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Minerology, geochemical composition and geotechnical properties of termite mound soil

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Termitarian, the epigeal biogenic structure constructed by termites are widespread in the forest and derived savannah regions of Nigeria. Soil modification, with particular focus on the mineralogy, variation in geochemical composition and geotechnical properties of termite mound soil samples collected from nine location in the Ika area, Delta State of Nigeria are the objectives of this report. The major elements geochemical composition of the termite mound soil samples determined by XRF was found to be mainly SiO_2 (40.25%), Fe_2O_3 (29.27%), Al_2O_3 (24.25%) and T_1O_2 (4.27%). The other major elements; CaO, MnO, MgO, Na_2O and P_2O_5 were present at less than 1%. Trace element compositions of the termite mound soil samples were found to be Cr (8.20- 23.10 $mg.kg^{-1}$), Pb (3.95- 13.85 $mg.kg^{-1}$); Cu (2.75-12.00 $mg.kg^{-1}$), Zn (3.60-9.60 $mg.kg^{-1}$) and Cd (1.90-3.15 $mg.kg^{-1}$). Minerological composition of the termite mound soil samples determined by XRD revealed significant hematatic composition with a range of 60.17-83.78%, antigorite (5.24 -24.17%) and quartz (7.14-14.67%). Anthophylite (19.92%) was found in only one termite mound soil samples. The geotechnical tests carried out on the termite mound soil samples included: Grain size, atterberg limit, compaction and triaxial tests. The range of values of the determined properties: Uniformity coefficient (3.75-7.50), coefficient of curvature (0.20-2.70), plasticity index (10.83-28.45%), plasticity limit (13.47- 19.57%), optimium moisture content (7.20-15.40%), maximum dry density (1.72-2.10g.cm^{-3}), angles of friction (2.83- 24.77°) and cohesion of up to about 50.11 $KN.m^2$, suggest that the termite mound soil may have limited application in soil stabilization and concrete works.

Key words: Ika, geotechnical, geochemical, termite, mound.

INTRODUCTION

The presence of living organisms is a major factor that distinguishes soils from disintegrated rock fragments from which they were derived. The wide variety and vast number of organisms in soil interact with environmental factor in complex cyclical and evolutionary process that transform fragmented rocks into mature soil. There is a vast literature on the role of organisms in soil processes and soil formation and in particular the interaction of

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microorganisms and invertebrates in decomposition and mineralization processes in becoming letter understood (Anderson, 1988). In general, soil provides a more stable environment for organisms than condition above the ground and therefore serves as a refuge for many epigeal invertebrates (Wood, 1988). In tropical regions, soil invertebrates macrofauna play a key role in organic matter, recycling (Levelle, 1994). The invertebrate fauna is dominated by termites in terms of density. Termites are terrestrial insects found approximately between 45°N and 45°S. Within these latitudinal limits they are restricted by a combination of extreme aridity and lack of vegetation and are rarely found at altitudes above 3000 m. Within this range, termites can be found in all soil types, except those which are semi- permanently water-logged and severally cracking vertisols (Wood, 1988). The impact of termites is usually due to their building ability where mounds (termitaria) represent spectacular biogenic structures. Termite mound density can be very high covering substantial land area (Levelle, 1994) and limiting available land for cultivation (Maduakor et al; 1995). The mode of mound construction differs among termite species: soil feeding species build their mounds with soil particles glued together with faeces (Wood et al., 1983); while funges – graving species mix soil particles with their saliva (Grasse, 1984). It has been suggested that mound building activity results in the upward transfer of clay, silt, sand and fine grain particles to the surface, a process which is opposite to leaching and this results in significant mobilization and dispersion of trace elements (Roquin et al; 1991; Chatupa and Dieng, 2000). The use of termite mound soil sampling in geochemical exploration has these become an active area of research (D'orey, 1975; Kedebe 2004; Petts et al; 2009). The ecological and geochemical significance of termite mound soils requires their systematic investigation. In this paper, the mineralogical and geochemical compositions and geotechnical properties of termite mound soil in the Ika area Delta State, Nigeria are reported.

MATERIALS AND METHODS

Geological setting

The termite mound soil samples were collected from the Ika area, Delta State, Nigeria. The area is located in the Niger Delta Basin, Southern Nigeria within latitudes 5° and 6°30 N and longitude 5°40' and 6°50'E. The Miocene-Recent Benin Formation (Reyment, 1965) typifies the Niger Delta basin and it is underlain successively in the north eastern (surface) Niger Delta by the paretic Ogwashi-Asaba formation, the Eocene Amiki Formation and the Paleocene Imo Formation. In the southwestern (subsurface) Nigeria, three diachronous units; (from top to bottom), Benin, Agbada and Akata Formations have been identified (Short and Stauble, 1967). The procleltaic marine Akata Formation composes mainly of shales and the poralic Agbada Formation consists mainly of sequences of sandstones shales, while the Benin Formation consists of sandstones and unconsolidated to partially consolidated sands and gravels with clay lenses (Nesbilt and Young, 1989) Figure 1 shows the geological setting of the study area.

Collection of termite mound soil samples

Termite mound soil samples were collected from nine locations (Abavo, Agbor Ekuku- Agbor, Idumuesah, Igbodo, Otolokpo, Owa, Umunede and Ute-Okpu) in the Ika area of Delta State (Figure 2). At each location, samples were taken from the top, middle and base of each of five mounds and composited. The samples were dried, ground in an agate motar and representative sample were taken for analysis.

Analyses of samples

The mineralogical composition of the termite mound soil samples was determined by x-ray diffraction (XRD) method using the Brauker D8 Advance x-ray diffractometer with a Lynx Eye detector. The scanning covered the 2Ө intervals of 4- 70° with a scanning angle step of 0.015° and a time step of 1 s. The mineral phases were quantified using a Riveted – based quantification routine with TOPAS® software.

Analysis for geochemical composition of the termite mound soil for samples was carried by x-ray fluorescence using the XRF – 1200 ARL, Advant's thermoscientific. Trace elements determinations were carried out on acid digestates of the termite mound soil samples using a Shimadzu GFA – 7000A AAS. The geotechnical tests were conducted in accordance with the BSI 1377 methods (1998). The percentage of difference sizes of the termite mound soil particles determined by sieve analysis were plotted as distribution (gradation) curve which allowed the uniformity coefficient Cc and coefficient of curvature, Cu of the test mound soil samples to be determine. Consistency limits were determined by the Atterberg tests and compaction test was used to determine the maximum dry density and optimum moisture content of the termite mound soil samples. Shear strength measured as cohesion and friction angle was determined by triaxial test.

RESULTS AND DISCUSSION

Minerological composition

The whole sample mineralogical composition of the termite mound samples are given in Table 1. All the termite mound soil samples revealed significant hematite content; with a range of 60.17 – 83.78% and an average composition of 72.51%. Hematite the mineral form of iron (ii) oxide (Fe_2O_3) is one of the several oxides widespread in rocks and / or highly weathered soils and along with other iron oxides or oxyhydroxides such as goethite is responsible for the red colour of many tropical soils. Antigorite, $(MgFe)_3$ SiO_5 $(OH)_4$, a form of serpentine mineral was the next most abundant in the termite mound soil samples studied, with a range of 5.24-24.17% and an average value of 14.86%; which quartz occurred in the range 7.14- 14.67% with an average value of 10.41%. Quartz mineral, the second most abundant mineral in Earth's continental crust after feldspar, composes of silicon and oxygen in a continuous framework of SiO_4 silicon oxygen tetrahedron and occurs in all mineral environments and is an important constituent of many

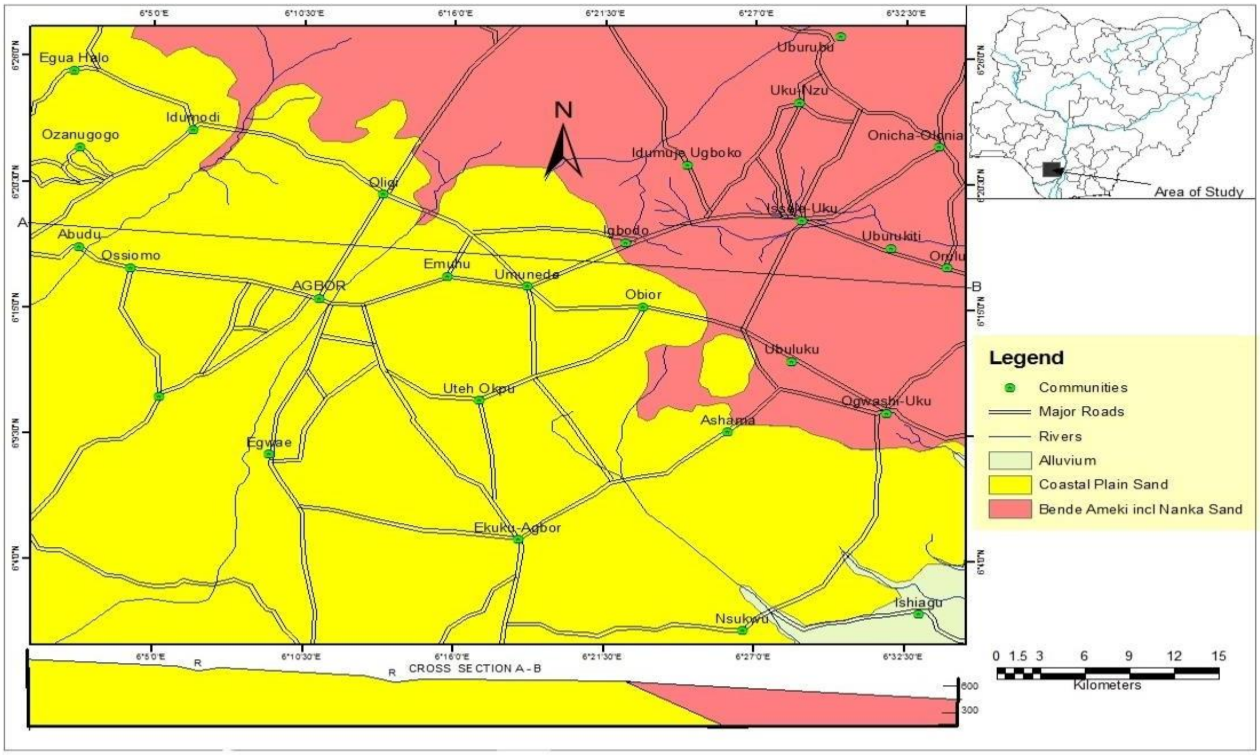

Figure 1. Geological map of study area.

rocks. Anthophyllite, Mg_2 Mg_5 SiO_8O_{22} (OH) magnesium iron inosilicate hydroxide, was found only in the termite mound soil sample from Abavo (19.92%). It is a rare stone that belongs to the Amphibole group found in schists and genises that are characterized by shales of brownigrey and off white colour, derived from magnesium rich metamorphic rocks found only in a few geographical locations (which may now include Abavo). The notable absence of clay minerals in the termite mound soil samples is significant and relevant in the potential geotechnical application of the termite mound soil.

Major element geochemistry

The concentration of the major elements analyses in the termite mound soil samples are given in Table 2. It can be seen that the termite mound soil samples contain mainly SiO_2 (40.25 ±1.14%), Fe_2O_3 (29.27±1.31%), Al_2O_3 (24.25 ± 0.92%) and TiO_2 (4.27± 0.46%). The amounts of MnO, MgO, CaO, Na_2O and P_2O_5 were all less than 1%. The use of geochemical indices, SiO_2/Al_2O_3, K_2O/Al_2O_3, Al_2O_3/TiO_2 etc. is important in relating chemical composition of sandstones to classification of terrigenous sands and shales and may be applied to the termite mound soil samples from the area of study. Cox et al. (1985) used the K_2O/Al_2O_3 rates to uses the original detrital mineralogy of mudstone with values of the index greater than 0.5 indicating dominance of alkali K- feldspar in comparison with other minerals; and values less than 0.4 suggesting minimal feldspar in the original mudstone.

The values of the K_2O/Al_2O_3 index for all the termite mound soil samples were all below 0.4, with a range of 0.007-0.012, and an average value of 0.009, thus indicating that the termite mound soils X have minimal K-feldspar. The SiO_2/ Al_2O_3 index can be used as indicator of mineralogical maturity and allow for distinction between quartz-rich high ratio sandstones and clay-rich low-rate shales (Pettijohn et al., 1972). The values of this index for the termite mound soil samples are about the same order of magnitude varying somewhat within the range 1.55-1.78, suggesting that the soil samples are quartz rich with high-ratio sandstones deficient of clay minerals. This is in line with the results of mineralogical composition which gave an average value of quartz content of the termite mound soil of 10.41% and absence of clay minerals. The Fe_2O_3/K_2O ratio may be thought of as an indicator of mineralogical stability. At the low temperature and pressure characteristic of sedimentary environment, the most stable rock-forming minerals are K-feldspar, muscovite, mican and quartz (Herron, 1988). In contrast, the less stable rock-forming minerals occurring commonly in lithic fragment tend to be rich in iron and magnesium. As a general rule, stable mineral assemblage have low Fe_2O_3/K_2O values less stable assemblage located close to the sediment source and

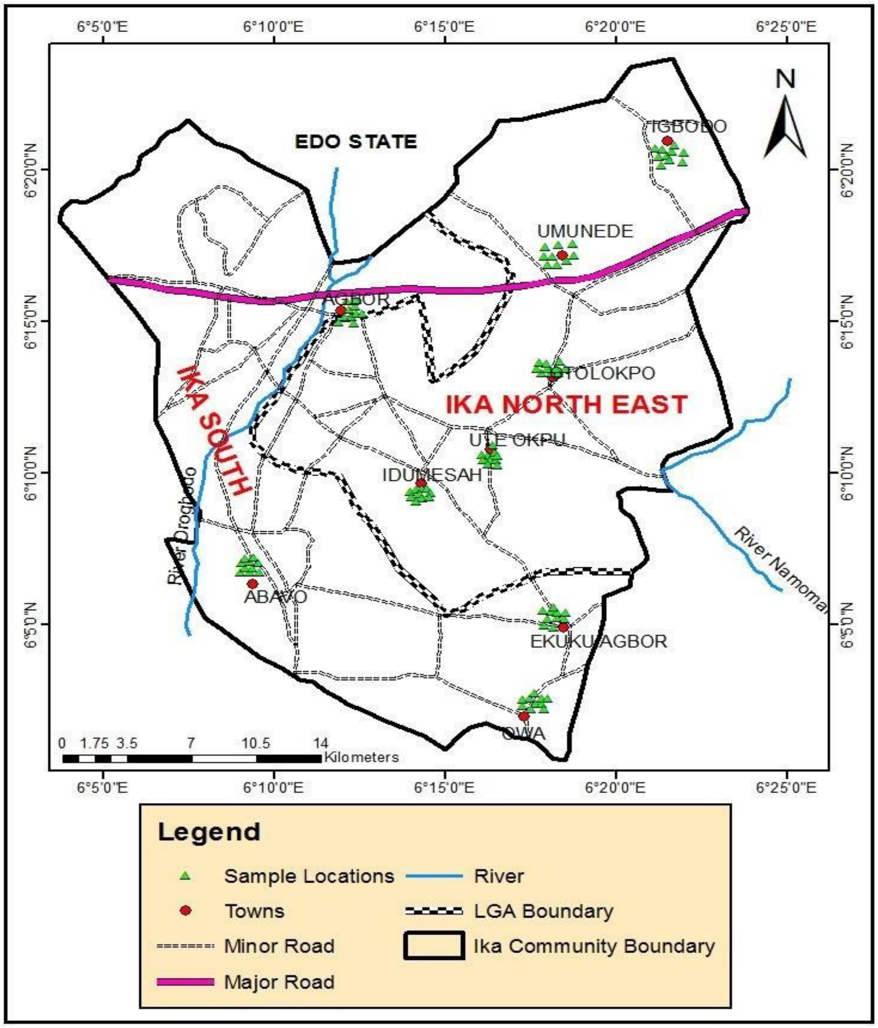

Figure 2. Map of Ika area showing sample locations.

Table 1. Minerological composition of termite mound soil samples from the study area sample.

Sample location	Minerological composition
Abavo	Quartz 14.67%; Hematite 60.17%
	Antigorite 5.24%, Anthophyllite 19.92%
Agbor	Quartz 10.92%, Hematite 73.11% Antigorite 15.97%
Owa	Hematite 68.93%; Antigorite 23.93%; Quartz 7.14%
Igbodo	Hematite 83.78%; Quartz 8.41%; Antigorite 7.81%
Umunede	Hematite 76.09%; Antigorite 12.83%; Quartz 11.08%
Otolokpo	Hematite 69.55%, Antigorite 14.14%, Quartz 8.90%
Ute-Okpu	Hematite 69.55%; Antigorite 17.67%, Quartz 12.78%
Ekuku-Agbor	Hematite 63.98%; Antigorite 24.17%; Quartz 11.85%
Idumuesah	Hematite 80.06%; Antigorite 11.97%, Quartz 7.98% _

containing abundant lithic fragments have high Fe_2O_3/K_2O values (Kedebe, 2004). A careful examination of the results in Table 2 indicate that the values of Fe_2O_3/K_2O index are relatively high with a range 93.63-

Table 2. Major element geochemical composition of termite mound soil samples.

Sample / Location	Major element composition (%)									
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	K_2O	CaO	MgO	Na_2O	Mno	P_2O_5
Abavo	39.62	28.44	25.65	4.49	0.21	0.11	0.02	0.04	0.03	0.04
Agbor	41.13	28.67	24.15	4.11	0.28	0.14	0.01	0.04	0.04	0.05
Owa	40.93	29.53	23.71	4.00	0.25	0.12	0.02	0.05	0.06	0.03
Igbodo	41.77	27.02	25.50	4.00	0.27	0.11	0.01	0.03	0.04	0.05
Umunede	40.67	28.09	24.13	5.00	0.30	0.13	ND	0.06	0.05	0.03
Otolokpo	39.90	30.50	24.99	3.78	0.20	0.12	0.03	0.05	ND	0.0
Ute-Okpu	38.08	31.12	23.74	3.91	0.19	0.11	0.02	0.05	0.05	0.03
Ekuku-Agbor	40.87	29.94	22.98	4.09	0.20	0.14	0.01	0.03	ND	0.02
Idumuesah	39.25	30.09	23.47	5.01	0.17	0.13	0.02	0.02	0.04	0.06

230.94 and on average value of 144.58 + 30.08. These high values of the Fe_2O_3/K_2O index may indicate Fe-rich shales or Fe-rich sands, the latter being more likely for the termite mound soils under study. The K_2O/CaO ratio is a useful index for charactering source area weathering (Mesida, 1981), with values less than 1.0 indicative of unweathered source rock and values greater than 1.0 suggestive of weathered source rock. The values of K_2O/CaO obtained for the termite mound soil (1.91-6.29) suggest a high degree of weathering, and is corroborated by the elevated values of TiO_2/Na_2O index (75.60-250.5). The Al_2O_3/TiO_2 ratio is orderly used for the discrimination of source rock littology: low values 3 to 8 indicative of mafic igneous rocks, 8 to 21 for intermediate rocks and 21 to 70 for felsic igneous rocks (Hayasali et al., 1997; Ocheli et al., 2018).

The value of Al_2O_3/TiO_2 obtained for the studied termite mound soils were in the range 4.68-6.61 supporting a line to passive continental margin (Ogala et al., 2015).

Weathering indices

Chemical index of alteration (CIA), chemical index of weathering (CIW). Plagioclase index of alteration (PIA) and mineralogical index of alteration (MIA) given as (Ocheli et al., 2018) are useful in the determination of the degree of weathering; a measure of the ratio of secondary aluminous minerals to feldspar (Eizien et al., 2004). Low values (of about 50) of weathering indices suggest unweathered or weak weathering, while values of 70-100 indicate intense weathering in which alkali and alkaline earth metals have been significantly removed relative to Al_2O_3 (Fello et al., 1995).

$$CIA = \frac{Al_2O_3}{(Al_2O_3 + CaO + Na_2O + K_2O)} \times 100 \quad (1)$$

$$CIW = \frac{Al_2O_3}{(Al_2O_3 + CaO + Na_2O)} \times 100 \quad (2)$$

$$PIA = \frac{Al_2O_3}{(Al_2O_3 + CaO + Na_2O - K_2O} \times 100 \quad (3)$$

MIA = 2 x (CIA - 50)

Intensity of weathering is indicated from values of MIA: 0-20% weak, 20 - 40% moderate, 40 - 60% intense and 60-100% extreme intensity of weathering. The range of values of weathering indices: CIA 98.13 - 99.08%; CIW 99.23 - 99.58%, PIA 100.13 - 101.66% and MIA 97.08-98.84% indicate clearly that the termite mound soils, as expected, are extremely weathered.

Trace elements geochemistry

The concentrations of selected trace elements in the termite mound soils are given in Table 3 in comparison with adjacent soil samples collected at 10 m from the base of the mound soil. The most abundant trace element in the termite mound soil was Cr (average value 15.86 $mg.kg^{-1}$), followed by Pb (7.44 mg. kg^{-1}) while Ca (2.51 mg. kg^{-1}) was the least abundant. The same pattern of variation was observed for the concentration of the trace elements in the surrounding soil samples: Cr (average value 10.33 mg. kg^{-1}); Pb (5.79 mg. kg^{-1}); Cu (3.98 mg. kg^{-1}), Zn (3.67 mg. kg^{-1}) and Cd (2.10 mg. kg^{-1}). These results show marked increase in the concentration of Zn, Cr and Cu in the termite mound soils of 50.41, 53.53 and 60.05% respectively over the in the surrounding top soil samples. The relative increase of Pb (28.49%) and Cu (19.52%) in the termite mound soils in comparison with the surrounding top soil samples were less marked. The spatial variation of the total trace elements in the termite mound soils and surrounding soil samples given in Figure 3 are in the range 22.55-50.65 mg. kg^{-1} and 15.56 - 41.40 $mg.kg^{-1}$ respectively and are apparently significant, and may indicate variations in the sub- surface geochemistry of the area.

Table 3. Trace elements composition of termite mound soil.

Location \ Sample	Element concentration (mg. kg^{-1})				
	Cd	Cr	Cu	Pb	Zn
Abavo	2.30 (1.95)	11.35 (7.35)	6.65 (3.45)	6.05 (3.30)	3.60 (2.20)
Agbor	2.65 (2.30)	8.20 (7.00)	3.75 (3.10)	3.95 (1.85)	4.00 (2.15)
Owa	2.80 (2.15)	14.05 (11.75)	12.00 (5.80)	13.85 (12.65)	7.95 (6.95)
Igbodo	3.15 (2.20)	17.50 (13.60)	5.80 (3.25)	5.60 (4.95)	6.25 (2.65)
Umunede	2.10 (1.80)	15.20 (9.60)	7.10 (5.12)	7.80 (4.00)	4.15 (2.50)
Otolokpo	2.35 (2.25)	23.10 (13.90)	5.95 (13.65)	7.30 (4.70)	5.21 (3.80)
Ute-Okpu	2.30 (2.00)	17.70 (14.50)	5.55 (2.80)	7.35 (6.60)	4.25 (3.30)
Ekuku-Agbor	3.05 (2.45)	21.40 (19.10)	6.30 (5.65)	8.45 (7.45)	9.60 (6.75)
Idumuesah	1.90 (1.80)	13.30 (9.75)	4.45 (3.00)	6.65 (5.50)	4.70 (2.71)

Values in parentheses are for surrounding soil samples.

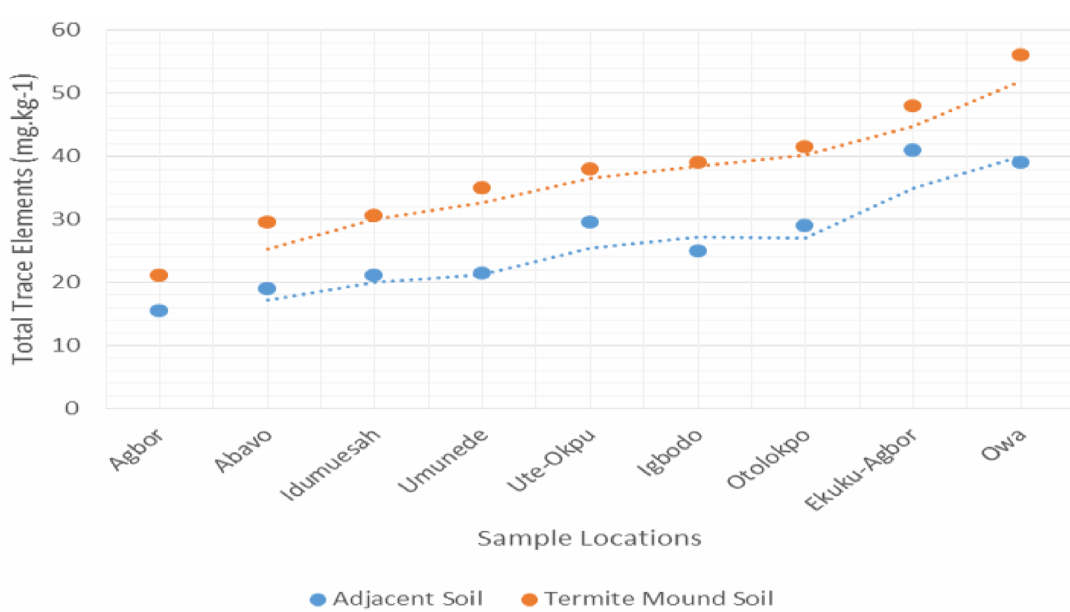

Figure 3. Spatial variation of total trace elements in the study area.

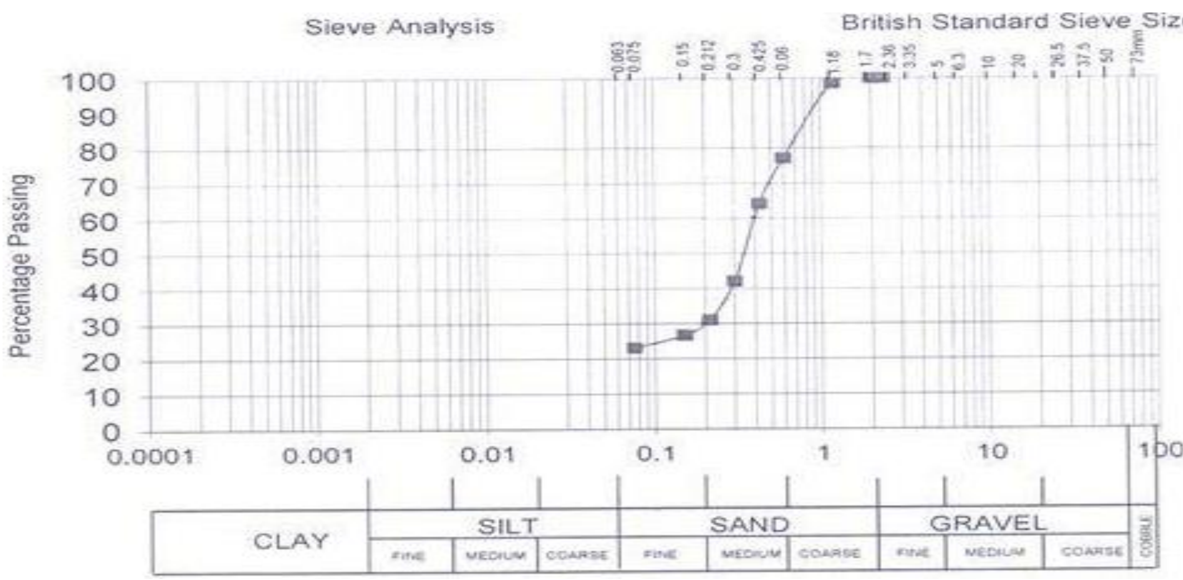

Figure 4. Typical particle size distribution curve.

Table 4. Geotechnical properties of termite mound soil.

Sample / Location	Particle size indices		Plasticity (%)			SP Gr.	Compaction		Shear strength	
	Cu	Cc	LL	PL	PI		MDD	OMC	Friction angle	Cohesion
Abavo	5.70	1.75	29.24	16.81	12.42	2.58	1.77	12.80	11.80	50.11
Agbor	4.38	2.30	24.64	13.49	11.15	2.55	1.74	15.40	10.08	21.11
Owa	3.75	2.70	31.63	18.25	13.37	2.48	2.10	14.40	24.77	0.00
Igbodo	5.00	0.20	30.55	19.72	10.83	2.55	1.91	13.80	3.95	36.24
Umunede	5.00	0.20	29.61	17.57	12.03	2.52	2.00	7.20	10.08	21.11
Otolokpo	5.00	0.20	32.32	18.56	13.76	2.48	1.74	17.10	9.69	19.79
Ute-Okpu	5.00	1.25	27.35	14.36	12.99	2.54	1.85	11.60	2.83	23.56
Ekuku-Agbor	5.00	0.20	30.50	17.56	12.94	2.34	1.82	12.00	8.13	42.86
Idumuesah	4.40	0.80	53.75	25.30	28.48	2.57	1.84	16.20	21.04	30.77

Cu = uniformity coefficient; Cc = coefficient of curvature, LL = liquid limit, PL = plastic limit, PI = plasticity index, Sp Gr = specific gravity, MDD = maximum dry density (g.cm^{-3}) OMC = optimum moisture content (%); cohesion KN.M^{-2}.

Geotechnical properties of termite mound soil

The results of the geotechnical tests carried out on the termite mound soil samples are given in Table 4. Typical particles size distribution curve for particles size analysis of the termite mound soil sample is given Figure 4. It revealed that the termite mound soils are largely constituted of fine to medium grain sands. The particle size indices uniformity coefficient, Cu and coefficient of curvature Cc obtained for the mound soils varied from 3.75 - 5.70 and 0.20- 2.70 respectively, suggesting that at the mound soils are coarse, poorly graded and poorly sorted (Hoitz and Kovacs, 1981; Das and Sobhan, 2013). The liquid- plastic - semi - solid - solid states of aqueous slurry, Atterberg limits of the termite mound soils are given in Table 4. The values of plasticity index, 0.82-28.45% indicate that the mound soils have low plasticity (Clayton and Juckes, 1978) medium plasticity (Burmister, 1948) and are cohesion (Prakash and Jani, 2002).

The specific gravity of the mound soils varied within a narrow range; 2.34- 2.58 and within the organic soil range (1.0Ɵ - 2.60) (Bowles, 2012). These results suggest that the mound soils may not be suitable materials for civil construction. The moisture content at which soils are compacted in the field is controlled by its optimum moisture content, while the compaction energy applied is determined by its maximum dry density. The optimum moisture content (OMC) and maximum dry density (MDD) of the mounds soils can be seen in Table 4 to vary from 7.20- 17.10% and 1.74 and 2.10 g.cm^{-2} respectively. The mound soils can therefore be classified as sandy soil (O'Flanerty, 1988) or loose with little amount of clay (Ishaku et al., 2002). The shear strength parameters of soils defined as cohesion and friction angle depend on the effective stress, drainage conditions, density of the particles rate of strain and direction of stain (Roy and Bhalla, 2017). These shearing strength is affected by the consistency of the material, minerology, grain size distribution; shape of particles, initial void ratio and features such as layers, joints, fissures and cementation (Poulos, 1989). The values of shear strength indices; cohesion and angle of friction for the mound soil have wide spatial variation; 0.00- 50.11 $KN.M^{-2}$ and 2.83-24.77° respectively. These relatively low values of shear strength indicator may be related to grallation and consistency of the mound soils; and suggests that the mound soils may have limited soil engineering applications.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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The role of logged timber stump sprouting in natural forest regeneration in the Akak forest area of Cameroon

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Natural forest regeneration is the renewal of a forest crop by self-sown seed or by sprouting of stumps. However, there have been few studies on sprouting in the Cameroon tropical rainforest. The main objectives of this study were to examine the influence of stump sprouting of timber species in natural forest regeneration in the Akak forest area in Cameroon. In this study, stumps were located in forest compartments that had been selectively logged in 2013, 2015 and 2017. Stumps attributes: (1) species, (2) the diameter at the top of the mother stump, (3) the height of the mother stump, (4) the number of sprouts, both living and dead, (5) the height of the tallest sprout, (6) the basal diameter of the tallest sprout, and (7) the extent of the decay of the stump were recorded at every sprouted stump using a Global Positioning System (GPS) device. Thirteen of the 20 tree species had some stumps which had sprouted. Stumps of *Nauclea diderrichii*, *Pterocarpus soyauxii* species, *Terminalia ivorensis,* and *Piptadeniastrum africanum* sprouted most frequently, with *N. diderrichii* having the greatest number of stumps with sprouts. Principal component factor analysis for all the species together showed that the first factor contributed 34.1% and the second factor contributed 19.1% of the observed variation, with a communality of 66.6% while for *N. diderrichii* alone showed that the first two axes of the PCA explained 62.8% of the variance suggesting that sprouting dynamics could only be partially explained by the attributes that were recorded. Multiple linear regression shows that the diameter of the tallest sprout can be used to predict the height of the tallest sprout for all the species combined (p=0.000). These predicting models could help in predicting the future growth rate and stand of a tropical rainforest.

Key words: Natural forest recovery, timber species, tropical rainforest.

INTRODUCTION

The importance of tropical rainforest ecosystems in terms of global biodiversity, environmental protection, human welfare, and more recently for carbon sequestration and climate stability, cannot be overestimated (Lamprecht, 1989; FAO, 2003). Tropical forests have shrunk in area by 35 to 50% since pre-industrial times (Wright and Muller-Landau, 2006). If losses continue at current rates, the last remnants of primary tropical forest will probably disappear sometime between 2100 and 2150, although global climate change (if unchecked) will undoubtedly accelerate the process (Wright and Muller-Landau, 2006). Despite greater general awareness and efforts

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made towards the sustainable management of these valuable natural resources, global tropical forest degradation persists (FAO, 2007).

After the first timber harvest in tropical rainforests, there is generally a qualitative and/or quantitative decline in subsequent harvests, and inadequate natural regeneration of some commercially valuable timber species in the residual stand. Securing sufficient natural regeneration of commercial tree species after logging is critical for sustainable forest management (Nzogang, 2009).

Most studies of tropical forest regeneration focus on tree recruitment from seeds. Consequently, regeneration is often viewed as depending on seed production, seed dispersal, seed viability, and the environmental requirements for seed germination and seedling establishment (Holl, 1999; Dalling and Hubbell, 2002; De Steven and Wright, 2002). However, sprouts from cut stumps (coppicing) may also contribute to the regeneration of tropical forests. Sprouting is a common response to tissue damage by woody plants and is a source of regeneration that contributes to the composition and development of many forest ecosystems (Bond and Midgley, 2001; Del Tredici, 2001). Sprouts can have a competitive advantage over other sources of forest regeneration (White, 1991; Dietze and Clark, 2008; Vickers et al., 2011) because rapid early growth of sprouts is supported by an established root system with stored carbohydrates (Del Tredici, 2001). Additionally, regeneration from sprouts can contribute to sustaining pre-disturbance species composition (Dietze and Clark, 2008). Several studies have shown that sprouts can constitute the majority of the dominant trees within a regenerating cohort after harvesting (Boring et al., 1981; Beck and Hooper, 1986; Arthur et al., 1997), although the capacity to sprout varies by species and site conditions. Furthermore, in forests in general, and in dry forests in particular, tree seedlings that do become established often grow more slowly than sprouts (Miller and Kauffman, 1998; Khurana and Singh, 2001).

Cameroon is well-endowed with tropical forest areas estimated at 21.5 million ha (Nasi et al., 2006; FAO, 2007). Efforts are underway to better understand forest regeneration after harvesting. However, there have been relatively few studies on stump sprouting in Cameroon’s tropical rainforest. This study is intended to help fill that gap.

The objectives of this study were to examine the role of stump sprouting of timber species in natural forest regeneration in the Akak forest area in Cameroon, specifically: (i) to identify tree species that sprout after logging and mapped the distribution of sprouted stumps; and (ii) determined relationships between sprouting characteristics (number of sprouts per stump, height of the dominant sprout, diameter of the dominant sprout, height, and diameter of mother stump) for all the species and the species with the highest number of stump sprouts (*Nauclea diderrichii*). This study was to provide baseline information on the sprouting ability of harvested tree species in the Akak forest area of Cameroon, as well as to provide recommendations for management in the Akak forest area to promote sprout development.

MATERIALS AND METHODS

Location of the study area

The Akak forest area of Cameroon is located between 5°20′ - 5°25’ N latitude and 9° 12’ - 9°30’ E longitude (Figure 1). Akak is comprised a semi-deciduous lowland rainforest of the Guineo-Congolian type (Kenfack et al., 2006). Precipitation is unimodal, with an annual average of around 4100 mm (Nchanji and Plumptre, 2003), with a three-month dry season from December to February (Groenendijk, 2015). The topography is relatively flat. Human interventions, primarily establishing large plantations of cash crops (palm oil, coffee), as well as natural factors, such as elephant disturbance and windfalls, have created large gaps in these forests. Logged forest sites are located in the “heart” of the Mukete Plantations Limited (MPL) concession and the forest in this area has undergone logging, both formal and informal, from 1995 to the present.

Sample design

The three areas sampled were logged in 2013, 2015, and 2017, respectively. Opportunistic sampling technique was used to select the three areas, since we had pre-information from community people living in Akak village (Former-workers of the logging concession, hunters and Non Timber Forest Products collectors) that they have observed some logged stumps in these areas sprouting. The 2013 site was logged by Transformation Reef Cameroon and local chainsaw millers. The 2015 and 2017 sites were logged by SEFECAM and local chainsaw millers. Trees selected for harvesting were widely scattered (less than 1 ha^{-1} in most places) and it proved difficult to locate stumps using any formal sampling design. Consequently, stumps were located by active searching of the logged areas. All stumps located, whether they had sprouts or not, were recorded.

Both sprouted and non-sprouted stumps were observed, but only sprouted stumps were marked and measured. The diameter and basal diameter for both stumps and sprouts were measured using a diameter tape at 1.3 m breast height while a 30 m measuring tape was used to measure the height for both stumps and sprouts. Once a stump with sprouts was located, its location was recorded using a Global Positioning System (GPS) device so that these stumps could be relocated for future follow-up. The attributes recorded for each sprouted stump were: (1) species; (2) the diameter at the top of the mother stump; (3) the height of the mother stump; (4) the number of sprouts, both living and dead; (5) the height of the tallest sprout; (6) the basal diameter of the tallest sprout; and (7) the extent of the decay of the stump.

Data analysis

The field data were imported into QGIS 2.8 so that the coordinates of the sprouted stumps could be digitized. Baseline information from the Cameroon official forest data and the Cameroon atlas were collected before any data manipulation commenced. After all digitizing was completed, a quality check was performed to ensure that no points or lines were missing. To ensure all of the data would display correctly, all of the shapefiles were projected to UTM 84, zone 32 N.

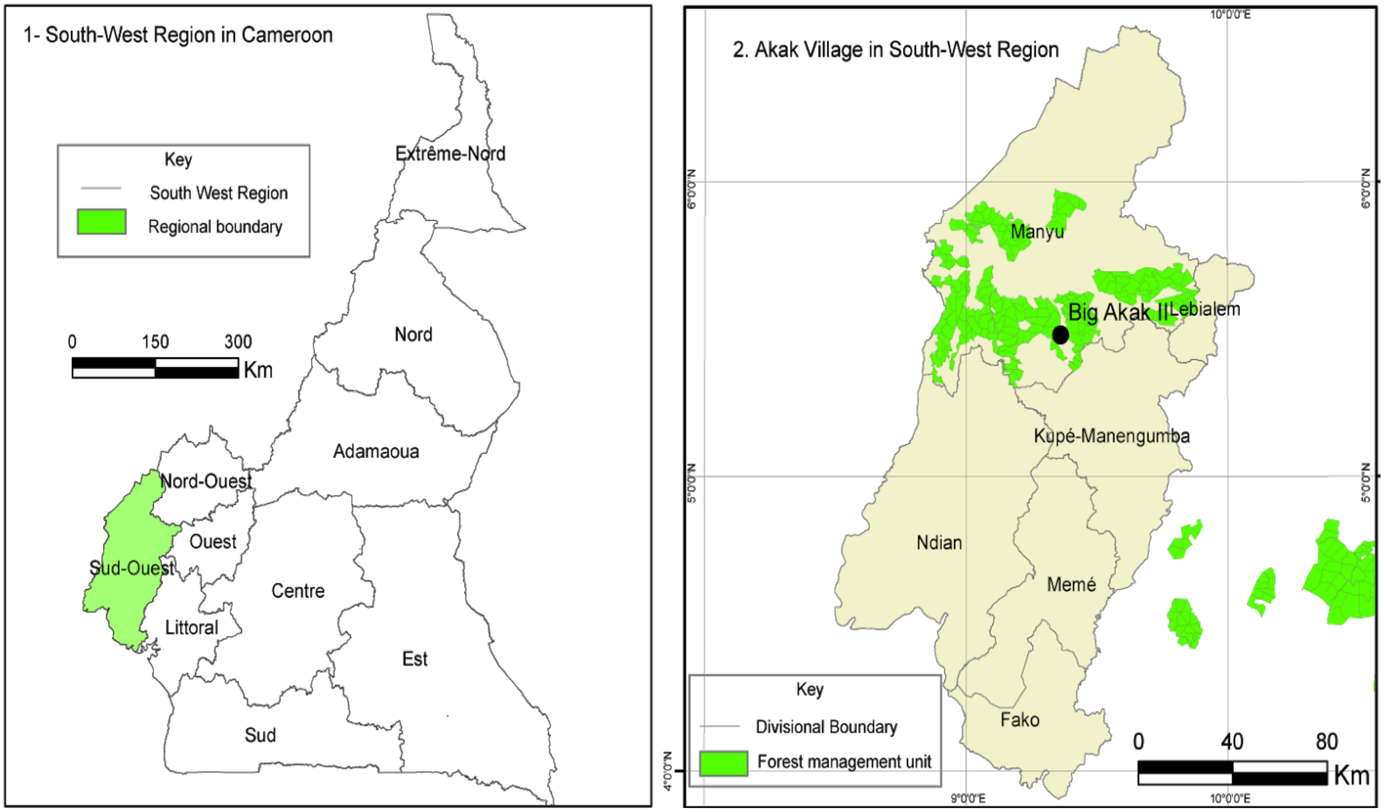

Figure 1. Akak forest area.
Source: Adapted from the Cameroon Atlas 2019.

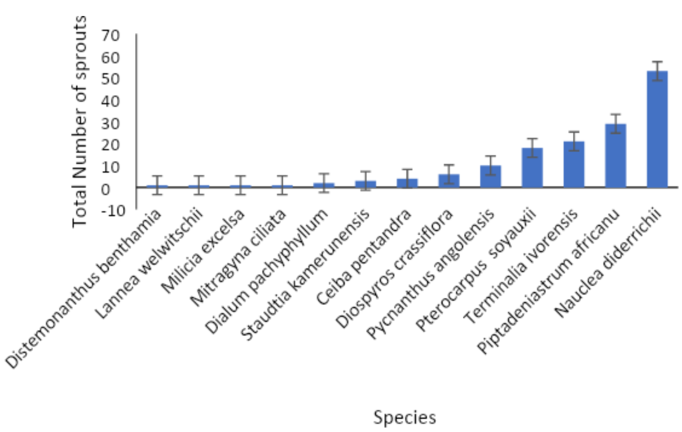

Figure 2. Number sprouts in the Akak forest area by species.

Multivariate factor analysis without rotation was done to explore relationships among the variables. Two factors were extracted and their contribution to explaining the resulting data patterns was determined by the percent variation and communality. This was followed by applying the Spearman rank correlation.

Step-wise regression was used to examine the relationships between (1) the heights of the tallest sprouts and number of sprouts per stump and stump diameter; (2) the heights of the tallest sprouts and the largest basal sprout diameter and the number of sprouts per stump; and (3) the heights of the tallest sprouts and the number of sprouts per stump and stump height. The data (all variables) were log-transformed to achieve a normal distribution for the residuals. These analyses were done independently for data collected in 2013, 2015 and 2017, and then for the entire study to determine the overall effects of the stump characteristics on the sprout characteristics.

All statistical analyses were done using Minitab Version 17 Statistical Package (Minitab Inc., PA, USA). The significance level (α) was set at 0.05.

RESULTS

Timber species that sprout in the Akak forest after logging and distribution of sprouted stumps

A total of 643 stumps from 20 tree species were located. Of these stumps, 56 (9%) had sprouted. Stumps from 13 different tree species (65% of the species that had been harvested) had sprouts (Figure 2 and Table 1). *N. diderrichii*, *Piptadeniastrum africanum, Terminalia ivorensis*, and *Pterocarpus soyauxii* were the most frequent sprouts. Collectively, these four species contributed almost 79% of the total number of sprouts observed.

Table 1. Distribution of sprouted and non-sprouted stumps.

Family name	Common name	Scientific name	Number of stumps observed	Number of sprouted stumps	Sprouted stumps by logging year 2017	2015	2013	% of overall sprouted stumps	Number of Non sprouted stumps	% of stumps sprouted	% of total sprouted stumps
Rubiaceae	Bilinga	*Nauclea diderrichii*	30	25	13	6	6	3.943218	5	83.3	44.6
Combretaceae	Framire	*Terminalia ivorensis*	30	7	-	4	3	1.104101	23	23.3	12.5
Fabaceae	Padouk	*Pterocarpus soyauxii*	30	6	1	5	-	0.946372	24	20.0	10.7
Leguminosae	Movingui	*Distemonanthus benthamianus*	9	1	-	-	1	0.157729	8	11.1	1.8
Rubiaceae	Bahia	*Mitragyna ciliata*	8	1	1	-	-	0.157729	7	12.5	1.8
Leguminosae	Eyoum	*Dialum pachyphyllum*	10	1	1	-	-	0.157729	9	10.0	1.8
Myristicaceae	Niove	*Staudtia kamerunensis*	30	2	2	-	-	0.315457	28	6.7	3.6
Leguminosae	Dabema	*Piptadeniastrum africanum*	30	6	1	5	-	0.946372	24	20.0	10.7
Malvaceae	Fromagi	*Ceiba pentandra*	25	1	-	1	-	0.157729	24	4.0	1.8
Moraceae	Iroko	*Milicia excelsa*	40	1	-	1	-	0.157729	39	2.5	1.8
Myristicaceae	Ilomba	*Pycnanthus angolensis*	30	3	1	1	1	0.473186	27	10.0	5.4
Anacardiaceae	Kumbi	*Lannea welwitschii*	10	1	1	-	-	0.157729	9	10.0	1.8
Ebenaceae	Eben	*Diospyros crassiflora*	5	1	-	1	-	0.157729	4	20.0	1.8
Ochnaceae	Azobe	*Lophira alata*	140	0	-	-	-	0.0	140	0.0	0.0
Sapotaceae	Moabi	*Baillonella toxisperma*	49	0	-	-	-	0.0	49	0.0	0.0
Caesalpiniaceae	Naga	*Brachystegia cynometriodes*	10	0	-	-	-	0.0	10	0.0	0.0
Meliaceae	Acajou blanc	*Khaya anthotheca*	7	0	-	-	-	0.0	7	0.0	0.0
Meliaceae	Dibetou	*Lovoa trichillioides*	9	0	-	-	-	0.0	9	0.0	0.0
Leguminosae	Tali	*Erythrophleum suaveolens*	48	0	-	-	-	0.0	48	0.0	0.0
Mimosaceae	Okan	*Cylicodiscus gabunensis*	84	0	-	-	-	0.0	84	0.0	0.0
Total	**20**	**-**	634	56	21	21	14	8.832808	578	-	100

The number of sprouts varied by species and period (Figure 3). *N. diderrichii* had the most sprouts (30) in 2017, 11 sprouts in 2015, and 12 sprouts in 2013, while *P. soyauxii* had 9 sprouts in 2013, 7 sprouts in 2015, and 2 sprouts in 2017. *T. ivorensis* had 4 sprouts in 2013 and 17 sprouts in 2015 and no sprouts in 2017.

The mean diameter of the sprouted stumps varied by species and ranged from 20.0 to 102.9 cm (Figure 4).

Generally, most sprouts originated from stumps with mean diameters between 70 and 100 cm. *N. didderrichii* and *T. ivorensis* sprouted from stumps with the highest mean stump diameters (102 and 103 cm, respectively). *Diospyros crassiflora* sprouted from stumps with a mean diameter of 20 cm and *Milicia excels* sprouted from stumps with a mean diameter of 30 cm. Both stump diameters are below the minimum diameter for logging as stated in the 1994 forestry law of Cameroon.

Most of the sprouts were found on stumps with diameters between 81 and 100 cm, but stumps between 41 and 60 cm had the highest number of sprouts (23) in a single year (2015) (Figure 5). The numbers of sprouts within the smaller stump diameter classes were small, as were those in the larger classes.

Generally, the mean height of sprouts increased with years since logging and varied among species (Figure 6).

One exception was *Pycnanthus angolensis,* which showed a mean sprout height of 55 cm 5 years after logging, 70 cm 3 years after logging,

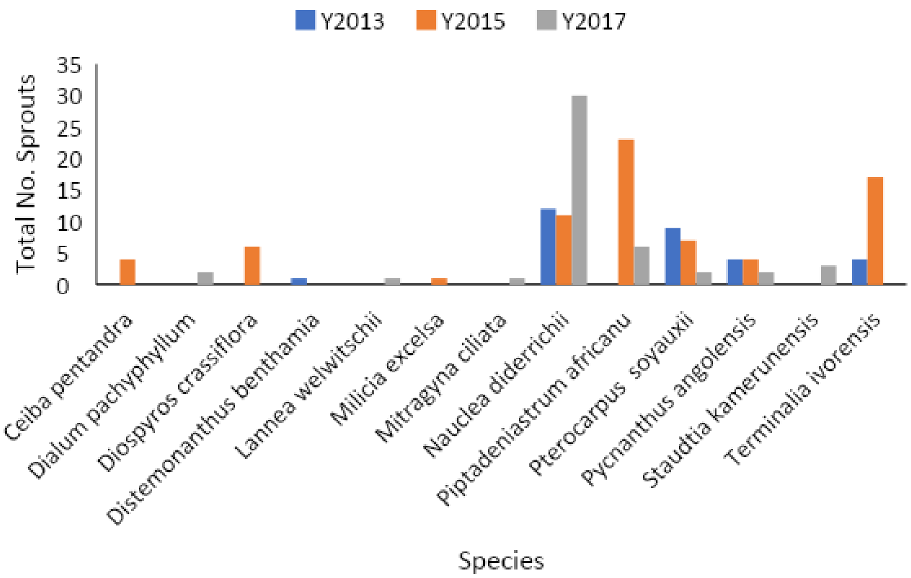

Figure 3. Distribution of sprouts by species and harvesting year.

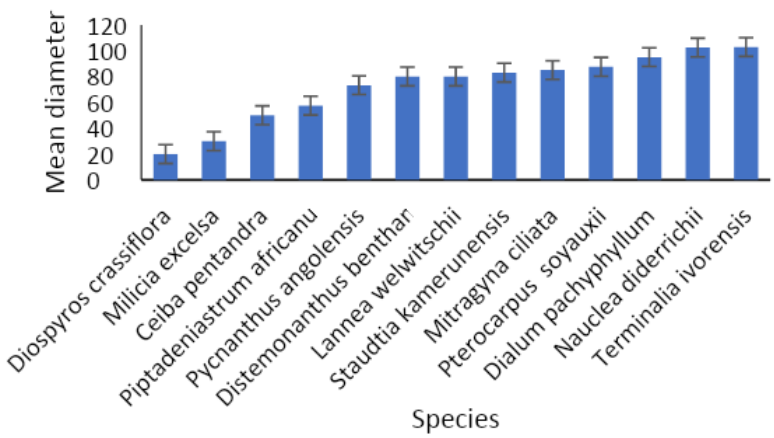

Figure 4. Mean stump diameter of sprouted species.

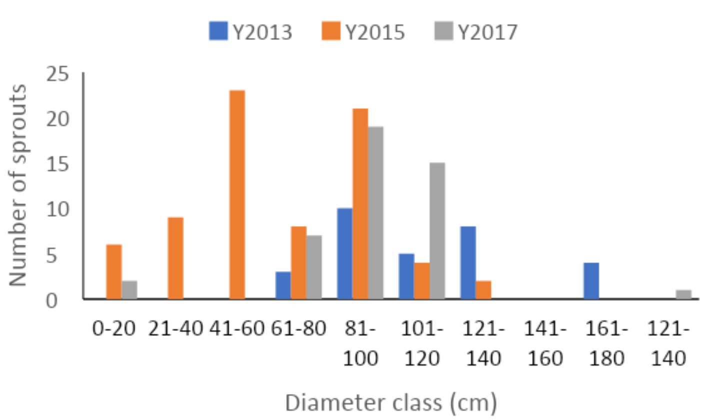

Figure 5. The distribution of sprouts by stump diameter class.

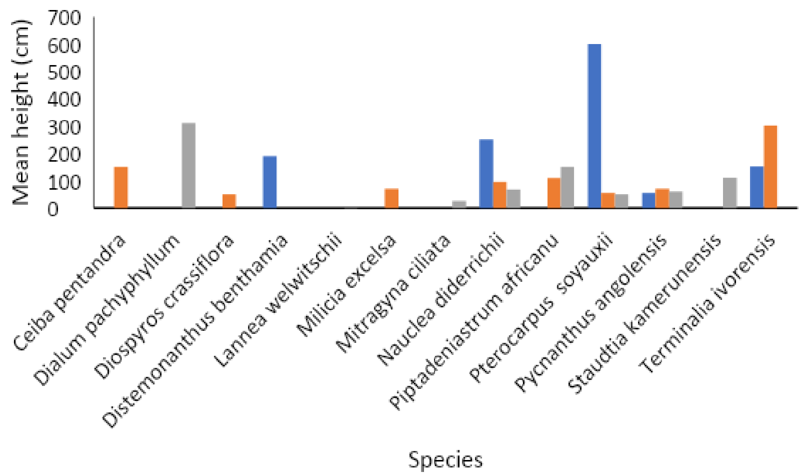

Figure 6. The distribution of mean height per species as per 2013, 2015 and 2017.

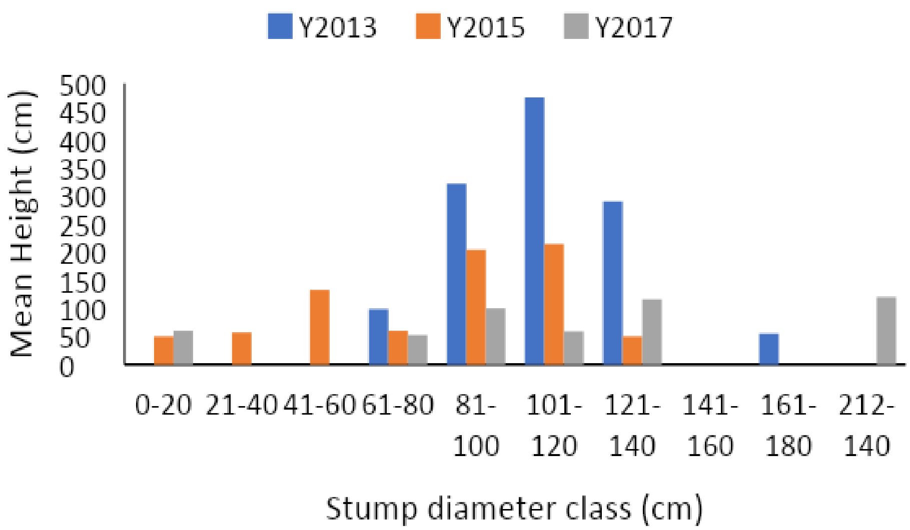

Figure 7. Distribution of mean height by diameter class and harvesting year.

and 60 cm 1 year after logging. Similarly, *T. ivorensis* had a mean sprout height of 301 cm 3 years after logging, but 152 cm 5 years after logging. These differences could be due to competition amongst sprouts, stump characteristics or several other factors. Stump diameter classes of 101-120 and 81-100 had the highest mean sprout height while the two smallest diameter classes had the lowest mean sprout height (Figure 7).

Most sprouted stumps were recorded in the compartments logged in 2015 and 2017 (21 stumps each) while in 2013 only 14 sprouted stumps were found (Figure 8). Also, the compartment from 2017 had more different species sprouting than the other two compartments.

Relationships between sprouting characteristics (number of sprouts per stump, height of the dominant sprout, diameter of the dominant sprout, height, and diameter of mother stump) for all the species and species with the highest number of stump sprouts (*N. diderrichii*)

The year of harvesting correlated negatively with the other variables (Figure 9). The correlation between the year of logging and sprout decay was weakly negative, but it had a significant effect ($P < 0.005$). Also, the correlation between the height of the tallest sprouts and stump diameter was weak but significant ($P < 0.032$). There was a highly significant relationship ($P < 0.0005$)

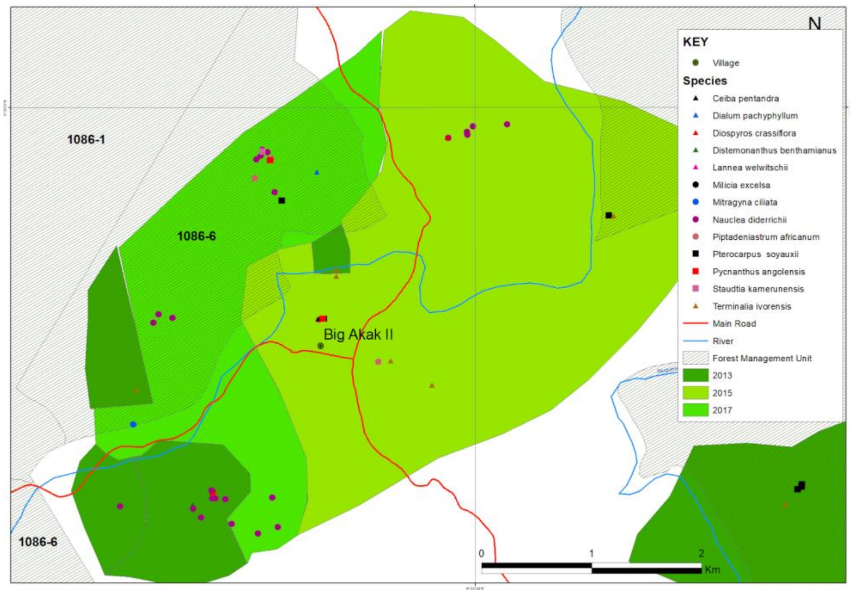

Figure 8. The location of sprouted stumps in the Akak forest area.

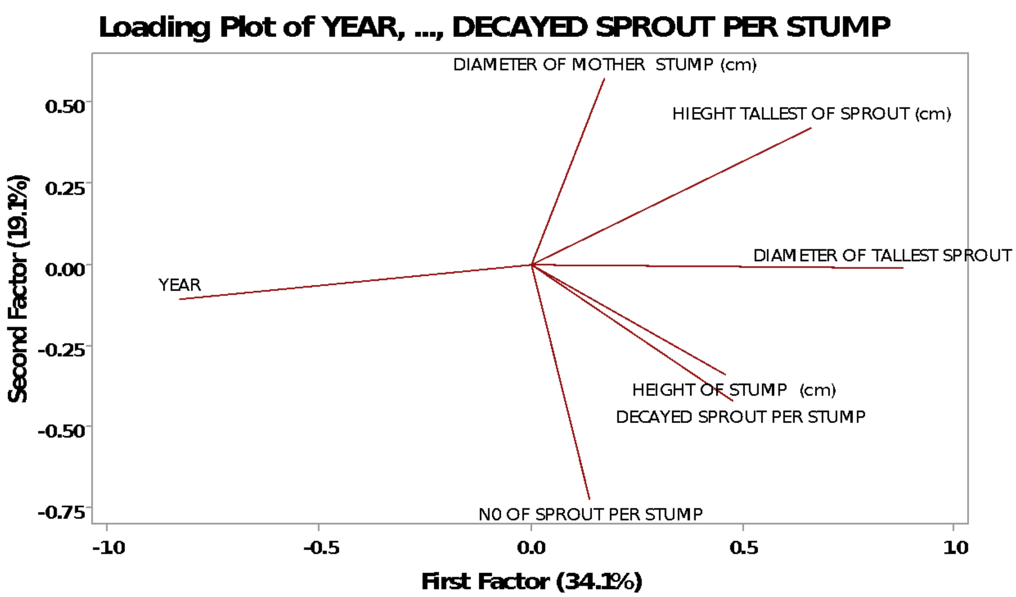

Figure 9. Loading of all variables in the principal component analysis.

between the height of the tallest sprouts and their basal diameter with a moderate correlation. There was also a significant relationship between the diameter of the tallest sprouts and the decaying state of the sprouts (P <0.001) signifying that as the diameter of the tallest sprout increased so did the decay of other sprouts (Table 2).

Principal component analysis (PCA) showed that the first factor contributed 34.1% and the second factor contributes 19.1% of the observed variation, with a communality of 66.6% (Figure 9 and Table 3) suggesting that the sprouting dynamics of the observed stumps could only be partially explained by the parameters measured.

The first two axes of the PCA for *N. diderrichii* explained 62.8% of the variance (Table 4 and Figure 10). The height of the stump correlated moderately negatively with the height of the tallest sprout indicating that as stump height increased sprout height decreased and the

Table 2. Spearman Rho (P-value) for all species.

Parameter	Year	Diameter of mother stump	Diameter of tallest sprout	Height of tallest sprout	Height of stump	Number of sprouts per stump
Diameter of mother stump	-	-	-	-	-	-
Diameter of tallest sprout	-	-0.028 (0.835)	-	-	-	-
Height of tallest sprout	-	0.287 (0.032)	0.462 (0.0005)	-	-	-
Height of stump	-0.197 (0.145)	-0.008 (0.951)	0.214 (0.113)	0.128 (0.346)	-	-
Number of sprouts per stump	-0.055 (0.688)	-0.107 (0.434)	0.112 (0.412)	-0.107 (0.434)	0.118 (0.385)	-
Decay sprout per stump	-0.367 (0.005)	0.065 (0.632)	0.447 (0.001)	0.081 (0.552)	0.183 (0.176)	0.224 (0.096)

Table 3. Principal component analysis of the correlation matrix for all sprouted stumps.

Variable	Factor 1	Factor 2	Factor 3	Communality
Year of harvest	-0.830	-0.110	0.191	0.737
Stump diameter (cm)	0.174	0.572	0.637	0.763
Tallest sprout diameter (cm)	0.880	-0.013	-0.235	0.829
Tallest sprout height (cm)	0.662	0.421	0.018	0.615
Stump height (cm)	0.461	-0.339	0.577	0.660
Sprouts per stump	0.139	-0.725	0.298	0.633
Decayed sprouts per stump	0.476	-0.422	-0.136	0.423
Variance	2.3881	1.3341	0.9379	4.6601
% Variance explained	34.1	19.1	13.4	66.6

Table 4. Principal component factor analysis of the correlation matrix for *Nauclea diderrichii*.

Variable	Factor 1	Factor 2	Communality
Diameter of Mother Stump (cm)	0.799	-0.375	-0.375
Diameter of Tallest Sprout (cm)	0.571	0.511	0.580
Height of Tallest Sprout (cm)	0.573	0.502	0.580
Height of Stemp (cm)	-0.505	-0.595	0.609
No. of Sprouts per Stump	0.638	-0.011	0.407
Decayed Sprouts per Stump	0.352	-0.801	0.765
Variance	1.7526	1.3869	3.1394
% Variance	35.1	27.7	62.8

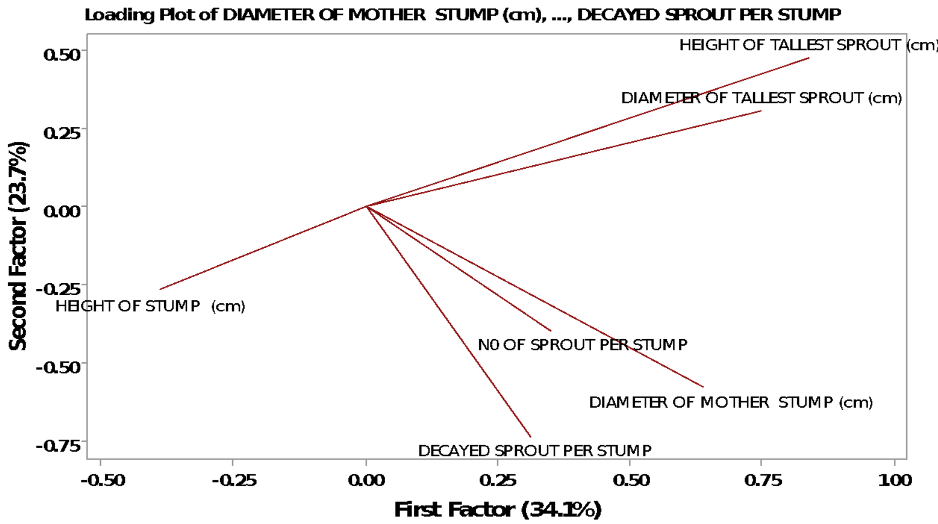

Figure 10. Loading for *Nauclea diderrichii* in the principal component analysis.

Table 5. Spearman Rho (P-value) for *Nauclea diderrichii*.

Variable	Diameter of Mother stump	Diameter of tallest sprout	Height of tallest sprout	Height of stump	Number of sprout per stump
Height of tallest sprout	0.236 (0.257)	-	-	-	-
Height of stump	-0.032 (0.880)	-	-0.595 (0.002)		-
Number of sprout per stump	0.290 (0.160)	-	0.018 (0.931)	-0.220 (0.290)	-
Decay sprout per stump	0.432 (0.031)	-	-0.133 (0.526)	0.174 (0.404)	0.195 (0.350)

Table 6. Model parameters for predicting the number of sprouts.

Species	Variable	R^2	Coefficient	SE	*t*-value	*p*-value
All species	Intercept	5.4	0.62	0.35	1.73	0.090
	Stump diameter		-0.0026	0.0030	-0.87	0.386
	Stump height		0.0049	0.0032	1.53	0.131
Nauclea diderrichii	Intercept	11.9	-0.90	1.73	-0.52	0.610
	Stump diameter		0.0295	0.0167	1.76	0.091

diameter of mother stump correlated moderately with decayed sprouts. These interactions were significant (P<0.002) and (P<0.031) respectively (Table 5). The correlations amongst stump sprouting parameters were not statistically significant (Table 8).

Neither the equation for predicting the number of sprouts for all species together or for *N. diderrichii* (Plate 1a and b) by itself were significant, although the latter relationship was stronger (Table 6). Thus, it is likely that stronger relationships might have been found if there were enough observations to separate the overall data by species or species cohort.

The diameter of the tallest sprout can be used to predict the height of the tallest sprout for all the species together (Table 7). Similarly, the diameter of the mother stump, the diameter of the tallest sprout, the height of the stump, and the decay level of the sprouts can predict the height of the tallest sprout for *N. diderrichii*. Again, it is likely that stronger relationships could be established if there were sufficient observations to allow species-specific equations to be fit for all species that sprouted.

The decaying state of the sprouts and the height of the

Table 7. Model parameters for predicting the height of the tallest sprout.

Species	Variable	R^2	Coefficient	SE	*t*-value	*p*-value
All species	Intercept	34.05	-166.4	75.5	-2.20	0.033
	Sprout diameter		30.91	6.64	4.66	0.000
Nauclea diderrichii	Intercept	81.92	-302	103	-2.93	0.008
	Stump diameter		2.533	0.862	2.94	0.008
	Sprout diameter		28.31	3.51	8.07	0.000
	Stump height		-1.231	0.514	-2.39	0.027
	Sprout decay		-205.2	53.8	-3.81	0.001

Table 8. Model parameters for predicting the diameter of the tallest sprouts.

Species	Variable	R^2	Coefficient	SE	*t*-value	*p*-value
All species	Intercept	37.86	8.737	0.556	15.71	0.000
	Sprout decay		2.029	0.667	3.04	0.004
	Sprout height		0.0105	0.0022	4.74	0.000
Nauclea diderrichii	Intercept	74.11	-34.6	56.3	-0.61	0.545
	Sprout diameter		28.97	4.09	7.09	0.000
	Stump height		-1.523	0.590	-2.58	0.017
	Sprout decay		-134.6	56.3	-2.39	0.026

Plate 1.a and b: Sprouted Stump of *Nauclea diderrichii*

tallest sprouts can be used to predict the diameter of the tallest sprouts for all species together (Table 8). Similarly, for *N. diderrichii,* the diameter of the stump, the height of the tallest sprouts, the height of stump and the decaying state of the sprouts can be used to predict the diameter of tallest sprout.

DISCUSSION

Timber species that sprout in the Akak forest after logging and distribution of sprouted stumps

Thirteen of the twenty harvested tree species sprouted after logging. Sprouting differed among stump diameter classes, with the highest number of sprouts found in stumps with 81 to 100 cm top diameters (Figures 2, 3 and 5). The highest number of sprouts was recorded 3 years after logging from stumps with 41 to 60 cm top diameters (Figure 5). This in contrasts with Gould et al. (2007) who indicated that most hardwood species sprout from small diameter stumps. The least number of sprouts were observed in the 121 to 140 cm diameter class. This is in line with Johnson (1977) and McGee (1978) who postulated that as the stump diameter increases, the number of sprouts reduces.

N. diderrichii, *P. soyauxii*, *T. ivorensis,* and *P. africanum* displayed considerable variability in sprouting response after logging (Figure 2). This result agrees with Benjamin et al. (2017) who found high sprouting probabilities across at least some parent tree sizes in their study. The small number of sprouts for *Distemonanthus benthamia*, *Lannea welwitschi*, *Staudtia Kamerunesis*, *Mitragyna ciliate,* and *M. excels* agrees with Wolfe and Pittillo (1977), Barnes (1985) and Stanturf et al. (2001) who found relatively low sprouting probabilities or low sprout persistence in their studies.

Johnson (1977) showed that four-year shoot elongation of the tallest stem among white and black oak increased as stump diameter increased up to a threshold of 6 inches (15.24 cm), and that, among black and white oak stump sprouts examined in southern Indiana, white oak had a marginal height advantage (Johnson, 1977). The present results showed a relatively high mean height with stump diameter that ranges from 121 to 140 for the year 2013, followed by the year 2015 as opposed to the year 2017 with relatively low sprout height.

Relationships between sprouting characteristics (number of sprouts per stump, height of the dominant sprout, diameter of the dominant sprout, height, and diameter of mother stump) for all the species and species with the highest number of stump sprouts (*N. diderrichii*)

It was found that the stump diameter can be used to predict the height of the tallest sprouts and the diameter of tallest sprouts *N. diderrichii* (Tables 3 and 4). This result agrees with many other studies. Sprouting ability is influenced by the amount of accumulated reserves in the stump and/or the activity of underground buds. Bigger stumps have more reserves and/or more active underground buds; therefore, bigger stump tends to produce more sprouts (Cirne and Scarano, 2001; Miura and Yamamoto, 2003; Ickes et al., 2003).

It was found that stump height and stump diameter influenced the height of the sprouts (Table 6). Sander (1971) noted that the early height growth of sprouts present after clear-cuts depended on the size of the stumps from which they originate, with sprouts from the largest stumps growing the fastest, with the most sprouts. For *N. diderrichii,* the height of the sprouts decreased with an increase in stump height (Table 8), in line with the findings of Johnson (1977), McGee (1978) and Gould et al. (2007).

None of the regression equations for predicting the number of sprouts were significant for all species together and for *N. diderrichii* alone (Table 2). This is in contrast to DeBell (1971) and El Houri (1977) who found an increase in sprouting with an increase in stump height working with other species. Harrington (1984) also reported that sprouting in red alder (*Alnus rubra*) was poor when the stumps were cut low. This may be due to the number of dormant or trace buds being small on such stumps (Hook and DeBell, 1970).

The first two axes of the PCA explained 62.8% of the variance for *N. diderrichii* (Figure 8). This indicates that there are other unmeasured parameters, such as soils, predation, and climate that could influence sprouting (Poskin, 1949). Stump height correlated moderately negative with the height of the tallest sprout ($P<0.002$). Shackleton (2001) also noted a negative correlation between the stump size and the shoot coppice lengths in the regrowth of an indigenous savannah tree species (*Terminalia sericea*). Khan and Tripathi (1986), working in northeast India, found decreasing coppicing with increasing stump size for four sub-tropical forest species. They thought this to be caused by the increased bark thickness of larger stems hindering the emergence of buds.

In general, sprouting contributes to a life history strategy of persistence that has been associated with root carbohydrate storage, relatively high root to shoot ratios, slow initial rates of shoot growth for true seedlings, large seeds, and relatively low seed production (Kruger et al., 1997; Bellingham and Sparrow, 2000; Bond and Midgley, 2001). Sprouting is important for promoting regeneration, especially of logged timber species, and for the overall dynamics of forest stands (Putz and Brokaw, 1989; Kammesheidt, 1998; Miura and Yamamoto, 2003). Thirteen of the 20 species harvested were found sometimes to produce sprouts, although sprouting was not consistent among the three logging areas and years examined. This could be due to anthropogenic, ecological, and environmental factors that were not measured (Poskin, 1949; Salk et al., 2011).

While stump sprouting appears to be an important mechanism of regeneration of some tropical timber species, seedling regeneration, either natural or artificial, must occur for the site to completely recover. Forest managers could have reduced the cost of artificial seedling regeneration by applying silvicultural treatments on sprouting species such as *N. diderrichii, P. soyauxii, P. africanum* and *T. ivorensis* which has a high ability of sprouting. Long-term research is necessary to monitor the growth and examine several unknowns concerning the role of stump sprouts in successful site recovery following harvesting. These include long-term sprout survival (including the impact of stump damage on survival), the quality of sprout-produced trees, and environmental and ecological factors influencing tropical tree species ability to sprout.

Clear cutting often prevents stumps from reaching an age and diameter in which sprouting declines rapidly (Johnson et al., 2002). Stump diameter is known to be an important predictor of sprouting probability (Johnson et al., 2002; Dey and Jensen, 2002).

Stump sprouts have the potential to grow quickly within the first ten years due to the large root mass and stored carbohydrates. Multiple flushes in growth can occur even under drought conditions, whereas most other growth forms are subject to single flushing (Johnson et al., 2002). Thinning of sprouts relatively early after harvest may improve growth rates of high-quality sprouts, resulting in mature stems with better growth form for future harvest and rapidly creating oaks capable of mast production (Johnson et al., 2002). Similar to other regeneration methods, site preparation methods aimed at reducing competitive vegetation before harvest, may be vital even for stump sprout regeneration. Harvesting timber at a relatively high diameter between 81 and 141 cm may have a greater probability of becoming the primary constituent in the future forest composition.

Conclusion

In this study, it was found out that 13 timber species sprouts in the Akak rain forest, *N. diderrichii* was the most frequent sprouted. Principal component analysis tells us that the relationship between sprouting parameters both for all the species combined and *N. diderrichii* could only partially be explained by the variables measured. Sprout diameter, stump diameter, stump height and sprout decay could be used to predict the height of the tallest sprout while sprout height, stump diameter and sprout decay could be used to predict the diameter of the tallest sprout. These predicting models could help in predicting the future growth rate and stand of the tropical rainforest.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interest.

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An assessment and local perception of sand deposits induced desertification in Sokoto State, Nigeria

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Sokoto State is one of the states in Nigeria that are prone to desertification. This study attempts to identify and delimit areas affected by desertification in the three northernmost Local Government Areas of Sokoto State, namely: Illela, Gada and Tangaza. Field study was carried out to verify the incident and occurrence of desertification and the menace of sand deposition. A simple random sampling method with questionnaire, combined with Focused Group Discussions and Key Informant Interviews was used to derive the local knowledge about sand transport and deposition, and, its socio-environmental impacts. The Digital Elevation Model of Tangaza, Gada, and Illela Local Government Areas for the year 2008 and 2014 were derived from ASTER images. The result indicated that the Gidan Kaura hill grew by about 30 m within the six-year period. This agreed with an overwhelming belief by 95% of the respondents that the area continues to suffer from sandstorms and sand deposition. This was visibly confirmed by the presence of sand dunes in most of the areas visited in the three local government areas. Normalized Difference Vegetation Index derived from Landsat images of the year 2013 and 2018 gave further insight into the current vegetation conditions.

Key words: Northern Nigeria, desertification, sustainability, geospatial analyses, environmental impacts.

INTRODUCTION

Desertification is a global environmental problem. It is defined as land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors including climatic variations and human activities (UN, 1992; Olagunju, 2015). Similarly, from the point of view of Jamala et al. (2013), desertification represents any process that intensifies or extends desert conditions, leading to reduction in biological yield, impacting biomass production negatively, resulting in insufficient land area for livestock management and reduced crop production to satisfy human nutritional needs. Some of the climatic variations that have been implicated in drought and

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desertification include increased sea-surface temperature (Giannini et al., 2003), rainfall shortages or drought (Dai et al., 2004) and sand transportation and deposition (Ikazaki, 2015); while the implicated human activities in desertification include deforestation, over-grazing and unsustainable fuel-wood harvesting that lead to reduced vegetation cover (Tucker et al., 1991).

Desertification was first addressed as a global environmental menace with profound socio-economic and environmental impacts in the United Nations Conference (UNCOD) on Desertification in 1977. The Conference led to the adoption of a Plan of Action to Combat Desertification (PACD), to which Nigeria is a signatory. This early global realization of the environmental menace of desertification and the capability of its transboundary extension necessitated the call by the UN General Assembly in Rio de Janeiro, Brazil in 1992, for an inter-governmental committee to prepare for a legally binding instruction that addresses the problem of desertification (UN, 1992). According to UNCCD (2013), desertification and drought are responsible for rapid increase in price indices of food stuff and other commodities. The impact of desertification on the socio-economic life of rural households leads to reduction in crop and animal production, as well as causing livestock deaths and rise in the prices of foodstuffs. People migrate as a consequence of drought and desertification to urban areas or to other rural areas, in order to engage in economic activities such as farming, grazing and fishing (Olagunju, 2015). Migration impact on family life leads to disruption of family ties. Viewed over a broad spectrum, other identified factors causing desertification include excessive wood extraction (Jamala et al*.,* 2013) for fuel exacerbated by increasing population and urbanization, and over-cultivation of marginal land.

The northernmost States of Nigeria, with an annual mean rainfall of less than 600 mm per year (Folaji, 2007) have been described as susceptible to desertification (Mohammed, 2015). In response to the menace of desertification, one of the Nigerian Government's efforts in combating desertification was through the Global Tree Planting Project, which started in 2005. The project was aimed at halting desert encroachment in 46 LGAs in the country's desertification frontline States. A 5 km tree planting in each LGA of Sokoto State was initiated under the oil Subsidy Reinvestment and Empowerment Programme (Sure-P). The Sure-P was a programme of the Federal Government of Nigeria, to ameliorate youth unemployment (Ugwu, 2012). Expectedly, all the efforts were confined to the northernmost part of Nigeria, where the menace is most prevalent (Olagunju, 2015). However, studies (Linacre and Geerts, 2002; Geist and Lambin, 2004) generally attempted to denounce this fact, by describing desertification as a succession of cycles of drought interspersed with high rainfall periods. However, with the rampaging ethno-religious insurgency prevailing in the most part of northern Nigeria, covering of the whole north as would have been expedient in this study became impossible. Consequently, Sokoto State, which is not affected by the Boko Haram insurgency was selected as the study area for the purpose of ease of accessibility to the affected sites and safely carrying out field observations. Therefore, the aim of this study was to carry out assessment of desertification or desert encroachment in northernmost part of Sokoto State of Nigeria.

Studies on the Sahel region of Africa (Eklundh and Sjolstrom, 2003; Aiguo et al., 2004) have focused on using time series medium resolution optical satellite image to track variations in Normalized Difference Vegetation Index (NDVI). The Earth observation satellite images that were used in other studies (Martin and Saha, 2009; Dasgupta et al., 2015) gave insight into environmental conditions of physically inaccessible terrains and large landscape that could not have been done through conventional ground-based survey methods. Given that desertification occurs over a long-term period, the accurate identification of affected areas will necessarily require time-series data rather than single datasets. The specific objectives are to carry out *in-situ* observations to identify specific areas of occurrence; and examine the local socio-environmental factors that are responsible for its occurrence. This study combined *in-situ* surveys with the Earth observation approaches adopted in the aforementioned previous studies to attempt to understand the local socio-cultural, economic and environmental impacts of desertification in the study area.

Study area

Sokoto lies on the north-west zone of Nigeria and shares its borders with Niger Republic to the north, Katsina State to the East, Niger State to the South-east, Kwara State to the South and Benin Republic to the west. The zone is found between latitudes 10°N and 13°58' N; and longitudes 4° 8'E and 6^0 54' E. The area so defined covers a land area of approximately 62,000 km^2 (Ekpoh and Nsa, 2011). The climate of the zone is controlled largely by the dry, dusty, tropical- continental air mass originating from the Sahara desert, and the warm, tropical-maritime air mass originating from the Atlantic Ocean. The influence of both air masses on the region is determined largely by the movement of the Inter-Tropical Convergence Zone (ITCZ), a zone representing the surface demarcation between the two air masses (Ekpoh and Nsa, 2011). The interplay of these two air masses gives rise to the wet season associated with the tropical maritime air mass, and the dry season, associated with the tropical continental air mass. The temperature ranges between 35 and 40°C, while the warmest months are February, March and April when daytime temperatures can exceed 45°C. The combined effects of temperature,

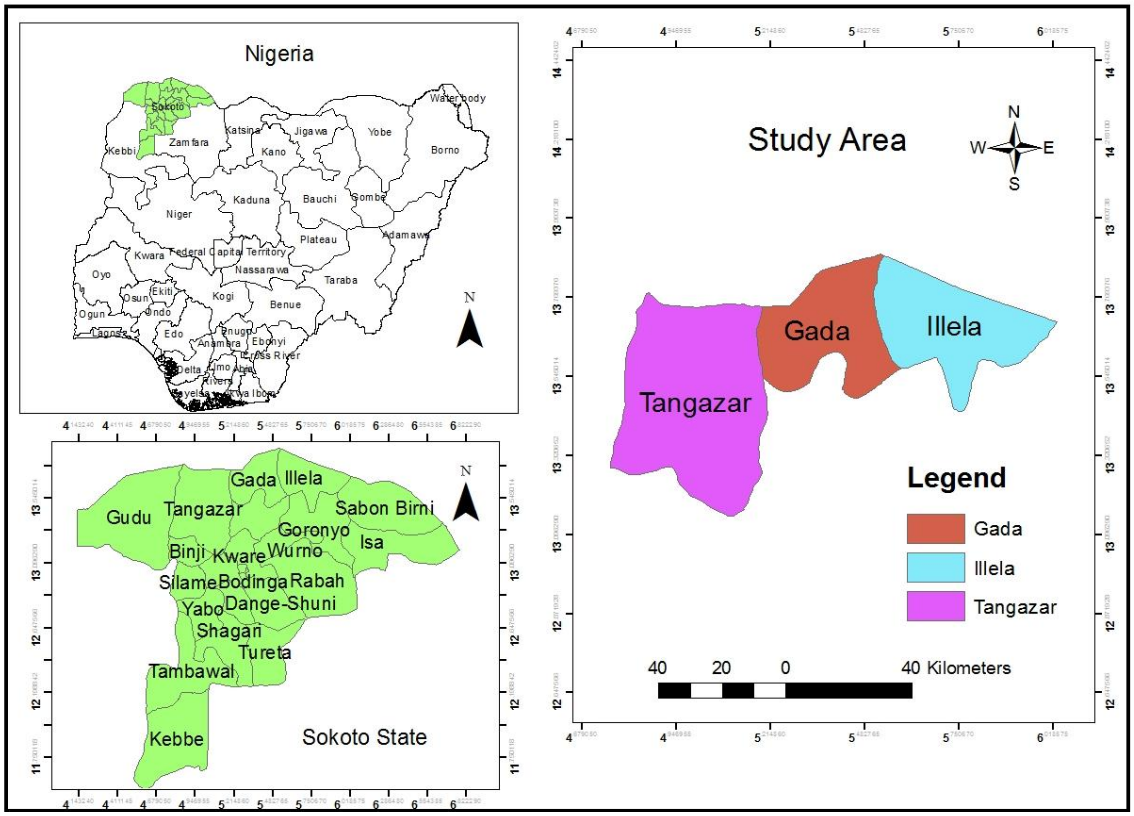

Figure 1. Gada, Illela and Tangaza Local Government Areas in Sokoto State.

humidity, rainfall, and other climatic variation, determine the different types of vegetation belts in the zones and the types of the indigenous or exotic crops that are and can be grown in Nigeria (Adetiloye et al., 2006).

Three northernmost Local Government Areas of Illela, Gada and Tangaza of Sokoto State (Figure 1) were selected to gather information on desertification; and, its impacts on the people and environment. Illela is on Latitude 13°43′ N and Longitude 5°18′ E with an area of 1,246 km²; Gada is located on Latitude 13°46′ N and Longitude 5°40′ E with an area of 1,315 km²; and, Tangaza, is located in Latitude 13° 31′ N and Longitude 4° 58′ E with an area of 2,477 km². Illela, Gada and Tangaza has a population of 248,267, 150,489 and 113,853, respectively (NPC, 2006). The study area is characterized by high wind speed with attendant transport and deposition of sand particles. It has few and scattered shrubs, with plantations of Neem (*Azadirachta indica*) trees serving as shelter belts, occupying many areas of the landscape. The three Local Government Areas share contiguous borders with the Niger Republic to the north. Across the three Local Government Areas, the field study took place in five areas, located at the Government Day Secondary School and Kalmalo village in Illela; Sabon-Gari Gidan Kaura village in Gada; and, Ruwa Wuri and Tsoni Gabas in Tangaza. These areas were affected by sand transport and deposition, with a massive presence of sand dunes.

METHODOLOGY

In order to gain access into the local communities of each Local Government Areas, for the purpose of field sampling, the team visited and got the permission of the local heads. At the community level, a total of 258 copies of a structured questionnaire were administered, using a simple random sampling method to derive local knowledge on sand transport and deposition, and the socio-environmental impacts. Key Informant Interviews (KIIs) and Focus Group Discussions (FGDs) were conducted with the Local District Heads and the local people, respectively, to receive their personal and communal perceptions on the occurrence of desertification in their environment. Respondent's feedbacks from the questionnaire were categorized as 'Yes, No and Don't Know' and analyzed descriptively. The insights gained from the FGDs and KIIs were used in the interpretation of the results. Areas of some biophysical features such as tree plantation, farmland and water body were visited to observe how they may have been affected by desertification and sand deposition. The Digital Elevation Model of Illela, Gada and Tangaza Local Government Areas for 2008 and 2014 were derived from ASTER images. The condition of vegetation in the study area was measured by Normalized Difference Vegetation Index (NDVI) using the dry season Landsat images of 2013 and 2018. NDVI was calculated according to Sahebjalal and Dashtekian (2013). All the geospatial analyses were performed in the Quantity GIS and ERDAS Imagine environments.

Plate 1. Sand dunes being quarried.

Plate 2. Neem trees as wind breakers.

Plate 3. Site of former River Kalmalo.

RESULTS AND DISCUSSION

Illela local government area

There was an expansive sand deposition around the Government Day Secondary School premises, Illela (Plate 1). High wind currents, lifting and carrying sand particles were observed in this area. This informed the earlier effort of the school authority to plant Neem trees around the premises as wind breakers (Plate 2). Neem trees are drought-resistant and are common landscape features, often grown to serve as shelterbelts and sun shield in the northern parts of Nigeria (Adesina and Gadiga, 2014).

In Kalmalo village, the former site of River Kalmalo (Plates 3 and 4), which is now dried up, once served as a source of fishing and irrigation for the local people. Findings from the Focus Group Discussions revealed two factors to be responsible for the drying up of River Kalmalo. First, the river was fed by River Magiya Lamido in Niger Republic, which was dammed at the upstream in the Niger, thus cutting off the source of River Kalmalo. Second, the river dried up due to secondary reason of sand deposition and siltation.

The villagers had therefore resorted to digging wells and drilling boreholes for their livelihood and dry season irrigation farming activities - an essential part of the socio-economic activity of the people; and, also to develop shelterbelts. According to Adesina and Gadiga (2014), shelterbelts are the most effective and environmentally friendly approach to achieving success in combating desertification in the arid and semi-arid environments.

Gada local government area

Plate 5 is the site of historic Kaddi Tudu village that was submerged overnight by rapid deposition of sand. Due to the tragedy, the community re-settled in Sabon-Gari GidanKaura (Plates 5 and 6). Enormous deposits of sand with elevation up to 338 m were observed at Kaddi Tudu, which contrasted sharply with the new settlement - Sabon-Gari GidanKaura, with an elevation of 284 m. It was observed that the neem plantation in the area was failing but still shelters the soil from erosion by reducing the rate of sand movement. The local people also made wells and boreholes to irrigate their farmlands and the shelter trees, to reduce desertification.

Tangaza local government area

At Ruwan Wuri, it was observed that deposition of sand takes place intermittently, settling on and destroying crops. The only lake in the area called Lake Karereyi (Plate 7), has dried up in response to the prevailing dry season. At Tsoni Gabas, the team observed a large area of fresh sand deposits (Plate 8) caused by the presence of hills and mountains acting as natural interceptions; and, farm fences acting as barriers to sand transport.

In contrast to the areas earlier visited, there were no noticeable planted shelterbelts to provide shelter from the wind and to protect soil from erosion in the whole area.

Plate 4. Interview with the village Head of Kalmalo.

Plate 5. Site of the extinct KaddiTudu.

Plate 6. Sabon-Gari Gidan Kaura.

Plate 7. Site of Lake Karereyi.

Plate 8. Fresh sand deposits at TsoniGabas.

Plate 9. Natural local surface relief.

Rather, the natural surface relief and farm fences acted as barriers to sand transport, leading to sand deposition and dune formation on the landscape (Plate 9).

Impacts on sustainable livelihood

Out of the total questionnaire administered, 162 copies

Table 1. Effects on local livelihood.

Research questions	Yes	%	No	%	DK	%
Are you aware of desertification?	67	86	11	14	0	0
Does desertification affect your economic livelihood?	62	79	7	9	9	11
Is desertification increasing over the years?	54	69	18	23	6	8
Is desertification affecting agricultural production?	69	90	1	1	7	9

Table 2. Social effects.

Research questions	Yes	%	No	%	DK	%
Is desertification contributing to underdevelopment?	52	67	19	24	7	9
Is your community making effort to reduce desertification?	66	85	1	15	11	14
Is your community committed to tree planting?	72	92	4	5	2	3
Is desertification affecting health and safety of the people?	57	73	9	12	12	15
Does sand overrun farmlands/communities?	62	80	5	6	11	14
Did the human population increase over the last 10 years?	65	83	7	9	6	8

Table 3. Effects on the environment.

Research questions	Yes	%	No	%	DK	%
Has your community been losing vegetated land to sand doom?	57	73	8	10	13	17
Do people use firewood and charcoal for cooking?	78	100	0	0	0	0
Is there any plan by government to reduce the rate of loss of vegetated land through tree planting, damming and irrigation?	62	79	3	4	13	17
Has there been a noticeable decrease in rainfall over the recent past years?	53	68	23	29	2	3
Has there been increase in temperature in this area in recent past years?	64	84	9	12	3	4
Do you experience Sand storms?	74	95	4	5	0	0

were recovered while only 78 were valid. The low validity could be attributed to the low level of education among many of the respondents. The interviewees expressed strong conviction that desertification poses a direct threat to their environmental sustainability, which validated and further established the findings from the questionnaire. Table 1 shows that 67 respondents, making 86% of the total sampled were aware of the impacts of desertification while 14% claimed not to be aware. The high rate of awareness of the impact of desertification will explain why 79% of the respondents believed desertification affected their economic livelihood and 69% believed that the rate of desertification has increased over the years. Even though, 90% agreed desertification affected agricultural production, farm yields over the years in the area were considered to have increased by 60% of the respondents, while 40% of the respondents considered farm yields have decreased. The increase in farm yield may not be unconnected with the prevailing practice of irrigation with which water sourced from wells and boreholes are used in irrigating farmlands off rainy season.

In Table 2, 67% of the respondent believed desertification is contributing to underdevelopment in the community and 85% of the respondents informed of the determination of the members of the local communities to reduce the rate of desertification, through the cultivation of tree plantation as agreed to by 92% of the respondents. A majority represented by 73% believed desertification is affecting the health and safety of the people living in the community.

Some of the effects are the frequent overrunning of farmlands and the communities by sand as agreed to by 80% of the respondents. Despite the menace that desertification poses in the communities, 83% of the respondents believed there has been an increase in the local population in the last 10 years.

In Table 3, it can be observed that the vegetation in the communities is being lost to desertification, caused by sand deposition as indicated by 73% of the respondents. This was corroborated by all the respondents, who said firewood and charcoal are predominantly used for domestic cooking. Nevertheless, other respondents (79%) agreed government is embarking on tree planting, dam

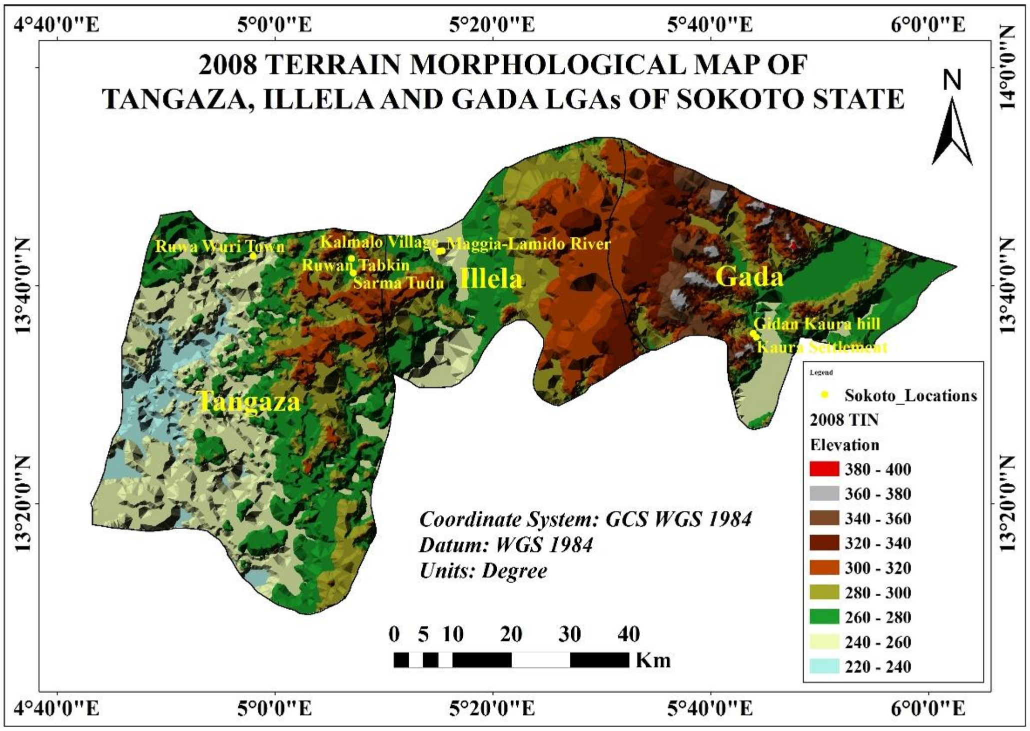

Figure 2. Terrain morphology of the study area in 2008.

construction and irrigation projects in the area. There was a general belief (68%) that rainfall has decreased, while 84% believed that temperature has increased in recent time in the study area. There was an overwhelming belief by 95% that the area continues to suffer from sandstorms and deposition. This was visibly confirmed by the presence of sand dunes in most of the areas visited by the research team.

Elevation changes

The Digital Elevation Model (DEM) of Tangaza, Gada, and Illela Local government areas of the year 2008 and 2014 are derived from ASTER images (Figures 2 and 3). From the two elevation images it can be clearly observed that the elevation of the areas is rapidly changing. It is clearly noticed that in the 2008, the highest height in GidanKaura Settlement in Gada local government was about 380 metres above sea level (Figure 4). However, by the year 2014 the terrain morphology map indicated changes in the height of the area in Gidan Kaura settlement was about 410 metres (Figure 5). Therefore, these results indicated that the Gidan Kaura hill grew by about 30 metres within the six-year period. Interestingly, these results correlated with the information obtained from the field survey at the Gidan Kaura settlement as expressed by the people living in the area that sand deposition has increased in recent time.

The findings show that the year 2018 had the highest NDVI values of 0.34 (17%) and 0.59 (9%). These NDVI values were higher than the values in 2013 with 0.34 (15%) and 0.59 (8%) respectively (Table 4). The NDVI values range between -1 and +1, while numbers between 0 and -1 suggest non-vegetated surfaces or distressed vegetation; healthy vegetated surfaces have NDVI values tending towards +1. The differences in the NDVI findings in this study can be attributed to the increase in farm yield, which may not be unconnected to the prevailing practice of irrigation in the northern parts of Nigeria (Ajiboye and Osundare, 2015). The farmlands and shelterbelts in the study area were irrigated with watersourced from wells and boreholes. However, it is important to note that the decreased NDVI values observed in the year 2018 in Tangaza and Illela Local areas (Figure 6) as against the NDVI values in Figure 7 can be attributed to drought. The drought was occasioned by the loss of water from River Magiya Lamido that was dammed in Niger Republic. The daming cut off the source of River Kalmalo, and in addition to sand deposition and siltation, the river dried up.

Conclusion

The study was able to establish that desertification is real and impacting negatively on the sustainable livelihood of the people in the study area. The findings from field work

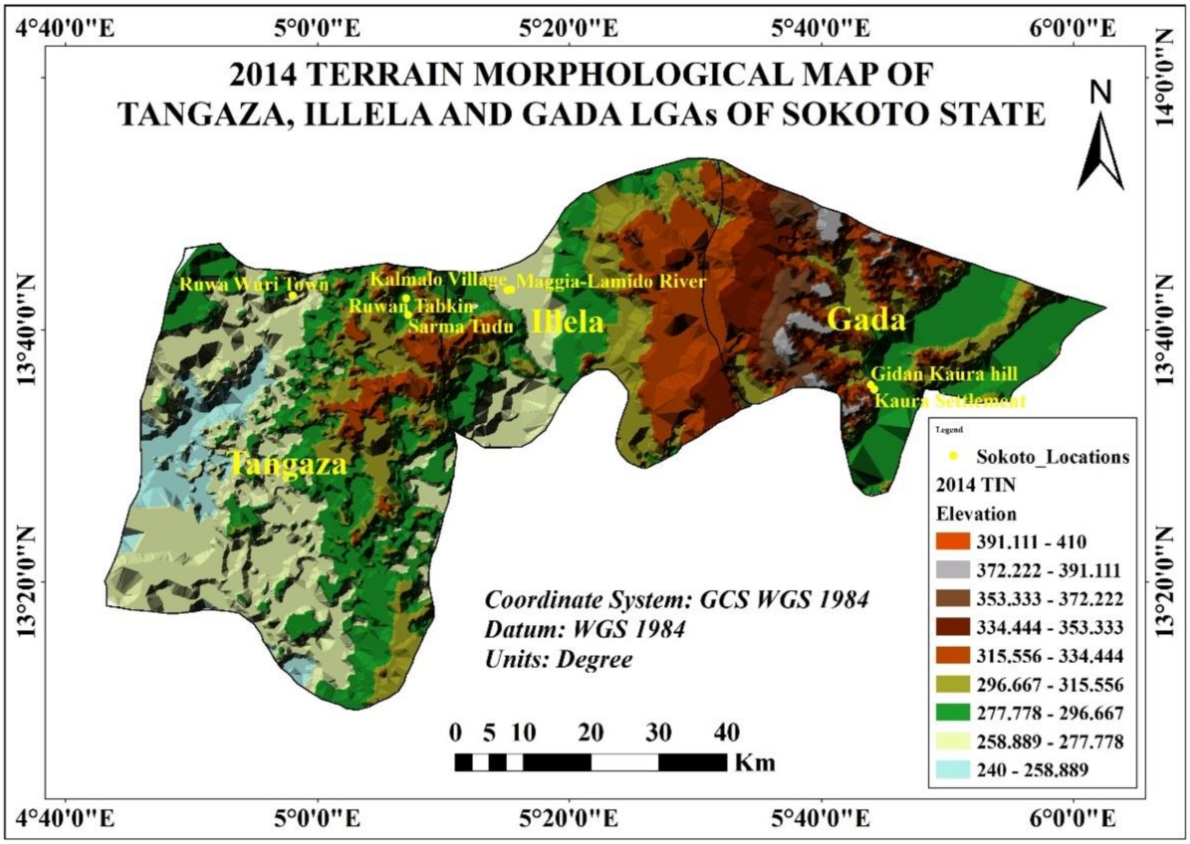

Figure 3. Terrain morphology of the study area in 2014.

Figure 4. Gada terrain morphology in 2008.

confirmed that there is frequent deposition of sand that destroys crops and causes siltation in the open surface waters in the communities. However, desertification was not seen to be advancing due to the effort of both government and the local inhabitants to farm the surfaces of the dunes and other sand depositions. Farming of the

Figure 5. Gada terrain morphology in 2014.

Table 4. NDVI analysis.

NDVI values	Area (2003)		Area (2008)	
	Ha	%	Ha	%
0.18	80276.31	65	77444.91	63
0.26	15108.75	12	13360.68	11
0.34	17834.4	15	21289.14	17
0.59	9340.38	8	10465.11	0

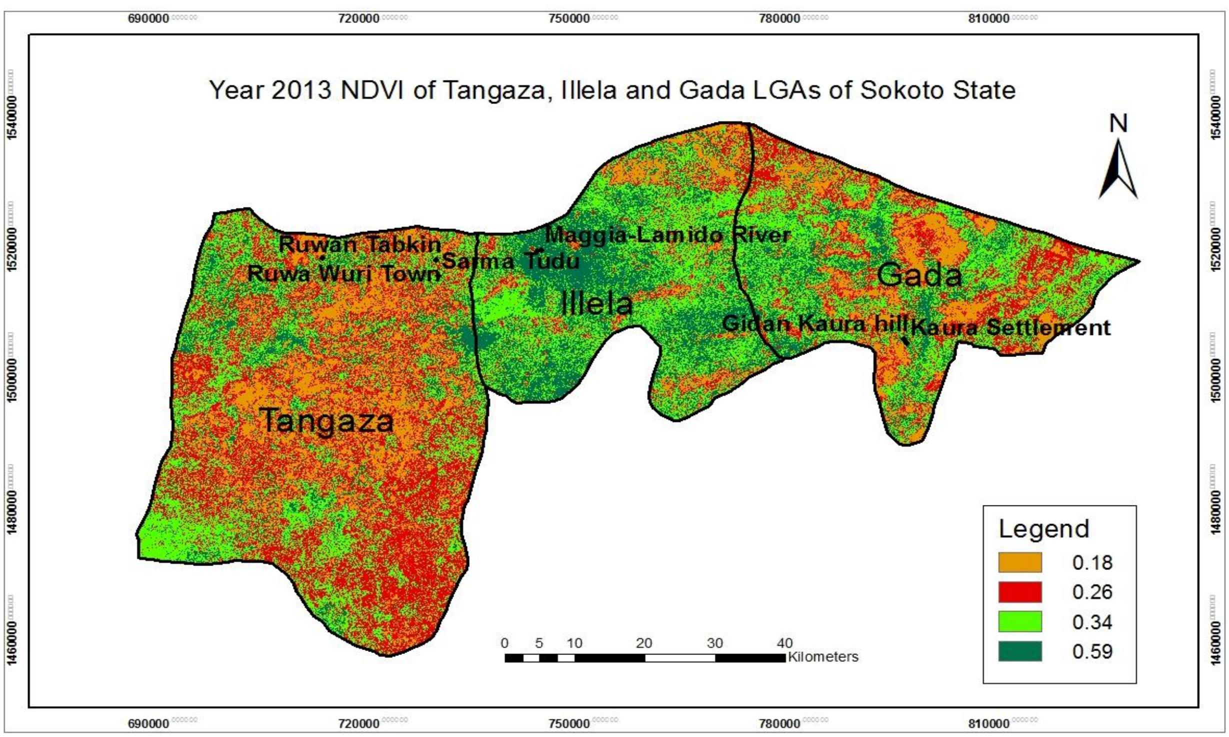

Figure 6. Spatial distribution of NDVI values in the study area in 2013.

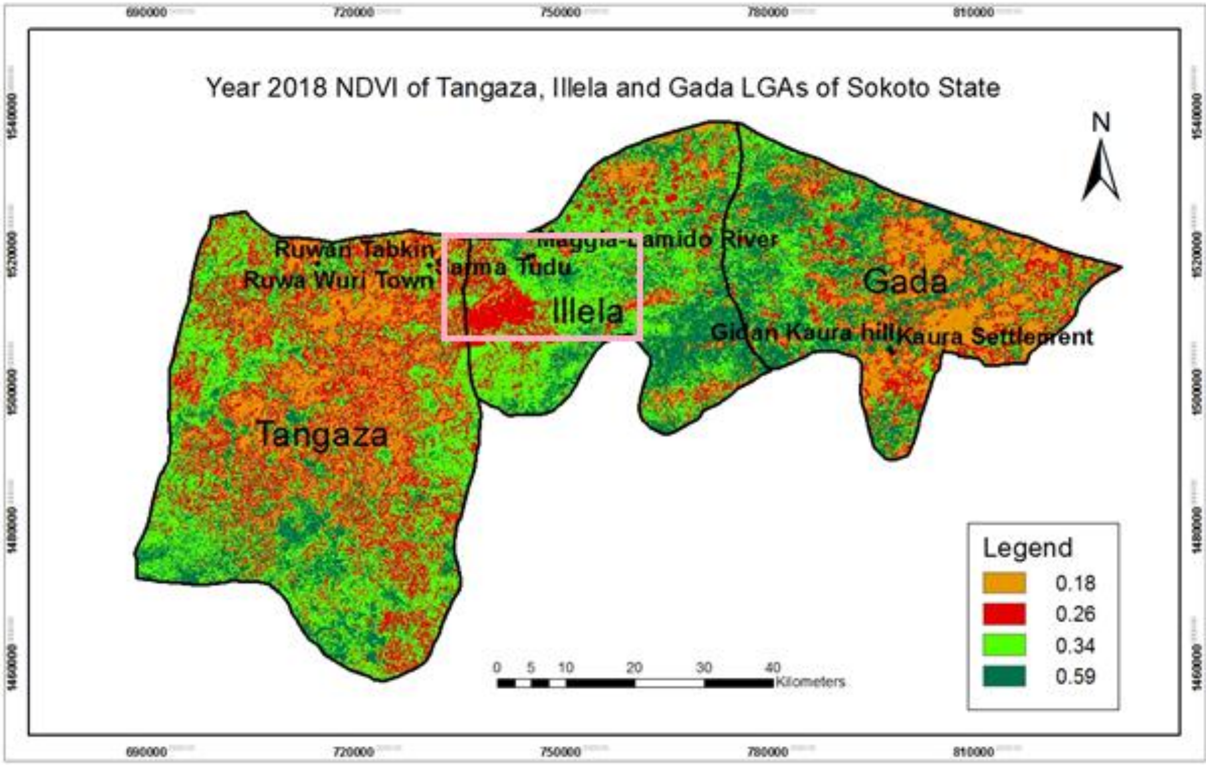

Figure 7. Spatial distribution of NDVI values in the study area in 2018.

surfaces of the sand dunes ensures continuous food provision and further, leads to soil compaction, which slows down sand transport. Other efforts at halting expansion of sand dunes and improving the livelihood of the people included the creation of shelterbelts and fences that act as barriers to widespread sand transport and deposition. Therefore, there is an urgent need for increased commitment to tree planting and proper management of existing shelterbelts to mitigate desertification in the affected areas. There is also the need for government to invest more in water project, especially for dry season farming and irrigation to sustain agricultural production that will promote sustainable livelihood of the people. This will also lead to increased greenery in the affected areas, which is able to slow down desertification. Desertification constitutes a significant menace to pastoralism and agriculture which are the major sources of food provisioning and livelihood in the affected local communities. If left unmonitored and unchecked, this situation may lead to a full-blown desert condition with all its attendant negative impacts on the people and sustainability of the environment.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Structure of *Acacia senegal* (L.) wild settlements in southwest Niger: Case of the gum tree site in the rural district of Guéchémé

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This study conducted in the rural district of Guéchémé (Tibiri county, Dosso region, Niger) aims at characterizing *Acacia senegal* settlements of the village of Lido. The methodology consisted in floristic sampling of 1000 m^2 plots, measuring diameters 20 cm off the ground for shrubs and 1.30 m for trees. The results made it possible to determine the structure of *A. senegal*, representing significant densities (238.75 plants/ha). The species represent a high regeneration rate on the site (24.71%) but with an increasing mortality rate over time. The diameter variations and average heights among plants of different plantation years are not significant. In contrast, the average annual growth variations in terms of diameter and height are not significant ($p = 0.005$). The settlements represent a shrubby structure, the C-shape parameter valued at 3.6 ($1 < C < 3.6$), feature a positive or right asymmetric distribution of monospecific settlements with dominant younger plants or plants with smaller diameters.

Key words: *Acacia senegal*, Guéchémé, Niger, structures.

INTRODUCTION

Tropical ecosystems constitute the basis for the existence of the majority of our planet's population. In fact, in the world, approximately one million people get their revenues from using wild natural resources (Garba et al., 2019). Africa is one of the richest continents in terms of biodiversity (Wieringa and Poorter, 2004). Forest exploitation is the main sources of revenue in the economies of several African countries. The intensive practice of this activity leads to the degradation of many forests and natural habitats as well as the rarefaction of several species (FAO, 2018). In Africa, 25 to 42% of plant species could be at risk of extinction due to the loss of 81 to 97% of favorable habitats by 2085 (Fandohan et al., 2013). The Sahel region is experiencing profound

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changes. With recurrent droughts, we observe a gradual degradation of ecosystems (Grouzis and Albergel, 1991) and a decrease of natural grazing lands. In Niger, the Sahelian zone corresponding to the forest and pastoral area is featured by steppes and savannahs with shrubs and trees dominated by spiny plants, essentially the Acacias. These woody settlements play a key role in the lives of populations in the Sahel. In Niger, the survey found and estimated annual production of 139.960 tons of arabic gum value at near 119 million CFA francs (Seybou et al., 2016).

In addition to the fodder relay that these woody settlements represent during the dry season, they constitute a dietary supplement and are used as service wood, lumber, medicines by local populations (Lykke et al., 2004). Nonetheless, these plant resources have been undergoing a significant degradation because of climate pejoration and anthropism for decades now (Sarr, 2008). These changes have triggered an ecological imbalance in the ecosystems, namely the activation of dunes previously fixed by vegetation (Pierre, 2004). Among these main fruit trees highly appreciated by local populations we have: *Ziziphus mauritiana* Lam., *Balanites aegyptiaca* (L.) Del., *Sclerocarya birrea* A. Rich., *Diospyros mespiliformis* Hochst. ex A. DC., *Boscia senegalensis* (Pers.) Lam. Ex., *Tamarindus indica* L., *Acacia senegal* (L.) *Willd., Grewia tenax* Forsk*, Adansonia digitata* L., *Vitellaria paradoxa* C.F. Gaertn. Etc. These spontaneous plants, by their diverse production, occupy an important place in the socio-economic life of local populations. Nowadays, these forest essences continue to play a key role in satisfying the essential needs of the poor, but still via the informal sector. Overexploited, these plants are now at risk of extinction. Their weak natural regeneration coupled with non-sustainable harvest practices accelerates the process (Abdoulaye et al., 2017). *Acacia senegal* (L.) Willd, commonly called « gum tree » is the subject of this study. This species, belonging to the family of Fabaceae-Mimosoideae, produces the Arabic gum, a very important non-wood forest product (NWFP) for the populations. The gum is used in diverse food and cosmetic industries, human medicine, and arts and crafts (FAO, 2010; Daniele et al., 2011). The interest in this non-wood forest product led to the drafting of a document of national production and trading boost strategy of the Arabic gum via executive order 2003-196-PRN-MHE-LCD of 24 July 2003 in Niger. This program of boosting the Arabic gum sector helped establish several thousands of acres of gum tree sites across the country.

Nevertheless, the expectations for these gum production plantations and carbon fixation proved to be very optimistic. The degradation of these resources under the influence of intense human and animal pressure has not entirely been stopped. A better management of these forest and pastoral reserves would require that these degraded ecosystems be restored from human and animal pressure (Akpo and Grouzis, 1996). This restoration ought to be based upon knowledge of the current state of these resources (Diallo et al., 2012), hence the interest of this study that aims at characterizing the *Acacia senegal* site of the cluster (cluster of the villages of Lido, Fada Wassangou, Bayawa, Rouga Peulh) of Lido in the rural district of Guéchémé (Tibiri country, Dosso region, Niger) called biocarbon site. This study is part of a perspective of sustainable management of this resource for the well-being of the Lido cluster populations.

MATERIALS AND METHODS

Description of study area and species

This study was conducted on the *A. senegal* plantation site of the cluster of Lido, located in the rural district of Guéchémé (Figure 3). This cluster consisted of five blocks of plantation of different ages: the 2006 block (13 years old), the block of 2007 (12 years old), the 2008 block (11 years old), the 2010 block (9 years old), and the 2011 block (8 years old). This was a land restoration site with forest half-moons. The site area was 506 ha. The settlement density was 317 plants/ha. After the plantation, each block was protected from wandering animals over the course of two years by means of caretaking ensured by the population Figures 1 and 2.

Prior to each plantation, the cluster consisting of five villages, including Lido, Fada Wassangou, Bayawa, Rouga Peulh, got assistance from environmental services in terms of anti-erosive half-moons (HM) whose density was 313 HM/ha. During the first year of plantation, each block was protected for two years followed by caretaking from members of the cluster against wandering animals in order to allow a better restoration of the degraded ecosystem. The following year, the site was left for animal grazing and for farming activities. The gum production started with a few trees of *A. senegal* following bleating by members of the cluster's surveillance committee. The district of Guéchémé is located southwest of Tibiri, Dosso region, Niger between longitudes 12° 45' 09'' and 13 °04' 06'' North and latitudes 03° 47' 03'' and 03° 54' 39'' East. The district is limited to:

(i) The north by the rural district of Koré Mairoua (Dosso region) and that of Sakadamna (Dosso region);
(ii) The south by the Federal Republic of Nigeria;
(iii) The east by the districts of Tibiri and Douméga (Dosso region);
(iv) The west by the districts of Kargui Bangou and Kara Kara (Dosso region).

Its area is estimated at 1265 Km^2, with a population of 125,263 people (INS, 2012). It is essentially composed of Hausas (majority), Fulanis and Djermas. Farming, cattle breeding and trading constitute the main economic activities of the district population (PDC, 2014). The landscape of the area is characterized by landscape units such as Dallol Maouri, dunes and plateaus.

The climate is of Sahelian type mainly characterized by two big seasons:

(i) A long dry season lasting eight months, from October to May and divided into two distinct periods: a dry and cold period (November – February) and a dry and hot period (March – May);
(ii) A rainy season from June to September.

The soil is subdivided into four types:

(i) More dominant sand area, located in areas with dunes and other plateau enclaves;
(ii) Sandy loam area in the major part of the Dallol bed;

Figure 1. Site prior to plantation.

Figure 2. State of site in 2019.

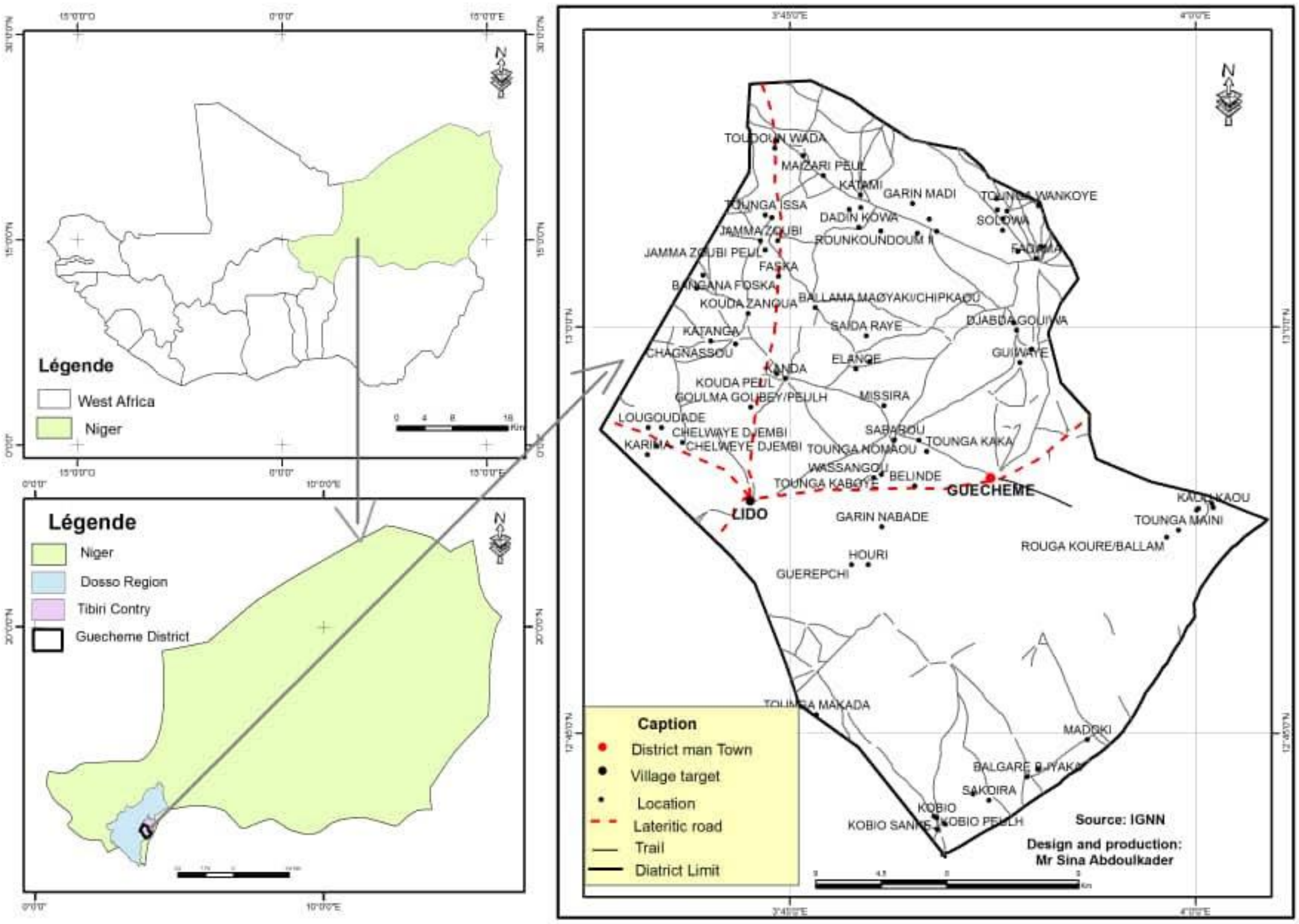


Figure 3. Geolocation of the rural district of Guéchémé.

(iii) Scattered hydromorphic lands in the Dallol bed;
(iv) Lateritic lands (ferruginous and tropical) on plateaus.

The woody and herbaceous vegetation was very diversified. In the woody stratum there were species such as: *Guiera senegalensis* J. G. Gmel*.*, *Piliostigma reticulatum* (DC.) Hochst.*, Ziziphus mauritiana* Lam.*, Combretum glutinosum* Perr. Ex DC.*, Sclerocarya birrea* (A. Rich.) Hochst., *Khaya senegalensis* (Desv.) A. Juss*.*, *Balanites aegyptiaca* (L.) Del.*, Acacia nilotica* (L.) Willd. Var. adansonii (Guill. & Perr.) O. Ktze*, Acacia seyal* De, *Diospyros mespiliformis,* Hochst. ex A. Rich*, Combretum micranthum* G. Don., *Combretum nigricans* Engl. Ex Diels, *Tamarindus indica* L.*, Vitellaria paradoxa* C.F. Gaertn., etc.

The herbaceous stratum was composed of species such as: *Cassia italica* (Mill.) F.W. Anders.*, Commelina benghalensis* L*, Commelina forskalaei* Vahl.*, Jacquemontia tamnifolia* (L.) Griseb., *Merremia pinnata* (Choisy.) f., *Merremia tridentata* (L.) Hallier. f., *Cyperus amabilis* Vahl, *Cyperus rotundus* L., *Fimbristylis hispidula* (Vahl.) Kunth.subsp, *Phyllanthus pentandrus* Schum. and Thonn*, Alysicarpus ovalifolius* (Schum. Et Thonn.) J. Léonard, *Indigofera hirsuta* L. var. hita, *Sesbania pachycarpa* DC, *Zornia glochidiata* Reichb. Ex DC., *Sida cordifolia* L. etc*.* These resources face diverse anthropogenic and climate pressures that could lead to their degradation if appropriate measures are not undertaken. The fauna is almost nonexistent in the area because of the degradation of its habitat. Nevertheless, we find a few reptiles, rodents (rats and squirrels etc..), lagomorphs (rabbits) and birds (Figure 3).

Data collection

Sampling

The gum site of Lido was divided into five blocks of plantations with different ages. Taking into account the density and age of the plantations of the different blocks, a stratified random sampling was chosen. A pre-inventory permitted to determine the average variation coefficient of 41%. On the basis of the coefficient and for a margin of error of 15%, the number of plots n was = $t^2 * cv^2/E^2$ (t =1.96, Cv coefficient of variation and E = margin of error). The minimal number of plots inventoried was 28.70. This number was rounded to 30 plots. Thus, circular plots of 1,000 m^2 (35.84-meter diameter) were marked out in each block in order to obtain at least twenty *A. senegal* plants. The division of three plots per plantation block was performed proportionally based on their area. The random sampling tool of the software ArcGIS 10.4® was used to determine the grids of the plots. The sampling rate was 3 ha/506 ha; which was, 0.6%.

In each circular plot, all the *A. senegal* plants as well as the other woody species with a minimum diameter more than or equal to two centimeters (d > 2 cm) were measured. Those with a diameter of less than 2 cm were deemed rejected. The summarized dendrometric parameters were:
(i) Diameter of 1.30 m off the ground by means of a forest compass for trees and 20 cm off the ground for all the shrubs by means of a grout;

(ii) The total height by means of a graduated pole;
(iii) The average crown diameter by means of a measuring tape;
(iv) The number of rejections or stalks with less than two centimeters.

Data related to stational factors such as soil texture, terrain geomorphology, plot center grids, and soil occupation type were also recorded. Collected data were handled and processed via Excel spreadsheet in order to compute structure parameters such as density, basal area, distribution, etc.

Actual density

It corresponds to the actual number of trees on the plot, estimated in hectares and calculated following the following formula:

$$N = \frac{\mathrm{n}}{\mathrm{s}}$$

N is the average number of plants per hectare; **n**, the number of trees in the plot, and s, the area per hectare.
(i) The index value of importance (IVI) of CURTIS and MACINTOSH (1951).

This index was determined via the formula: IVI= ∑[(rf + rd +rdom)]
rf is the relative frequency of the species, *rd* the relative density (number of trees/ha) of the species and *rdom* is relative dominance referring to the basal area of the species. The index value of importance is a quantitative index that helps identify the species that are ecologically important within the plant community (Adomou et al*.,* 2009; Dossou et al*.*, 2012). It varies from 0 (absence of dominance) to 300 (mono-dominance). The relative frequency of a species is the sum of its specific frequency divided by the total specific frequencies of all the species, multiplied by 100.

$$\mathrm{rf} = \frac{specific\ species\ frequency}{total\ species\ frequcny} \times 100$$

The specific frequency (SF) is equal to the figure expressed in percentage of the number (ni) of times the species **i** is present in the floristic list divided by the total number of trees inventoried.

$$\boldsymbol{Fs} = \frac{\mathrm{ni}}{N} \times 100$$

The relative dominance of a species is the quotient of its basal area with the total basal area of all species;

$$rdom = \frac{\text{Species basal area}}{\text{Total basal area of all species}} \times 100$$

The basal area is determined by following the formula:

$$\boldsymbol{G}(\mathbf{m^2}/\boldsymbol{ha}) = \frac{\pi}{40000S} \sum_{i=1}^{n} \mathrm{di}^2$$

di stands for diameter (in centimeter) of the tree **i** of the plot and s the area of the plot (in ha).
(i) The relative density of a species is the sum of its absolute density divided by the total absolute densities of all the species multiplied by 100.

$$\mathrm{rd} = \frac{Number\ of\ plant\ species}{Total\ number\ of\ plants} \times 100$$

The settlement recovery is the sum of crown areas of all the plants of the settlement. This area is obtained by means of the average tree foliage diameter assimilated to a circle by projection to the ground. It is obtained via the following formula (Rondeux, 1999):

$$\mathrm{SC} = \sum \frac{\pi\, \mathrm{D}^2}{4}$$

Sc = Crown surface in (m^2); D = average diameters to East/West and North/South.

Structure in diameter and height

In order to better analyze the data, the observed structure was modeled from the Weibull theoretical distribution parameters whose density probability function (Rondeux, 1999) is expressed through the formula:

$$\mathbf{f(x)} = \frac{c}{b} + \frac{(x-a)}{b}^{\mathrm{C}-1} e^{x}\left[-\left(\frac{x-a}{b}\right)^{c}\right]$$

x stands for the diameter of trees and **f(x)** its value; **a** represents the position parameter; **b** is the parameter of scale or size and c is the parameter of shape as it relates to the structure in diameter or in height given. In this study, the position parameter **a** is set at 2 centimeters for the minimum diameter of *A. senegal* trees*.* The software Minitab 14 was used to adjust the different histograms constructed via the Weibull (Husch et al., 2003) theoretical distribution. Based on the parameter value **C**, the main shapes of the Weibull theoretical distribution were interpreted as follows : (a) C < 1 indicated a distribution in « Inverted J», featuring the multi-specific or uneven-aged settlements; (b) C = 1 indicated an exponentially decreasing distribution, a feature of settlements in extinction ; (c) 1 < C < 3,6 implied a positive asymmetric distribution or right asymmetric, a feature of monospecific settlements with predominant young plants or plants with smaller diameters; (d) for C = 3,6 : the distribution was asymmetric; normal structure, feature of uneven-aged settlements or monospecific with the same cohort ; (e) C > 3,6 negative asymmetric or asymmetric left, feature of monospecific settlements with predominant older trees.

The regeneration rate of the settlement (RRS) which was the difference between the total number of young plants (Ø < 4 centimeters for shrubs, or 10 centimeters for trees) and that of all the tree settlement (Poupon, 1980). According to Poupon, a 50% rate indicated a balanced settlement where there were as many young trees as adult trees ; a rate that was less than 50% (< 50%) represents an ageing settlement, the density of whose young plants is less than that of adult plants; a rate higher than 50% (> 50) characterized a settlement in full expansion following a significant regeneration; young plants were more important than adults.

RESULTS

Specific abundance

The gum site inventory of the Lido cluster permitted to inventory a total number of ten woody species classified

Table 1. Number of woody species inventoried on the Lido gum site.

Species	Number	Family	Total	Frequency
Acacia ataxacantha DC.	1	Fabaceae-Mimosoideae	1	10
Acacia nilotica (L.) Willd. ex Del.	2	Fabaceae-Mimosoideae	1	10
Acacia senegal (L.) Willd.	191	Fabaceae-Mimosoideae	1	10
Boscia senegalensis (Pers.) Lam. ex Poir.	1	Capparaceae	1	10
Cassia sieberiana DC.	18	Fabaceae-Ceasalpinoideae	1	10
Combretum micranthum G. Don	14	Combretaceae	1	10
Guiera senegalensis J.F. Gmel.	47	Combretaceae	1	10
Maerua crassifolia	4	Capparaceae	1	10
Piliostigma reticulatum (DC.) Hochst.	20	Fabaceae-Ceasalpinoideae	1	10
Ziziphus mauritania Willd.	2	Rhamnaceae	1	10
Total	300		10	100

Table 2. Average *A. senegal* diameters and heights based on plantation years.

Blocks	Average diameters (cm)	VC	Average heights (m)	VC
2006	10.1± 4.39	43.22	3.06±1.16	38.09
2007	8.34±3.25	39.04	2.44±0.76	31.29
2008	6.96±3.82	54.98	2.42±1.28	52.88
2010	10.84±2.84	26.25	4.16±1.47	35.43
2011	7.69±3.37	43.86	2.52±0.95	37.97
	P* = 0.479		p* = 0.937	

CV = Variation coefficient.

into ten families (Table 1), the most significant of which were the Fabaceae-Mimosoideae representing (30%), followed by the Capparaceae, the Combretaceae, and the Fabaceae-Caesalpinioideae, each of which represented (20%), and the Rhamnaceae (10%).

Actual density, importance value index and recovery

Table 3 shows the structural parameters of woody species inventoried at the *A. senegal* gum site. This table shows that the actual *A. senegal* is 238.75 trees/ha with an importance value index of 220.38%, and a recovery of 1329.37 $m^{2.}$

Average diameters and heights of Acacia senegal based on plantation years

Table 2 summarizes the average diameters and heights of *A. senegal* based on plantation years. The results analysis of the results showed that there was a variation.
relatively to these two structural parameters of *A. senegal* based plantation years. The statistical test of ANOVA One-Way proved that this variation between average diameters and heights based on plantations years was not significant (P = 0.479) for average diameters, (P = 0.937) for average heights.

Structure of *Acacia senegal* settlements

Structures in terms of diameter

Chart 4 illustrates the structure in terms of diameter of *A. senegal* plants based on plantation age. The distribution of trees in classes of diameter of the plantation year 2008 presented an inverted "J" trend for (Figure 4c). The observed distribution adjusted to the Weibull theoretical distribution in a C-shape = 1.349. For plantations of the years 2006, 2007, 2010 and 2011, the distribution of trees in classes of diameter showed a bell-shape distribution. The observed distribution adjusted to the Weibull theoretical distribution with the values of the C-shape parameter, which were equal to 1,969 for the 2006 site, 1, 981 for the 2007 site, 3,157 for the 2010 site, and 2,088 for the 2011 site (Figure 4a, b, d and e). The Kolmogorov Smirov testing between the observed distributions and the Weibull theoretical distributions resulted in P-values greater than 0.05, which indicates that the two types of distributions did adjust.

Structures in terms of height

Figure 5 displays the *Acacia senegal* plants in terms of height. The distribution in classes of height presented an « inverted J » distribution. It adjusted to the Weibull

Table 3. Structural value parameters of inventoried species on the Lido gum site.

Species	Total	Rf (%)	Rd (%)	RBA (%)	IVI (%)	CS (unit)
Acacia ataxacantha DC.	1	0.33	0.33	0.064	0.73	2.51
Acacia nilotica (L.) Willd. ex Del.	2	0.67	0.67	0.71	2.04	10.52
Acacia senegal (L.) Willd.	191	63.67	**63.67**	93.06	**220.39**	**1329.37**
Boscia senegalensis (Pers.) Lam. ex Poir.	1	0.33	0.33	0	0.67	0
Cassia sieberiana DC.	18	6	6	1.037	13.04	73.61
Combretum micranthum G. Don	14	4.67	4.67	0.74	10.07	52.05
Guiera senegalensis J.F. Gmel.	47	15.67	15.67	0.68	32.01	32.7
Maerua crassifolia Forsk.	4	1.33	1.33	0.024	2.69	0.016
*Piliostigma reticulatum (*DC.) Hochst.	20	6.67	6.67	1.62	14.95	22.96
Ziziphus mauritania Willd.	2	0.67	0.67	0	1.33	0
Total	300	100	100	97.935	297.94	1523.736

Rf = relative frequency, Rd = relative density RBA = relative basal area, CS = crown surface.

theoretical distribution with the C-shape parameter c = 1, 887; c = 2.271; c = 1.349; c = 1.849, respectively for the plantations of the years 2006; 2007; 2008 and 2011 (Figure 5f, g, h, j). The distribution in classes of height of the 2010 plantation showed a bell distribution. It adjusted to the Weibull theoretical distribution with the C- form parameter c = 2.221 (Figure 5i) (Table 3).

Average annual growth and mortality rate of *A. senegal* based on plantation years

Table 4 illustrates the variation of average annual growth (AAG) in terms of diameter and height of *A. senegal* plants in 2019. The results indicated that the highest average growth rate in terms of diameter and height were recorded in 2010, and then in 2011. This growth rate varied depending on the year. The significance of this variation between plantation years was certified via the ANOVA one-Way statistics test with a probability P = 0.001.

The curve in chart 6 shows the global mortality rate of *A. senega*l plants based on plantation year. This curve indicates that the highest plant mortality rate was recorded in 2009 (Mr =17%), then 2008 and 2010 recording proportionally equal mortality rates (Mr = 15%). In 2011, when we recorded a mortality rate of A (Mr = 10%), mortality rate values of the other years decrease continuously until they reached (Mr = 0). The ANOVA one-way statistics test confirmed that the mortality rate. variation in terms of year was highly significant (P = 0.005) (Figure 6).

Regeneration capacity of woody species

Figure 6 illustrates the regeneration rate of species inventoried on the *A. senegal* site. The analysis of the chart shows that the regeneration of the settlement was 80%. The species that contributed the most to this rate were the *A. senegal* and *Guiera senegalensis* representing equal proportions, the highest rejection rate (24.71%), followed by the *Combretum micranthum*, *Cassia sieberiana* and *Piliostigma reticulatum* in relatively respective equal proportions of 15.04; 7.21 and 5.87%. In this contribution, species like *Maerua crassifolia, Bossia senegalensis, Acacia nilotica* and *Zizipus mauritiana* represented the lowest regeneration rate (Figure 7).

DISCUSSION

The study of the current structure of *A. senegal* settlements on the gum site of Lido permitted to record an actual density, an important recovery and regeneration rate. However, the study also helped to show the presence of a consequential mortality rate related to the species. This mortality rate observed with the species was likely linked to anthropogenic pressures (abusive cutting), intensive grazing of animals on the site without the surveillance committee knowing. The usage of this species for the reconstitution of the degraded ecosystem permitted the creation of a microclimate favorable to the regeneration of certain species such as *Guiera senegalensis, Combretum micranthum*, *Cassia sieberiana* and *Piliostigma reticulatum* whose contributions to the reconstitution of the plant cover is quite significant. They contribute up to 52.83% to the settlement recovery. These species regenerated either by zoochory or anemochory. *A. senegal* is a legumin whose leaves are eaten perpetually by animals while the grains are highly demanded in feeding cattle. This trend was reported by previous studies (Alassane, 2006; Diallo et al., 2011). According to Tybirk the absence of a significant number of younger plants observed with *A. senegal* (Tybirk (1991) might be linked to the usage of grains and fruit in feeding cattle, and/or the competition

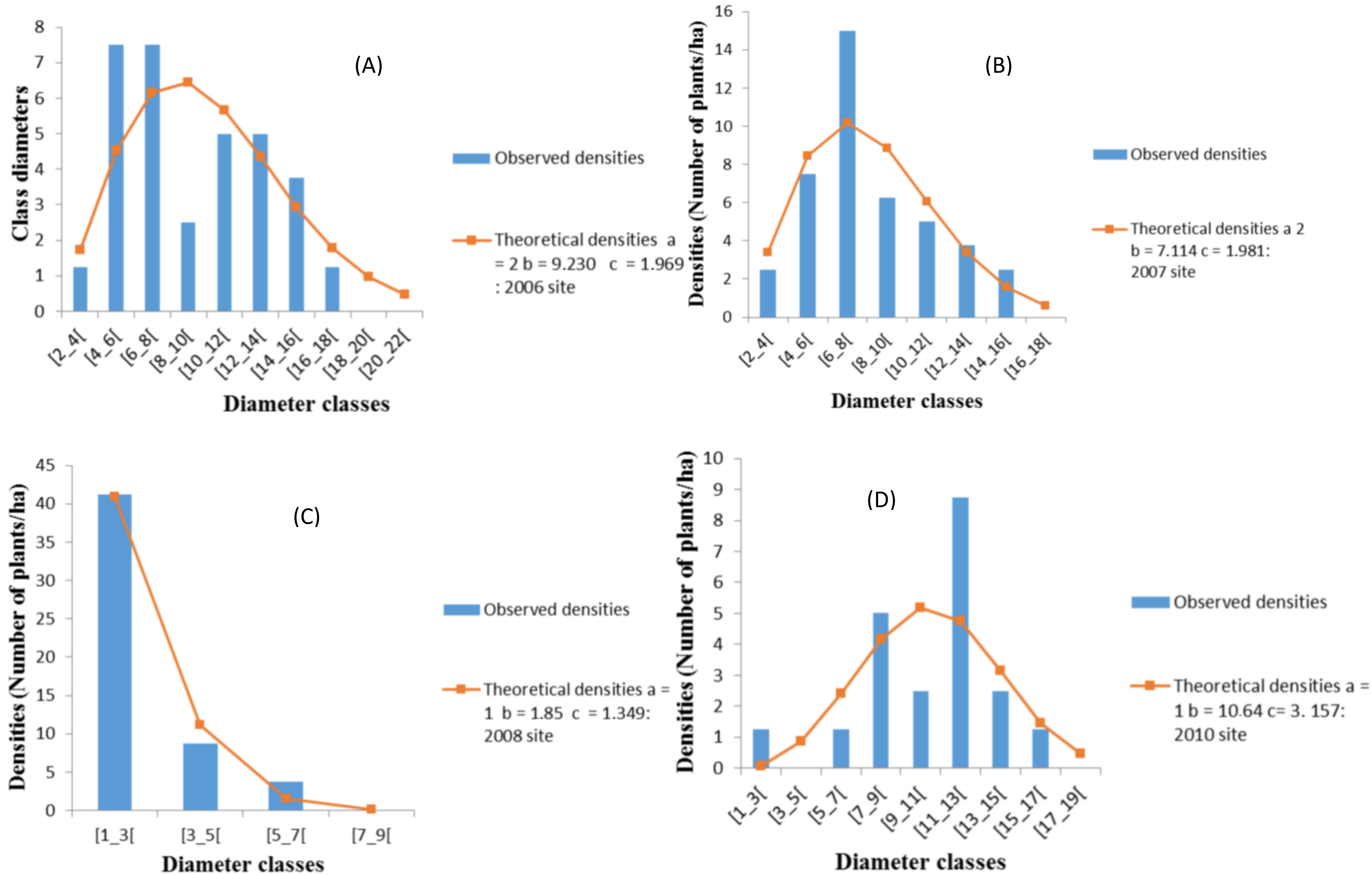


Figure 4. Structure of classes in diameters of *A. senegal* settlements based on plantation year.

on the stock of water available with grasses (Sharman, 1987). In addition to this, we have the impact of overgrazing through the selection of young plants eaten on the growth rate of young plants (Miehe, 1990; Diallo et al., 2012). The different average diameter and height variations

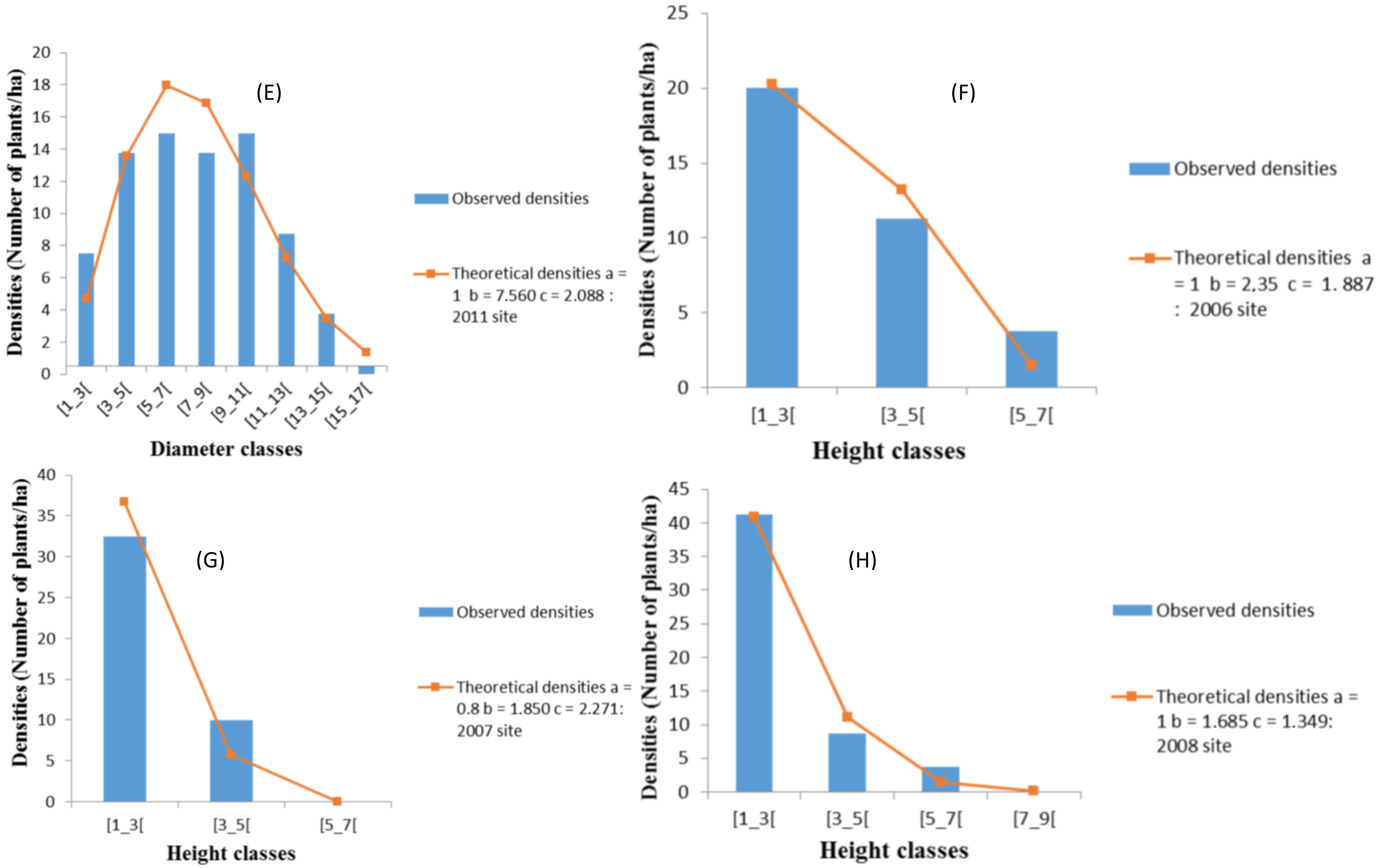
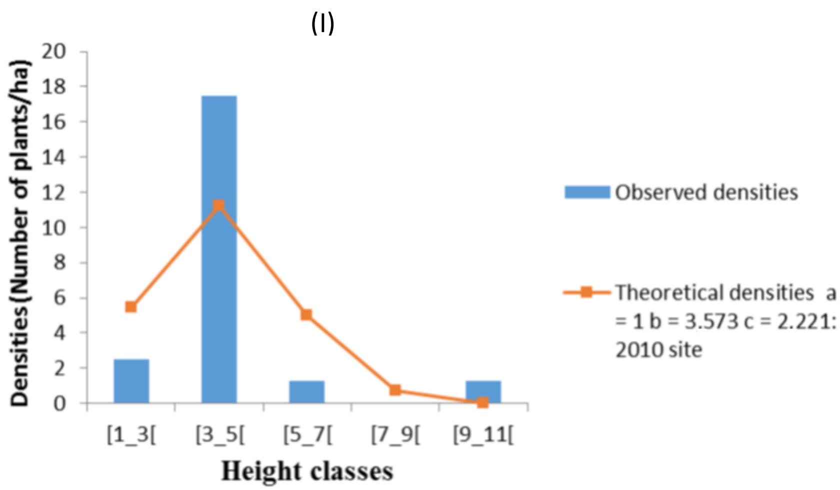


Figure 4. Contd.

and the average annual growth observed with *A. senegal* based on plantation year were linked to the variability of rainfall through the years. Thus, after a plantation, good rainfall surely offers pedoclimatic conditions suitable for the emergence of species. The inverted « J » distribution that the classes of plant diameter of the 2008 plantation structure represented, with the C-shape parameter of less than 3,6 value positive



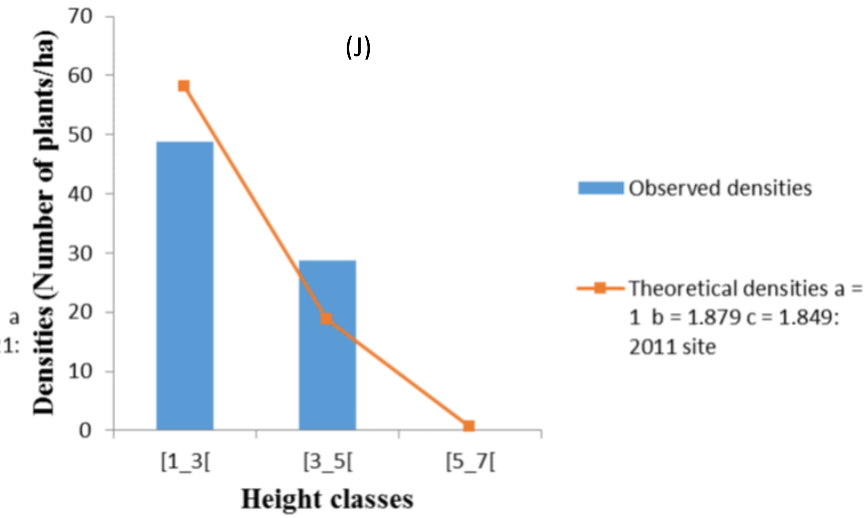


Figure 5. Structure height classes of *A. senegal* settlements based on plantation year.

Table 4. Average annual growth rate and mortality rate of *A. senegal* plants.

Blocks	Plant diameter based on plantation year (cm)	Average diameters in 2019 (cm)	AAG (cm)	Average plant height based on plantation year (m)	Average height in 2019 (m)	AAG(m)
2006	0.3	10.1	**0.75**	0.3	3.06	**0.21**
2007	0.3	8.34	**0.67**	0.3	2.44	**0.18**
2008	0.3	6.96	**0.61**	0.3	2.42	**0.19**
2010	0.3	10.84	**1.17**	0.3	4.16	**0.43**
2011	0.3	7.69	**0.92**	0.3	2.52	**0.28**

P* = 0001, AAG = Average Annual Growth.

asymmetric curve or right asymmetric, was characteristic of monospecific settlements with a predominance of younger plants or those with smaller diameters. This structure was dominated by plants of the first class belonging to the class diameter. The « crown » distribution representing the structures of diameter classes of plantations of other years with the C-shape parameter value of less than 3,6 (also features a positive asymmetric distribution or right asymmetric), was a feature of monospecific settlements with a predominance of younger plants or plants with smaller diameters. In contrast to plants of the 2008 plantation, these structures represented a smaller proportion of younger plants in the first classes of diameter and plants with larger diameters were scarce. The absence of trees of large diameters in these blocks of plantation implied the impact of the

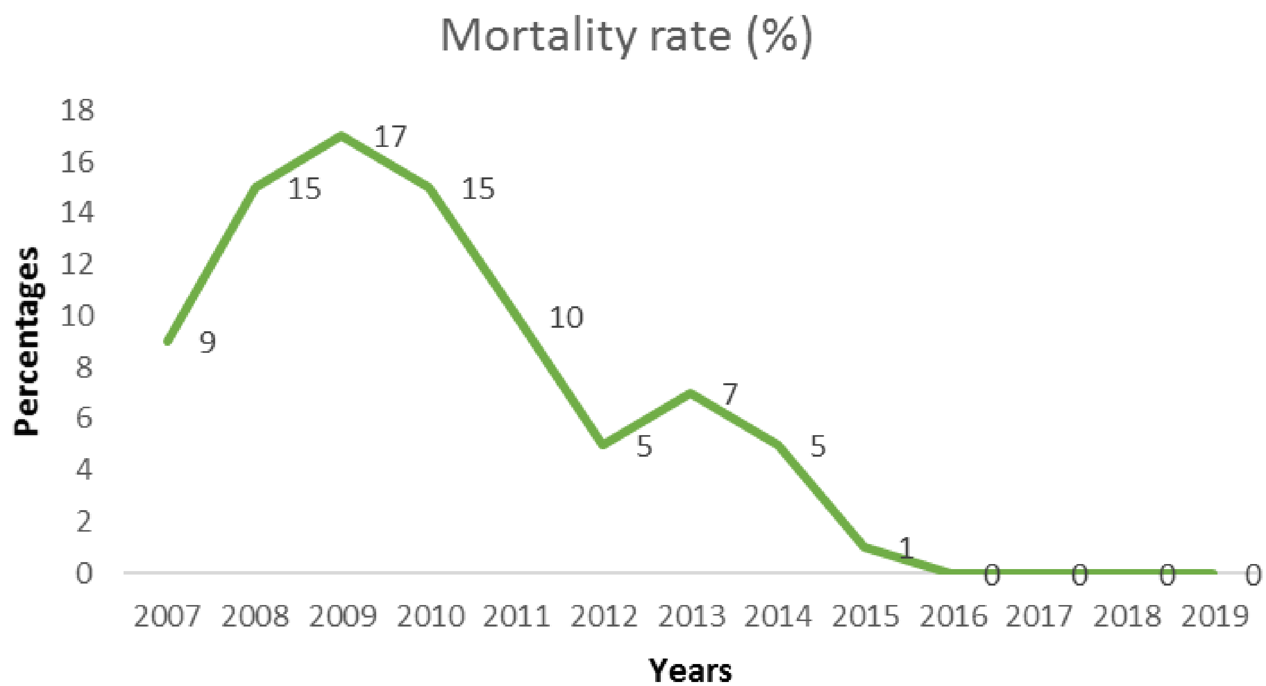


Figure 6. Mortality rate variation of Acacia *senegal* plants over the years.

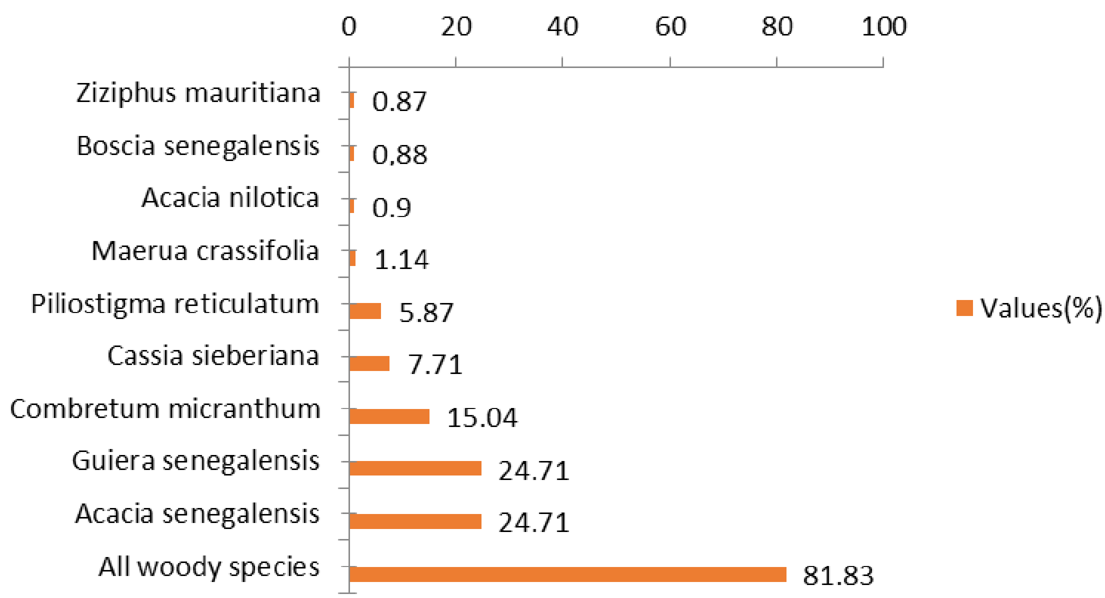


Figure 7. Regeneration variation rate of species on the site.

aridity of the Sahelian climate on the growth of species in diameter and thickness. This observation was signaled by Diallo et al. (2011). It might also be linked to the impact of anthropic factors such as bleating and pruning of plants of the species in these blocks. It may also be due to intensive grazing on the plants from their first age of growth by animals. The inverted « J » distribution representing the class structures in terms of height characterizes the Sahelian type of vegetation that was essentially shrubby. Thus, of all the plantation years, the plants of *A. senegal* of seven meters high were very scarce, often nonexistent. This situation was foremost due to the pressure of anthropogenic and climate factors, and also grazing. Overexploitation obviously led to stress and traumatism on the plants of these settlements with regard to these two dendrometric parameters (Kebenzikato et al., 2014; Ngarnougber et al., 2017). During the dry season, younger seedlings of *A.senegal* were highly appreciated in cattle feed (Dan Guimbo et al., 2010), which constituted a major constraint on the dynamic of future regeneration of this species.

Conclusion

For the development of non-wood forest products, namely the Arabic gum, this study provided additional information on the current state of the *A. senegal* settlements in the Lido terroir plantation site. The structure of these settlements, shrubby in nature, remains dominated by younger trees with smaller diameters. It was highly tributary to the pedoclimatic conditions and upset by anthropogenic, climate factors and the effect of grazing. The objective sought through these plantations, which was the production of Arabic gum, was therefore strongly compromised. These settlements represented a smaller regeneration rate (24.71%), which could compromise the long-term survival of the settlements of the species. For the sake of a sustainable conservation of this species for the well-being of populations, it is indispensable for the public interest to integrate afforestation actions, protection and restoration in the development of Sahelian and Sudan ecosystems of *A. senegal* across the gum sites of the country.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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