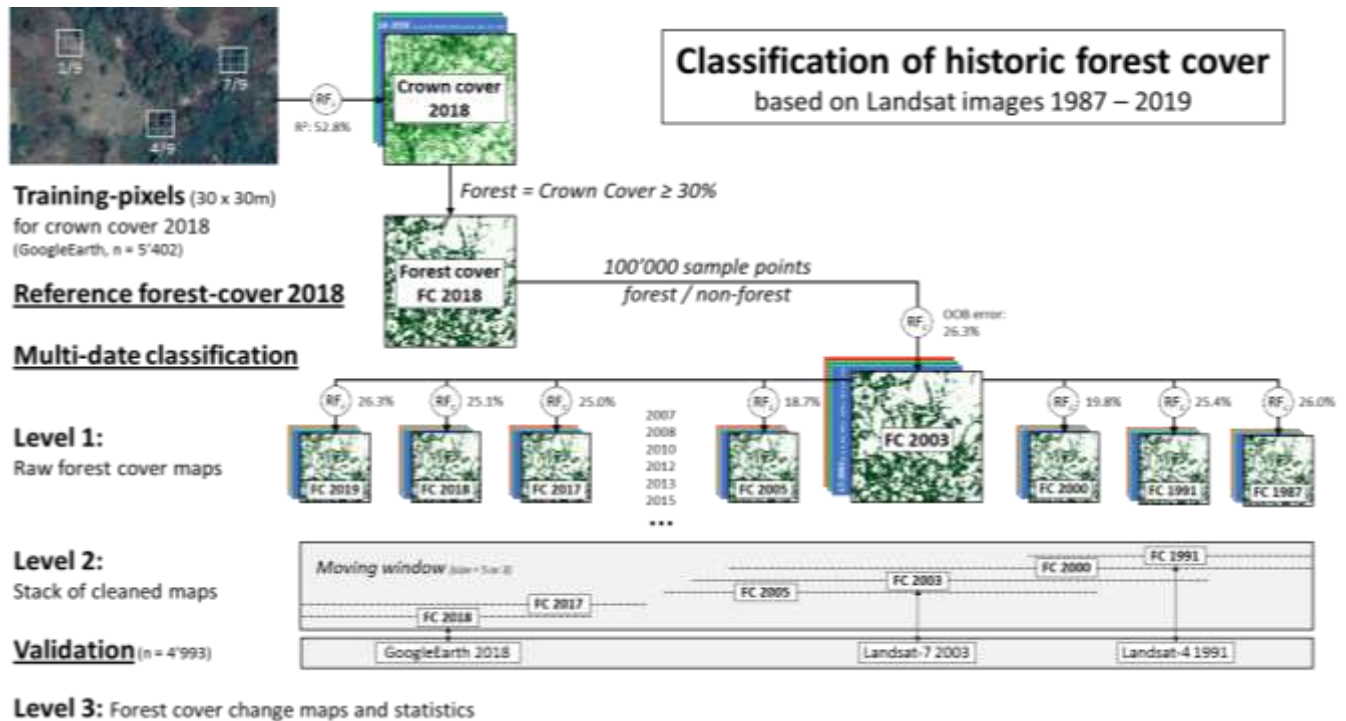
Figure 3. Flow chart of mapping of mapping deforestation from remote sensing and field forest inventory data: RF stand for Randomforest, FC for Forest cover, OOB stand for Out-of-bag.

Table 1. Acquisition date and sensor of Landsat images used for historical analysis of deforestation between 1987 and 2019. The covered WRS2 scenes are p193r054 and p193r055.

Year	Acquisition date	Sensor
2019	16/02/2019	L8 / OLI
2018	12/01/2018	L8 / OLI
2017	25/01/2017	L8 / OLI
2015	04/01/2015	L8 / OLI
2013	23/02/2013	L7 / ETM+ (SLC-off)
2012	04/01/2012	L7 / ETM+ (SLC-off)
2010	30/01/2010	L7 / ETM+ (SLC-off)
2009	27/01/2009	L7 / ETM+ (SLC-off)
2008	25/01/2008	L7 / ETM+ (SLC-off)
2007	22/01/2007	L7 / ETM+ (SLC-off)
2005	01/02/2005	L7 / ETM+ (SLC-off)
2003	27/01/2003	L7 / ETM+
2000	04/02/2000	L7 / ETM+
1991	10/01/1991	L4 / TM
1987	23/01/1987	L5 / TM

$$SAVI = (NIR-red) \times (1+L)/(NIR+red+L) \quad \text{(Huete, 1988)} \quad (4)$$

where NIR is the reflectance value of the near infrared band, RED is reflectance of the red band, and L is the soil brightness correction factor; (5) the Modified Soil Adjusted Vegetation Index (MSAVI) is calculated as:

$$MSAVI = (NIR-red) \times (1+L)/(NIR+red+L) \quad \text{(Qi et al., 1994)} \quad (5)$$

where RED is the red band reflectance from a sensor, NIR is the near infrared band reflectance, and L is the soil brightness correction factor. The difference between SAVI and MSAVI, however, comes in how L is calculated and (6) the Normalized Burn Ratio (NBR1 et NBR2) calculated as:

$$NBR = (NIR-SWIR)/(NIR+SWIR) \quad \text{(Key and Benson, 2005)} \quad (6)$$

where NIR is near-infrared and SWIR is short-wave infrared bands.

The utility of the different spectral bands and indices for the identification of classes: forest and non-forest has been tested with a recursive elimination of variables with the RFE algorithm available in the R-package "caret" (Kuhn, 2016). The most important variables for the prediction of tree cover were in the following order: SWIR2, SWIR1, NBR, NDMI and G but the best prediction of crown cover was obtained by using all six spectral bands and seven indices. 10-fold cross-validation, repeated three times, resulted with an R^2 of 52.9% and a mean error of the crown cover of 0.19.

Forest definition for the analysis of satellite imagery

The 7th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) adopted a general forest definition that allows some flexibility for national definitions: "Forest" is a minimum area of land of 0.05-1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10-30 per cent with trees with the potential to reach a minimum height of 2-5 m at maturity in situ. A forest may consist either of closed forest formations where trees of various stories and undergrowth cover a high proportion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10-30% or tree height of 2-5 m are included under forest, as are areas normally forming part of the forest area which are temporarily un-stocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest. The FAO definition of 'forest' includes all areas of at least 0.5 ha size with canopy cover of more than 10% of trees higher than 5 m, or trees able to reach these thresholds in situ (FAO, 2010). This is also the forest definition adopted by Togo. It may seem advantageous to define forest at this low canopy-cover threshold, because doing so would ensure that most lands that contain tree cover will be classified as forest and will thus be eligible for REDD+ incentives either through reduced degradation, reduced deforestation, or enhancement of carbon stocks. However, according to (Achard et al., 2014) these "thresholds cannot be 'measured' from Landsat satellite imagery with high accuracy" . A more "feasible assessment is that the canopy density be greater than 30%" (FAO and JRC, 2012). Most countries are defining forests with a minimum crown cover of 30% for UNFCCC reporting (FAO and JRC, 2012).

In case of this study forest was defined with a minimum canopy cover of 30% because the study area is the "forest zone" of Togo, where natural vegetation has canopy cover between 30 and 80% (Bastin et al., 2019) and lower rates are a sign of advanced forest degradation or beginning regeneration (fallows and secondary forests) within agricultural slash and burn cycles. Using this threshold, the tree cover map 2018 was converted to a corresponding forest cover map. Forest loss is used to refer to a scenario where a pixel loses forest cover and moves from above 30% crown cover threshold in a year, to below the threshold in a subsequent year. Forest gain was defined as the inverse of forest loss (Hansen et al., 2013).

Producing of forest cover maps

First the forest cover map 2018 was used for calibrating another reference map for the year 2003. Therefore, 100'000 pixels were randomly selected within a 3-pixel buffer around the forest edge 2018 and used the forest/non-forest observations in 2018 for classifying the 2003 image using again the RandomForest algorithm. By using this approach, the 2018 was reproduced using the satellite image 2003. The resulting forest cover map is as close as possible to the 2018 map. By using this approach of backward projection, it was implicitly assumed that a) the proportion of pixels that change land cover, i.e. the error introduced by using training

pixels from another date is relatively small, b) the error is not biased (change from forest to non-forest at least partially compensated by changes from non-forest to forest) and c) the classification algorithm is relatively robust towards errors in the training data. There is a risk of methodologically induced bias if these conditions are not met. However, the criteria seem to be fulfilled by the study area and the classifier chosen. Nevertheless, 2003 the was used instead of the 2018 forest cover map as reference map for classifying all 15 Landsat images in the time-series using the same approach (Figure 3). Using the 2003 map in the middle of the analysed 32-year period (1987-2019) for calibrating further maps in both directions should reduce the risk of methodologically induced bias compared to using the 2018 map as reference for backwards projection only. Out of bag errors, a measure of disagreement of the resulting map with the classes of the 100'000 pixels used for calibration ranged between 19% and 26% depending on the number of years between the dates.

The raw forest/non-forest maps were cleaned by calculating for the 15 dates the majority class of each pixel, in a sliding window of size five. Thereby, a given pixel at a given date is assigned with the class that occurs most often in the pixel's series that includes the two precedent and following dates. For the second and the second last date in the series (1991 and 2018), a sliding window of size three was applied. Cleaning of the time series was repeated until convergence. Besides the smoothing of forest/non-forest transitions, this temporal filter also allows for filtering out noise from cloud and shadow and the missing values of the ETM+ SLC-off images. Forest cover changes were analyzed by comparison of the cleaned forest cover maps for the years 1991, 2003 and 2018. The initial and the last year of the series (1987 and 2019) were not considered in the analysis as they were not being cleaned at all because of missing anterior or posterior information and might thus contain a lot of noise compared to the cleaned images of the other dates.

Accuracy assessments of the estimates of forest cover changes

Assessing land cover change maps is known to be difficult and challenging (Hansen and Loveland, 2012) mainly due to "the difficulty in obtaining accurate land cover change reference datasets". Field surveys of historical change are constrained since "they involve questioning people with a deep knowledge of the area's history" (Grinand et al., 2013). Accurate assessment of forest cover change therefore requires particular attention. A total of 5'000 validation pixels (30m x 30m) were randomly selected from the study area and used for assessing the accuracy of the cleaned 1991, 2003 and 2018 forest cover maps and corresponding transitions. The forest/non-forest status of each validation pixel in the year 2018 was assessed by determining the tree cover within the pixel using high-resolution images for the year 2018 available in Google Earth (Quickbird) and considering as forest when tree cover is at least 30%. The forest/non-forest status for the years 2003 and 1991 was then determined by comparing Landsat images. If a change from forest to non-forest or vice versa could be observed compared to the 2018 image, their status was changed accordingly (Figure 4). For the resulting three-date transition classes the overall accuracy, Cohen's Kappa as well as the producer and user accuracy of the different classes were calculated including corresponding confidence intervals and area estimates as proposed by Olofsson et al. (2014).

Field validation of forest regeneration

The validation of the forest cover maps is complemented by a field mission for field control. Main objective was to get first-hand information
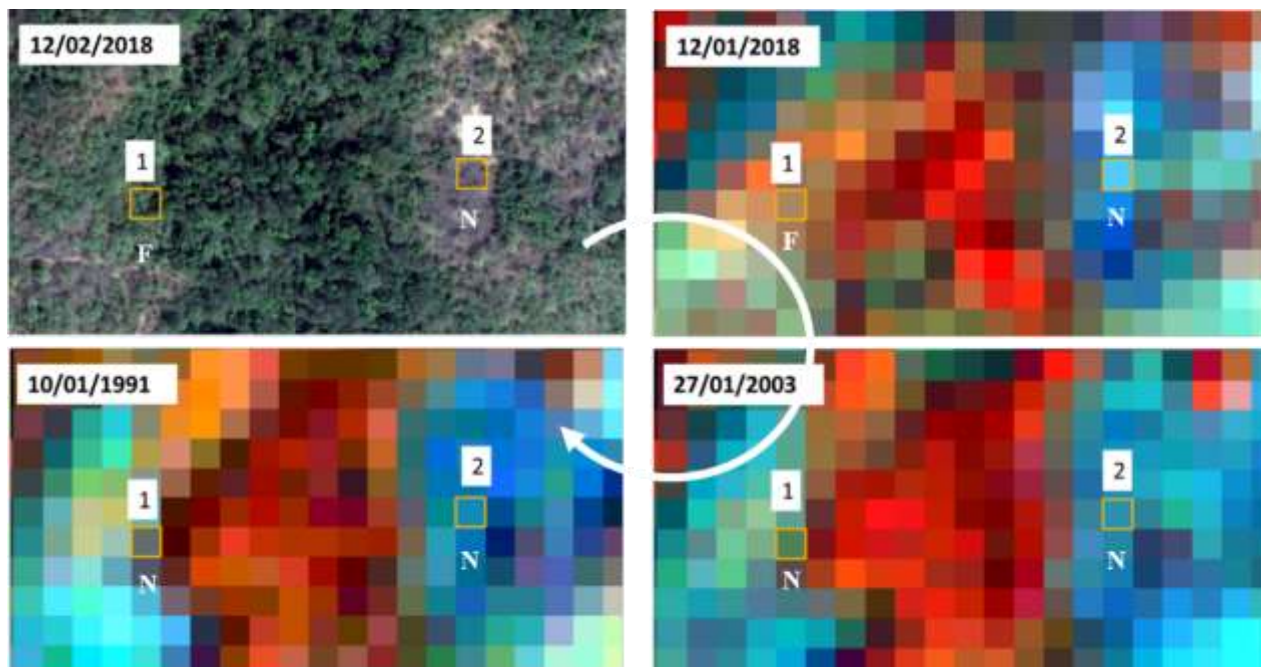
Figure 4. Examples of visual interpretation of validation plot for land cover change using QGis, QuickBird/Google Earth images and Landsat images. From top left to bottom right: cluster of training plots overlaying QuickBird images from Google Earth (12/02/2018) and Landsat (OLI, ETM+ and TM) false color composite RGB = 4, 5, and 3 acquired at dates 12/01/2018, 27/01/2003 and 10/01/1991.

information of the land-cover and land-use types where regeneration was detected on the maps. Therefore 106 pixels were randomly selected within the forest gain classes in the "Plaine of Litime" sub region and visited those locations in the field, determined current land-cover and land-use and assessed its history.

Validation with field data

The classification of satellite images was complemented by a field mission for field control. For this activity, geographical coordinates of the control points were acquired to ensure the accuracy of the classification carried out previously and in order to characterize the classification in the ground. To do this, a representative number (106 points) of field control points was selected in the change strata (forest gain) previously identified in the "plaine of Litime area". This method, based on the evaluation of control points, consists in verifying in the field the points previously identified during the classification for each of the land-use classes and in determining the percentage of verified points that actually correspond to those previously established.

Forest change rates estimation

The annual rate of forest change is calculated by comparing the area A under forest cover in the same region at two different times t. The standardized formula was used in the following equation proposed by (Puyravaud, 2003) for calculating the annual net forest cover change rates as well as rates of gross forest loss and regeneration.

Equation: $\theta = 1/(t2 - t1) \ln A1/A2 \times 100$

RESULTS

Accuracy assessment of the model

Model accuracy assessment

The overall accuracy of the three-date transition map is 88.7% with Cohen's kappa of 82.4%. As shown in the error matrices (Table 3) producer and user accuracies were highest for non-change classes (90- 96%), medium for deforestation classes (62-94%) and lowest for regeneration classes (34-79%). Further, change detection looked to be more accurate for the 2003–2019 period (66- 96%) than for the 1991-2003 period (34-65%). Reasons might be lower radiometric quality of the satellite images, or lower quality of validation data used as reference due to the lack of high-res images for the first period.

Errors of commission and errors of omission are relatively well balanced for stable forest and non-forest classes. Forest loss and forest gain classes show a bit higher variation in the individual periods, but are also relatively well balanced over the whole period. When using these errors for adjusting mapped areas, slightly different figures than presented above were obtained, but figures that confirm the trends observed (Table 4).

In general, forest area is estimated to about 4.5% higher than those on the maps. However, the adjusted figures confirm the loss of about 15'000 ha forest cover in

Table 2. Accuracy assessment table according to Olofsson et al. (2014).

	Number of validation plot	FFF	FFN	FNF	FNN	NFF	NFN	NNF	NNN	U
FFF	1527	28.28	0.42	0.24	0.22	0.08	0	0.08	0.87	93.7 (±1.4)
FFN	301	0.68	4.62	0.23	0.34	0.04	0.15	0.06	0.23	72.8 (±4.0)
FNF	64	0.09	0	0.82	0.07	0.09	0	0.04	0.07	68.8 (±6.1)
FNN	167	0.09	0.19	0.36	1.97	0.15	0.09	0.09	0.21	62.3 (±6.6)
NFF	53	0.29	0	0.13	0.03	0.83	0	0.05	0.05	60.4 (±7.9)
NFN	27	0.02	0.09	0	0.02	0.05	0.33	0.02	0.09	51.9 (±14.7)
NNF	280	0.46	0.02	0.37	0.21	0.46	0.04	3.57	0.27	66.1 (±5.0)
NNN	2574	1.67	0.14	0.28	0.26	0.34	0.08	0.68	48.26	93.3 (±0.7)
P		89.5(± 1.2)	84.4(± 5.0)	33.8(±11.4)	63.1(±7.4)	40.6(±13.3)	47.5(±19.2)	77.6(±5.6)	96.4(± 1.0)	

Note: Proportional error matrix (% of mapped areas in a specific category), with User and Producer accuracy (in %). Overall accuracy is 88.7% with a 95% confidence interval of ± 0.8%.FFF: Forest 1991–2018; FFN, Forest loss between 2003 and 2018, FNN: forest loss between 1991 and 2003; NNN: No-forest; NNF: Forest gain between 2003 and 2018; NFF: Forest gain between 1991 and 2013.

first period. On the other hand they indicated that forest cover might even have increased in the second period. This second observation is however not significant, due to uncertainties in the adjusted forest areas (confidence interval of ±1.7%) (Table 5). The adjusted figures also confirm that gross deforestation nearly doubled from one period to the next where it compensated by increased regeneration.

Field validation

More than 80% of forest gains are low biomass formations such as fallows, forest recruits and in some cases oil palm plantations. Different types of forest formations are found in stable forest. These are dense forests, degraded dense forest, forested forest / savannah, agroforests, fallow, and sometimes plantations. These formations are called stable forest in the context of this study as long as they kept their state between 1991 and 2018.

Forest cover and forest cover change

The resulting maps show an overall decrease of the forest area during the last 30 years by about 6.7%, from 246'915 ha in 1991 to 230'390 ha in 2018 (Table 2). The corresponding forest cover in the study area thereby dropped from 40.9% to 38.1% (Figure 6). Net annual loss of forest cover was seven times higher in the period 1991-2003 (-0.49%) than in the period 2003-2018 (-0.07%). a different picture was seen when comparing gross forest loss. There, the rate increased from 0.94% in the 1991-2003 period to -1.33% in the 2003-2018 period (Figure 7). The forest regeneration compensated only half of the forest loss in the first period, or more or less completely compensated for deforestation observed in the second period. In the study area, forest area loss and forest regeneration was generally small-scale at the edge of forests. Variability of the annual de-forestation rate was observed, depending on the

study area.

The forest loss rate (2.23% year^{-1}) occurred in the Kpele area (a part of the study area) is higher than the average forest loss rate in the study area in the period 1991 to 2018 (Figures 5 and 6). In the same period, the rate of forest loss in the "Plaine of litime" site is 0.068%·yr^{-1} (Figure 6). The low forest loss rate in "Plaine of litime" can be explained by the land use system in that area. Indeed, this area (cocoa plantation area) is characterized by different forest types that mix up with fallows, secondary forests and cocoa plantations (Soussou, 2009). The area is known for the systematic destruction of forests for growing of cocoa (Nyassogbo et al., 1996). There is not a clear boundary between forest and agriculture area in that region. This mix up is difficult to be detected as forest loss because the cocoa plantation and agroforest are forest according to the forest definition based on canopy cover solely. The high rate of deforestation in Kpele area can be explained by the conversion of forest mainly for shifting cultivation and palm oil

Table 3. Estimated areas of transition categories as obtained by the maps and the adjusted values incl. confidence intervals following the guidelines provided by Olofsson et al. (2014).

	Number of validation plot	Mapped area	Adjusted area (validation plots)	Confidence interval	
		ha	ha	ha	%
FFF	1527	182,257	190'745	± 3'715	1.9
FFN	301	38,372	33'097	± 2'462	7.4
FNF	64	7,195	14'650	± 2,235	15.3
FNN	167	19,089	18,847	± 2,273	12.1
NFF	53	8,309	12,367	± 2,104	17.0
NFN	27	3,801	4,153	± 1,239	29.8
NNF	280	32,628	27,793	± 2,488	9.0
NNN	2574	312,319	302,318	± 3,734	1.2

FNN: Forest loss between 1991 and 2003; NNN: No-forest; NNF: Forest gain between 2003 and 2018; NFF: Forest gain between 1991 and 2013.

Table 4. Estimated forest area in 1991, 2003 and 2018 according to Olofsson et al. (2014).

	Mapped area (ha)	Adjusted area (validation plots) (ha)	Confidence interval	
1991	246,915	256,854	± 4,045	1.6
2003	232,741	241,194	± 4,152	1.7
2018	230,390	245,364	± 4,286	1.7

Table 5. Evolution of forest and change area in 1991, 2003 and 2018.

Year	1991	2003	2018
Forest area (ha)	246,915	232,741	230,390
Period	1991-2003	2003 - 2018	1991-2018
Forest loss (ha/year)	-2,190 (-0.94%)	-2,812 (-1.33%)	
Forest gain (ha/year)	+1,009 (+0.40%)	+2,655 (+1.05%)	
Net change (ha/year)	-1,181 (-0.49%)	-157 (-0.07%)	
Net change (ha/year)	-	-	612 (-0.26%)

plantation (Table 6).

DISCUSSION

Forest cover dynamic

The results show, that forest cover in the area is highly dynamic. Gross forest loss and forest gain, to a large extent; compensate for each other and that net forest cover change is just a fraction of the overall dynamic observed. Together with the facts, that changes occur often gradual, disperse and on small scales, makes it extremely difficult to quantify net forest cover change. The comparison of independently produced forest/non-forest maps, might not be able to capture those dynamics accurately as minor deviances in the definition of the class "forest" leads to considerable differences between the maps that have nothing to do with changes on the ground and true changes might remain unobserved (Hansen and Loveland, 2012).

Direct, multi-date classification is often suggested as a more accurate method for mapping of lanes, avoiding to a certain extent the use of different "forest" definitions (GFOI, 2016). However, in such complex situations and with a lack of high-resolution historical imagery, it seems
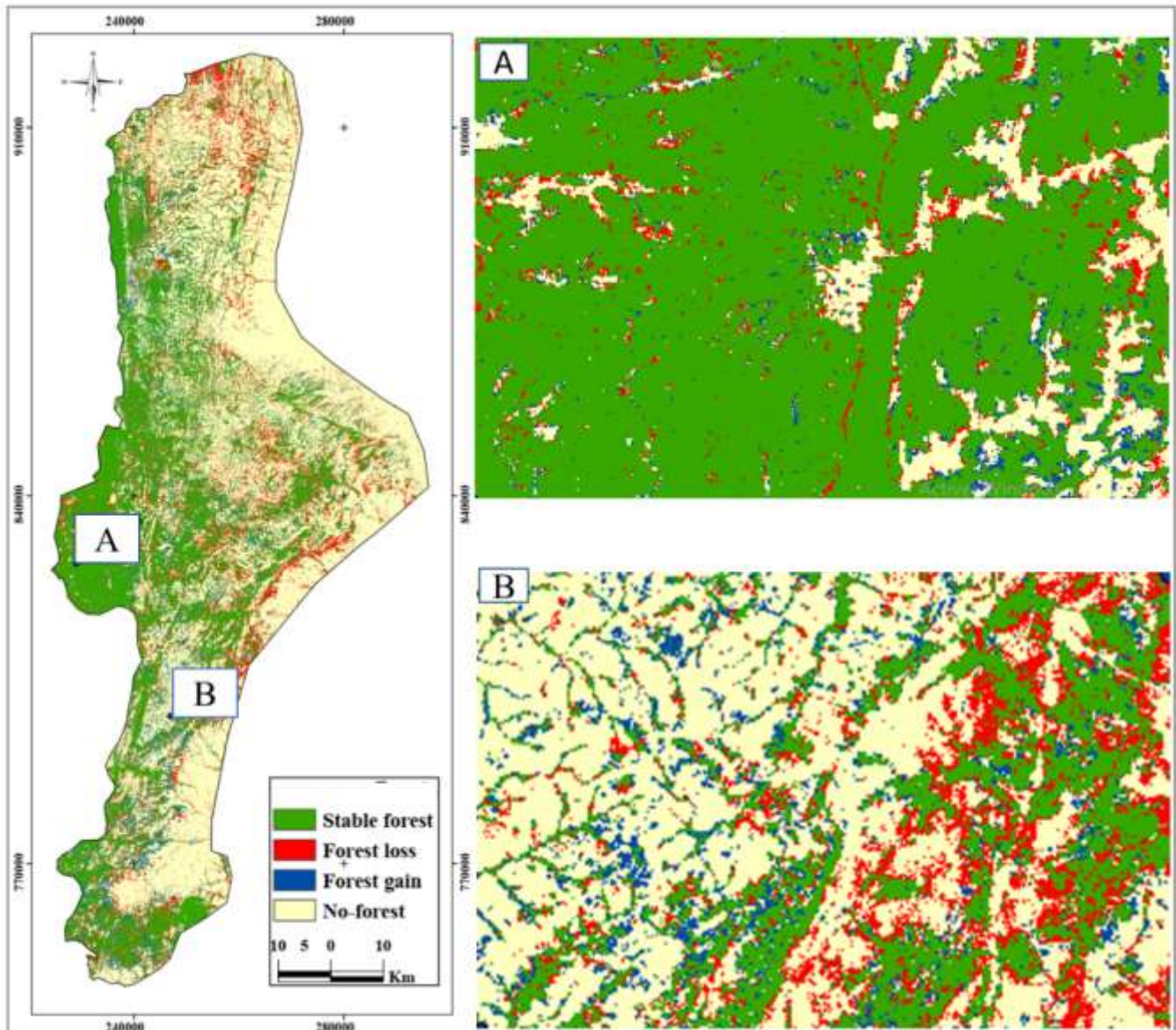
Figure 5. Forest cover change map for the period 1991 to 2003: A in kpele area; B in "plaine de Litime

to be far from evident to correctly attribute transition classes to training plots. Further, it is nearly impossible doing this just for a two-date comparison, but a whole time-series, with a sufficient number of training plots in order to ensure that all transition categories that are to be mapped are sufficiently represented.

The approach used in this study combines the above mentioned approaches and thereby overcomes many of those obstacles. A single date forest/non-forest map is produced based on available high-resolution images. For the classification of all other dates, the same forest definition is enforced by calibrating the classifier with this reference image. As a result, forest/non-forest maps that are most similar were obtained one to another; thus

underestimating rather than overestimating land-cover changes.

Once the reference map is defined, this approach allows for automatic classification of time-series of several images. The advantage of time-series is that it can be used for cleaning the resulting maps. Time-series approaches have many other advantages, as they are not so dependent on the conditions at the time the individual images were collected (GFOI, 2016; Kennedy et al., 2007; Zhuravleva et al., 2013). In this study, a simple majority filter was used, but more complex rule-based filters for filtering out for example forest loss and regeneration in agricultural rotation cycles is possible. The longer the time-series at disposal, the better are the
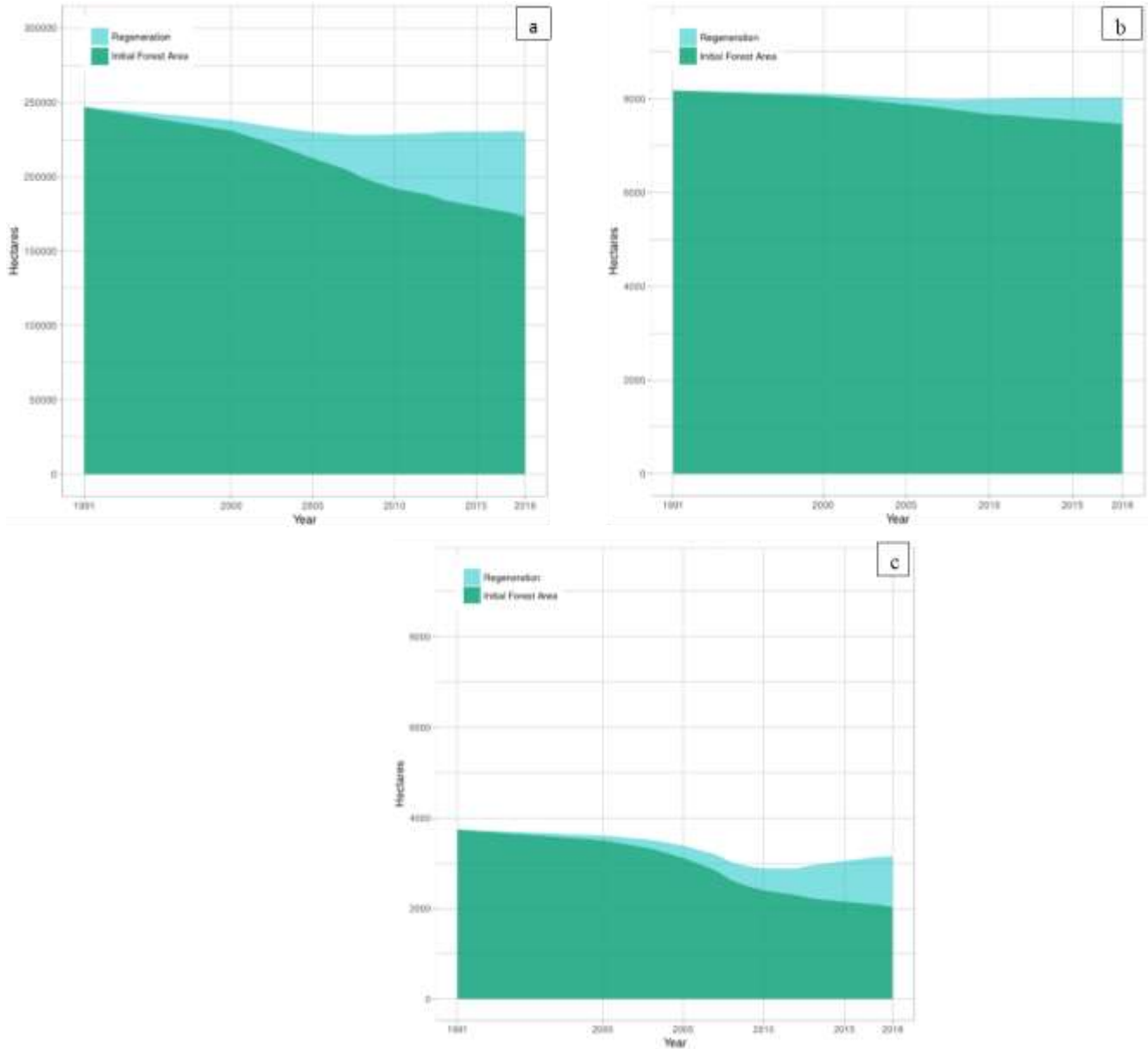
Figure 6. Evolution of forest area respectively in: a) the ecological zone VI, b a part of Kpele prefecture and in a portion of "Plaine of Litime.

possibilities for tracking land-use changes instead of just land-cover changes (Broich et al., 2011; GFOI, 2016).

The same approach could also be used for continuous monitoring, where time-series would be reevaluated annually with recently acquired Landsat images and with additional reference maps whenever new high-resolution data becomes available (Cohen et al., 2003). In principle it would even be possible to do the same analysis using a different forest definition (such as 10% crown cover) or doing analysis with different crown covers in order to assess forest degradation and regeneration within forests. Although there seems to be room for improvement, the study probably provides the most accurate figures on

forest cover change available in Togo. The Cohen's kappa of the three-date forest/non-forest transition map (1991-2003-2018) is 82% which, according to Pontius (2000), shows that the map is accurate.

Various forest cover change estimation rates

This paper shows that for all study areas combined the net forest lost is 0.5% during the 1991-2003 period, 0.1% during 2003-2018 period, 0.2% during 2000-2015 period and 0.4% during the 1991-2000 period. There are very few studies on forest cover change in Togo based on

consistent methodology. Therefore, it is difficult to compare the results of this study with those of similar studies in the country since the methodologies and the forest definition are not the same. Nevertheless, the study investigated the results of this study by comparing them with previous studies in the country.

Togo is recognized to be part of countries with the highest annual deforestation rate (5.1%·year^{-1}) (FAO, 2010). Previous studies of forest cover had included the land use map using RapidEye satellite images 2013/2014; the interpretation of aerial photos taken between 1976 and 1985 and Landsat image from 1990 to 2015 (MERF 2018). The latter recorded a decrease of forest loss rate from 0.733 % in 1990-2000 period to 0.2% between 2000-2015. Forest loss rate was compared to the forest loss rate presented in this paper even if the area and the period are not the same. The same forest loss rate was found on the overlapping period (2000-2015).

Significant difference was found comparing (FAO, 2010) forest loss rate to the rate of deforestation of this study. Three possible explanations were identified for these marked differences. First, FAO rate of forest loss is based on estimation of national data. Secondly, the definition of forest was not exactly the same in the two studies (10% vs. 30 crow cover). Finally, the exact period and the details methodology of FAO estimation were not known.

According to Mayaux et al. (2013), net deforestation of African rainforest is estimated at 0.28% year[-1] for the period 1990–2000 and 0.14% year[-1] for the period 2000-2010. The forest loss rate in the study area (0.4% year[-1]) for the period 2000-2010 is higher than the forest loss rate in West Africa in the same period. However, the forest loss rate in the study area (0.26% year[-1]) for the period 1991 to 2018 is very close to forest loss rate in West area even if the period considered are not exactly the same.

Composite-based approaches have proved successful for large scale change mapping and been used for making global maps of tree cover change at annual basis (Hansen et al., 2013).

Remaining forests status

This study shows, that overall forest cover did not change significantly over the last decade and that forest loss was compensated by forest gain. However, this study does not provide an answer whether the quality of the forests lost and those gained are the same. Are the forests lost just fallows and secondary forest cleared in the agricultural cycle and continuously compensated with fallows on abandoned land elsewhere? Or to what extent does this forest loss concern dense or open forests that are newly converted to agricultural land and masked with increased abandonment of agricultural land?

Several previous studies (Adjossou, 2004, 2009; Adjossou and Kokou, 2004; Adjossou et al., 2019) have shown that the remaining forests in the sub-humid mountainous area today is very fragmented and is practically reduced to forest buffers in hard-to-reach areas and along rivers. Based on the field observation, the majority of remaining forest are agroforests, fallow and early secondary forest. These remaining forests are technically "forests" in the forest definition above. The agroforest which is an agricultural land is considered as forest according to the definition of forest in this study. The low rate of forest loss from this study can be explained by the fact that there is small-scale clearance at forest edges difficult to visual on Landsat image (Grinand et al., 2013). The small-scale clearance is mainly for shifting cultivation and logging. Therefore, open-canopy areas, secondary forest or plantations in the estimates of forest areas were included. The analysis is therefore limited to forest cover. Land use was not a consideration in the mapping as in the study of Hansen et al. (2013).

Further research is needed on this issue: assessing quality of forests (such as biomass), degradation and regeneration within forests (not just forest/non-forest), longer time-series and analysis of land-use patterns instead of land-cover solely.

Conclusion

This study has updated forest cover statistics and assessed the rate of forest change in the forest zone in Togo. Even if this rate of forest loss slowdown from 2003-2018, the status of the remaining forest (mainly fallow and degraded forest) should alert all stakeholders working to preserve the remaining forest in the forest zone of Togo. Coupled with rigorous work to delimit training and validation plots by photointerpretation, this study provides a method for monitoring the forest dynamics. This research responds to the necessity of capturing local forest change dynamics for small scale. However, the use of Landsat images may not be satisfactory given its relatively low spatial resolution to detect very small scale of forest cover change. Therefore, the availability of higher resolution images such as orthophoto, SPOT 6, Sentinel-2 or radar could be very beneficial in the analysis and validation of time-series of Landsat images. For example, the Sentinel-2 mission will generate data that when combined with Landsat data will enhance time series analysis of forest cover change. This research can support policy approaches towards reducing emissions from deforestation and degradation (REDD+) in Togo. Regular updates to these data are very important to enable more rapid and adaptive response to forest loss threats in Togo.

The information content of the presented datasets, provides a consistent basis on which to quantify critical

environmental issues, including (i) the drivers of the mapped forest cover change; (ii) the biomass mapping and associated emissions of disturbed forest areas; (iii) the status of remaining forests; (iv) the economic drivers of natural forest conversion to more intensive land uses; (vi) the relationships between forest dynamics and social welfare, health and (v) forest dynamics associated with governance and policy actions.

DATA AVAILABILITY

The data regarding this research work will be readily available when requested.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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