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Characterization and Carbon Sequestration Potential of Sahelian Agroforestry Parklands of Chad

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Abstract: Agroforestry parklands are agroforestry systems which farmers created by preserving useful species on their farms. These species are those whose flowers, fruits, seeds, barks or leaves can be processed into useful products. Parklands are thus the result of human intervention in natural vegetation dynamics and their diversity results from ecological factors affecting the neighborhood and the management of trees. The purpose of this work is to characterize and assess the carbon potential of Chad sahelian agroforestry parklands. A total survey area of 90 hectares of parklands of which 30 ha per site were explorated. Compass and GPS were used to establish transects of 50 m in length over 20 m in width and the community sampling units were established (20 sampling plots/ha). In each plot, plants were identified and enumerated. Diameter of plants was measured at 1.30 m aboveground for trees and at 0.30 m for shrublets. The dendrometric parameters measures effectuated throughout transects follow standard forestry methods. The result revealed that three types of agroforestry parklands exist in sahelian zone of Chad among which *Hyphaene thebaica*, *Balanites aegyptiaca* and mixed *Acacia senegal* - *A. nilotica* parklands. Their structure varies according to the specific flora and dominant species. Floristic survey showed a total of 4801 trees recorded and distributed in 22 species, 17 genera and 14 families. The ecological services of the Chad sahelian parklands fluctuate from 20.25 tCO_2/ha in *Balanites aegyptiaca* parkland to 77.36tCO_2/ha in *Hyphaene thebaica* parkland, confirming the heterogenous carbon sequestration potential of the parklands. These informations will help to develop the REDD+ mechanisms in the area.

Keywords: Agroforestry Parklands, Chad, Carbon Sequestration, Structure, Ecological Service

1. Introduction

The biodiversity of natural ecosystems, already fragilized by anthropic pressures, are accelerated by climate change [1]. These degradation factors provoke plant cover reduction leading to loss of plant diversity with consequences in reducing carbon sequestration potential and increasing temperature [2]. In the semi-arid and sub-humid zones of West Africa, farmers have for generations implemented a traditional land use system where trees are deliberately associated with crops in a dispersed spatial arrangement dominated by one or more useful species whose flowers, fruits, seeds or leaves can be processed into useful products [3-5]. This system, known as agroforestry parklands, serves several needs and functions ranging from agricultural production to the production of wood and non-wood forest products [6, 7]. In sahelian zone of Chad, parklands are overexploited by local populations through wood usage (fuelwood or charcoal, service wood and agriculture). However, these agrosystems contribute effectively to the conservation of biodiversity, the improvement of the living conditions of the populations and the maintenance of the carbon sequestration capacity.

The accumulation of biomass by agroforestry parklands depends on their floristic composition and structure. Therefore, the effects of climate changes and anthropogenic activities influence the structure of these woody formations and consequently their carbon sequestration capacity [8]. Despite the great ecological, social and economic importance of these production systems, which have been traditionally practiced for many generations, scientific knowledge is certainly huge but scattered and especially very little renewed. In sahelian zone, a comprehensive compilation of scientific works on agroforestry parklands was made [9, 10]. Nevertheless, its inspection revealed nothing concerning Chad. Recently, a few works were carried out on this problematic. Traditional agroforestry systems and biodiversity conservation of the Tandjile East were characterized in Chad [11]. In addition, the spatial dynamics of *Borassus aethiopum* parklands in the Loug - Chari Department was studied [12] while the ecological and ethnobotanical potential of *Borassus aethiopum* parklands in Mayo Kebbi East were treated [13]. Knowledges on the structure and carbon sequestration potential of agroforestry parklands in Chad is still very limited. In the REDD+ perspective, the ecosystem services provided by carbon markets on the international level, agroforestry parklands deserve special attention.

The study aims to identify, characterize and assess plant diversity and carbon sequestration potential of the Sahelian agroforestry parklands of Chad.

2. Materials and Methods

2.1. Study Site

The sahelian zone of Chad is located between LN: 10° 0'0'' - 15° 0'0'' and LE: 14° 0'0'' - 24° 0'0''. The climate of the area is a dry tropical sahelian type characterized by two seasons: a dry season which remains 9 months (October – Juin) versus 3 for the rainy one (July-September) with low precipitations. The annual average rainfall is 422.6 mm while the annual mean temperature is 26.73°C which fluctuates between 24.48 in January to 43°C in October [14]. From 1986 to 2015, the climate of the sahelian zone shows a positive and negative variation of precipitation (Figure 1). The sahelian soil is clayey - sand characterized by a succession of sand dunes and valleys. The vegetation of the area is composed of steppes and clear forests (*Acacia tortilis*, *A. seyal*, *Anogeissus leiocarpa*, *Hyphaene thebaica*). The explorated study sites were Mandelia (LN: 11°46. 486'; LE: 015°14. 124'; ALT: 298m); Gassi (LN: 12°00.499'; LE: 015°12.089'; ALT: 297m) and Linia (LN: 12°03. 084'; LE: 015°19. 214'; ALT: 298m).

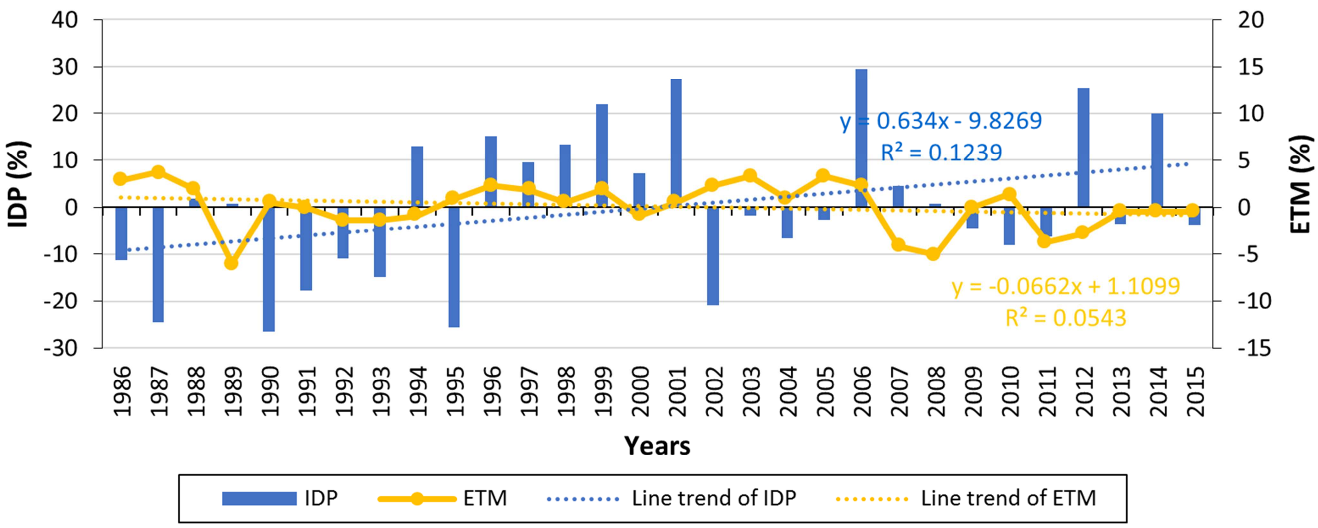

Figure 1. *Variability of climate parameters in the sahelian zone (1986-2015).*

Source: Meteorological station of N'Djamena [2016]
IDP=Precipitation Deficiency Index, ETM=Gap of Mean Temperature

2.2. Methodology

For the floristic data, a total survey area of 90 hectares of parklands of which 30 ha per site were explorated. Compass and GPS were used to establish transects of 50 m in length over 20 m in width and the community sampling units were established (20 sampling plots/ha). In each plot, plants were identified and enumerated. Diameter of plants was measured at 1.30 m aboveground for trees and at 0.30 m for shrublets. The dendrometric parameters measures effectuated throughout transects follow standard forestry methods [15]. Likewise, for measuring diameter at breast height (dbh), diameter of canopy and height of trees, instruments like dbh meter and Finnish Caliper and measuring tape were employed for all woody species.

Data processing and analysis

The aboveground biomass (BA) of tree species is calculated using standard allometric equations applicable to the study area [16]. This model takes into account the trees of large and small diameters also the rainfall and the temperature of the environment. Aboveground biomass (BA) = exp [−1.803–0.976E + 0.976ln(Ω) + 2.673ln(Dbh)−0.0299 [ln(Dbh)]^2], where, Dbh is a diameter of the tree at breast height (m); ρ is density of wood (t/m^3 dried at 0.65). Exp = exponential; ln is natural logarithm. In Arecaceae (*Hyphaene thebaica*, *Borassus aethiopium*), aboveground biomass (BA) specific equation was used [17]: BA = 6.666 + 12.826 ∗ (HT) 0.5 ∗ ln(HT). HT is total height. The underground biomass was determined using the following model [18].

1) Underground biomass (BU) = exp (−1.0587+0.8856∗ln (BA). Total biomass is the sum of the above and underground biomass (BA +BU).
2) The carbon of a tree is estimated by multiplying its biomass by the factor 50% [19]. The total stock of carbon estimation in t/ha was converted into equivalent amount of CO_2eq absorbed using the ration CO_2/C corresponding to 44/12. The ecosystem service was subsequently converted into monetary value. In the carbon marketplace, due to the unsteadiness of prices, the mean cost of 1 ton of CO_2 for five years (2015-2020) is 10 USD.

For all the quantitative data, analyse of variance was performed using the program Statgraphic plus 5. 0.

3. Results

3.1. Typology of Sahelian Parklands

In the sahelian zone of Chad, farmers practice three kinds of agroforestry parklands according to the truncation line of the dendrogram fixed at the similarity index 0.1145066 (Figure 2). The three well known types of agroforestry parklands characterized are *Hyphaene thebaica* parkland (A), *Balanites aegyptiaca* parkland (B) and mixed *Acacia senegal* - *Acacia nilotica* parkland (C). The dominant plant species (*Acacia senegal*, *A. nilotica*, *Balanites aegyptiaca*, *Hyphaene thebaica)* of parklands are of socio-economic interests. They are retained in farms by peasants during farming clearing. Their fruits, seeds, flowers, leaves, barks, gums, etc. are processed into useful products which are eaten and/or sold, contribute to the welfare of the households [7].

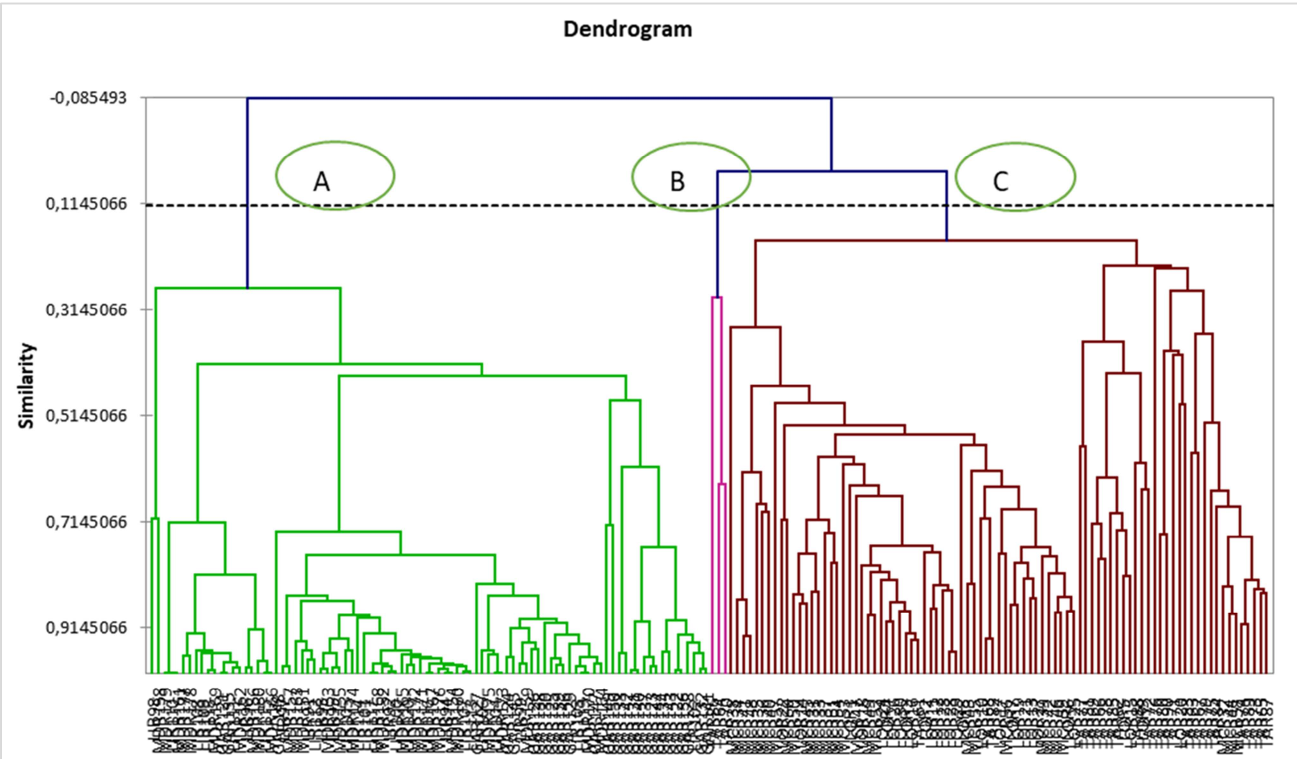

Figure 2. *Dendrogram of parkland repartition in the Sahelian zone of Chad.*

The above main dendrogramm can be summarised in three categories (C) as presented below. Each category or type (C) of parkland in the table below is caracterized by Ri parklands where i is the number from 1 to 180.

Table 1. *Typology of agroforestry parklands in the sahelian zone of Chad.*

Type	1	2	3
Variance intra-classe	**256,024**	**65,667**	**461,652**
	LOR1	TAR64	LIR91
	LOR2	TAR70	LIR92
	LOR3	TAR86	LIR93
	LOR4		LIR94

Type	1	2	3
Variance intra-classe	**256,024**	**65,667**	**461,652**
	LOR5		LIR95
	LOR6		LIR96
	LOR7		LIR97
	LOR8		LIR98
	LOR9		LIR99
	LOR10		LIR100
	LOR11		LIR101
	LOR12		LIR102
	LOR13		LIR103
	LOR14		LIR104
	LOR15		LIR105
	LOR16		LIR106
	LOR17		LIR107
	LOR18		LIR108
	LOR19		LIR109
	LOR20		LIR110
	LOR21		LIR111
	LOR22		LIR112
	LOR23		LIR113
	LOR24		LIR114
	LOR25		LIR115
	LOR26		LIR116
	LOR27		LIR117
	LOR28		LIR118
	LOR29		LIR119
	LOR30		LIR120
	MCR31		GAR121
	MCR32		GAR122
	MCR33		GAR123
	MCR34		GAR124
	MCR35		GAR125
	MCR36		GAR126
	MCR37		GAR127
	MCR38		GAR128
	MCR39		GAR129
	MCR40		GAR130
	MCR41		GAR131
	MCR42		GAR132
	MCR43		GAR133
	MCR44		GAR134
	MCR45		GAR135
	MCR46		GAR136
	MCR47		GAR137
	MCR48		GAR138
	MCR49		GAR139
	MCR50		GAR140
	MCR51		GAR141
	MCR52		GAR142
	MCR53		GAR143
	MCR54		GAR144
	MCR55		GAR145
	MCR56		GAR146
	MCR57		GAR147
	MCR58		GAE148
	MCR59		GAR149
	MCR60		GAR150
	TAR61		MDR151
	TAR62		MDR152
	TAR63		MDR153
	TAR65		MDR154
	TAR66		MDR155
	TAR67		MDR156
	TAR68		MDR157
	TAR69		MDR158
	TAR71		MDR159
	TAR72		MDR160

Type	1	2	3
Variance intra-classe	**256,024**	**65,667**	**461,652**
	TAR73		MDR161
	TAR74		MDR162
	TAR75		MDR163
	TAR76		MDR164
	TAR77		MDR165
	TAR78		MDR166
	TAR79		MDR167
	TAR80		MDR168
	TAR81		MDR169
	TAR82		MDR170
	TAR83		MDR171
	TAR84		MDR172
	TAR85		MDR173
	TAR87		MDR174
	TAR88		MDR175
	TAR89		MDR176
	TAR90		MDR177
			MDR178
			MDR179
			MDR180

3.2. Hyphaene Thebaica Parkland

The physiognomy of this type is dominated by *Hyphaene thebaica* species. This Arecaceae species represents 47.33% of trees of the woody population (Figure 3). The population density is 59.84 trees /ha, all species overcome of which 28.88 stems /ha for *H. thebaica*. This Arecaceae is followed by *Balanites aegyptiaca* (7.94 individuals/ha), representing 13.01% of species. The specific richness of this parkland is 22 species. The density aforementioned is differend than the one reported in the Niger's *H. thebaca* parkland which is 27 trees /ha [9]. This parkland has an equilibrated structure because farmers cut palms for fuel, also to manufacture ropes and for house construction. In addition they collect fruits for consumption and selling.

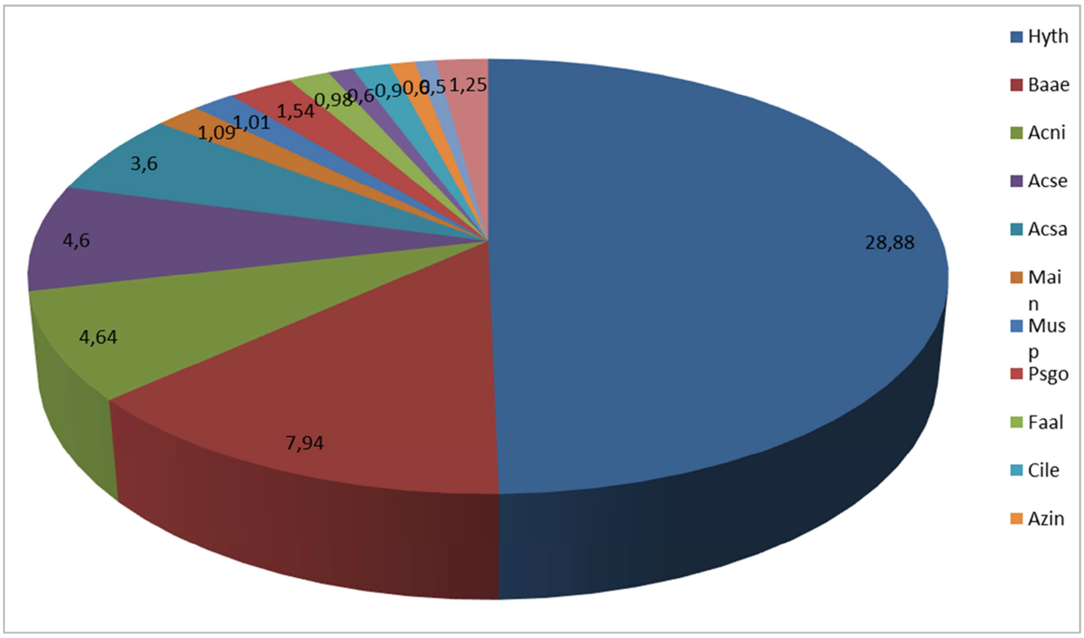

Figure 3. *Proportion of companion species in Hyphaene thebaica parkland.*

Hyth = Hyphaene thebaica, Baae = Balanites aegyptiaca, Acni = Acacia nilotica, Acse = Acacia senegal, Acsa = Acacia seyal, Main = Mangifera indica, Musp = Musa sp., Psgo = Psidium guajava, Faal = Faidherbia albida, Pith = Piliostigma thonningii, Acat = Acacia ataxacantha, Cile = Citrus lemon, Azin = Azadirachta indica.

3.3. Balanites Aegyptiaca Parkland

The *Balanites aegyptiaca* parkland is a monospecific one with a density of 41.78 trees/ha. This *Zygophyllaceae* represents 37.94% of woody species of the population. The density of the dominant species is 16.53 trees /ha. It is followed by *Acacia senegal* (6.62 feet/ha) and *Hyphaene* *thebaica* (5.84) (Figure 4). The specific richness of the parkland is 21 species.

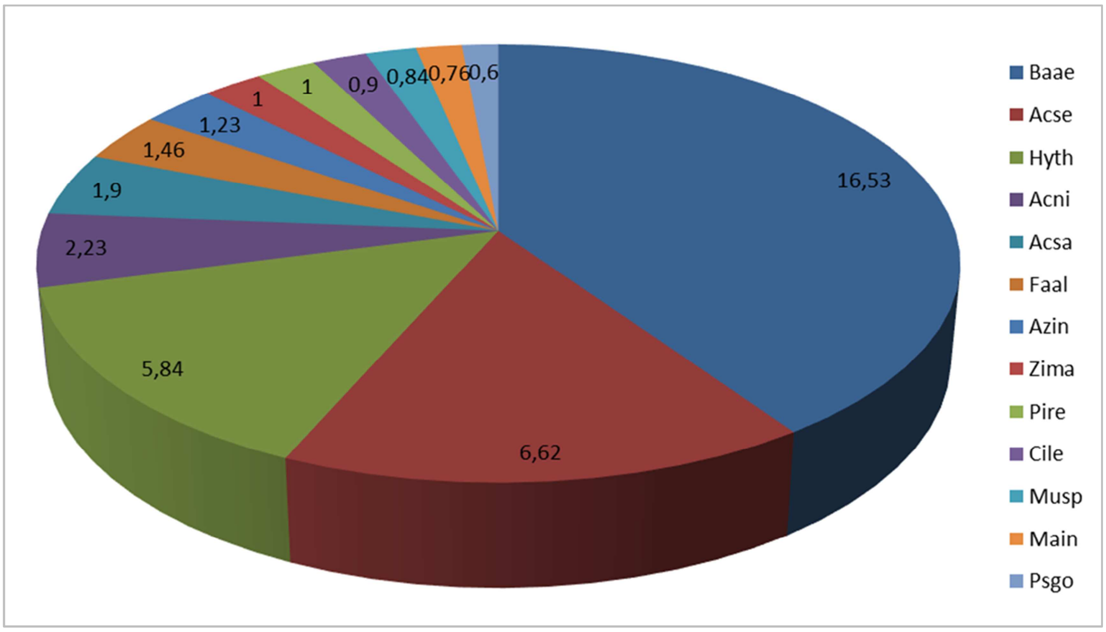

Figure 4. *Proportion of companion species in Balanites aegyptiaca parkland.*

Baae = Balanites aegyptiaca, Acse = Acacia senegal, Acni = Acacia nilotica, Acsa = Acacia seyal, Main = Mangifera indica, Musp = Musa sp., Psgo = Psidium guajava, Faal=Faidherbia albida, Acat = Acacia ataxacantha, Zima = Ziziphus mauritiana, Pire = Piliostigma reticulatum, Cile = Citrus lemon, Hyth=Hyphaene thebaica, Azin = Azadirachta indica.

3.4. Mixed Acacia Senegal - A. Nilotica Parkland

The physiognomy of the parkland is dominated by two species of which their numbers is the highest in the woody population. Species characterizing this agrosystem flora are *Acacia nilotica* - *Acacia senegal* (Figure 5). *A. senegal* is the most representative (34.32%) followed by *A. nilotica* (23.46%). Their densities are 21.05 trees/ha and 14.38 stems/ha respectively. The specific richness of this parkland is 20 woody species with a density of 57.84 trees /ha.

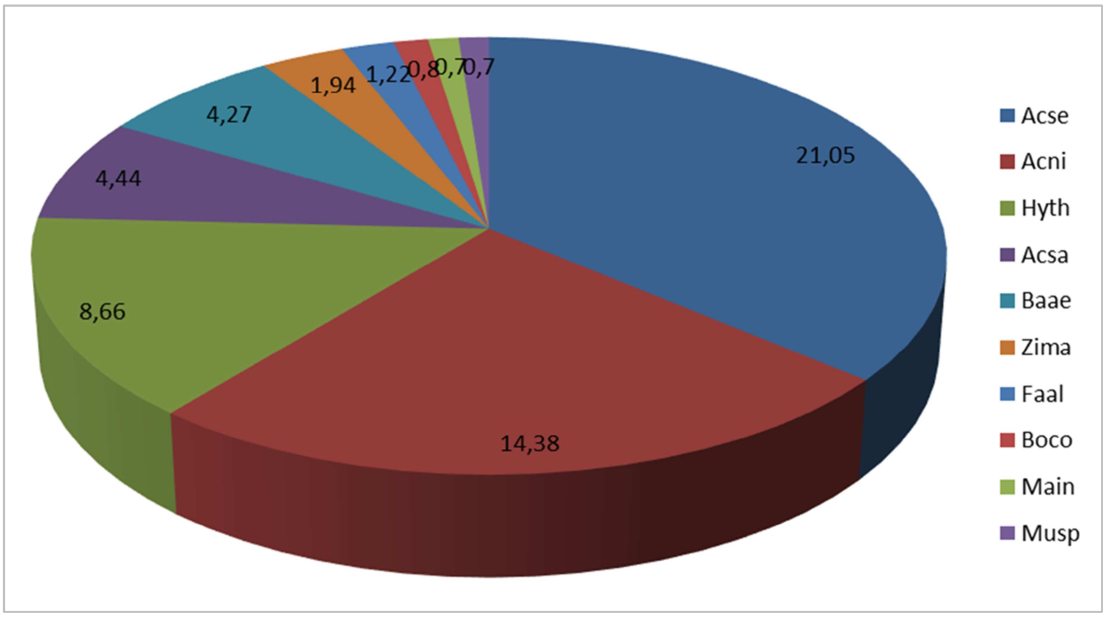

Figure 5. *Proportion of companion species in Acacia nilotica - Acacia senegal parkland.*

Acse = *Acacia senegal*, Acni = *Acacia nilotica*, Hyth = *Hyphaene thebaica*, Acsa = *Acacia seyal*, Baae = *Balanites aegyptiaca*, Main = *Mangifera indica*, Faal = *Faidherbia albida*, Zima = Ziziphus mauritiana, Musp = *Musa* sp.

The companion species diversity related to each population physiognomy varied with parkland type and crops production characteristics as well as the objectives of the farmers. Some of these multipurpose tree species are regular while others are scarce. Representative species met in these parklands are composed by *Acacia nilotica*, *Acacia senegal*, *Balanites aegyptiaca*, *Faidherbia albida*, *Hyphaene thebaica*, *Ziziphus mauritiana.* The scarce one are represented by *Azadirachta indica, Mangifera indica, Psidium guajava, Musa* sp., *Moringa oleifera, Ziziphus mauritiana, Bombax costatum, Piliostigma thonningii* and *Citrus lemon.* Exotic species in these parklands include: *Azadirachta indica, Mangifera indica, Psidium guajava* and *Moringa oleifera* while the rest is natural. The fruits, leaves, flowers, gums, barks, etc. of these trees species of socio-economic importance can be transformed into useful products which are eaten and/or sold in local and regional markets.

3.5. Specific Richness and Floristic Diversity of Agroforestry Parklands

Floristic survey revealed a total of 4801 trees recorded and distributed in 22 species, 17 genera and 14 families. The shannon index varies from 1.2 in mixed *Acacia senegal - A. nilotica* parkland to 2.91 bits in *Hyphaene thebaica*. This trend indicates a low floristic diversity of the sahelian parklands (Table 2). The Fabaceae and Arecaceae families were the most representative. The value of the Simpson index confirms the low diversity aforementioned.

Table 2. *Diversity characteristic of agroforestry parklands.*

Parkland Type	Number of trees	Specific Richness	Shannon index	Simpson index	Pielou Equitability
Hyphaene thebaica parkland	3112	22	2.91	0.92	0.95
Balanites aegyptiaca parkland	585	21	1.73	0.77	0.91
Mixed *Acacia senegal - A. nilotica* parkland	1104	20	1.62	0.7	0.82

3.6. Structure of Sahelian Parklands

The global parkland structure varies according to tree parameters considered.

3.6.1. Diameter of the Trees

The diameter distribution of the species in sahelian parklands presents a belt shape apart from the type of parkland. The maximum of individuals is observed in the interval 10.1-40 cm independently of the parkland selected (Figure 6). This suggests that in these parklands, regeneration of seedlings and maintenance of old trees are difficult. Generally, these agroforestry parklands present a homogenous diametric structure. The belt shape exhibited is similar with those reported in the Niger's parklands [9].

3.6.2. Height of the Trees

Like in diameter at the breast height, vertical distribution of trees in sahelian parklands, shows analogous shape (Figure 7). These parklands present a dynamic trend according to relative dominancy of young individuals. The density of trees is high in lower woody and shrubly layers. The high existence of young individuals in the lower shrubly stratus indicates appreciable recruitment of the population between 5.1-20 m in the height.

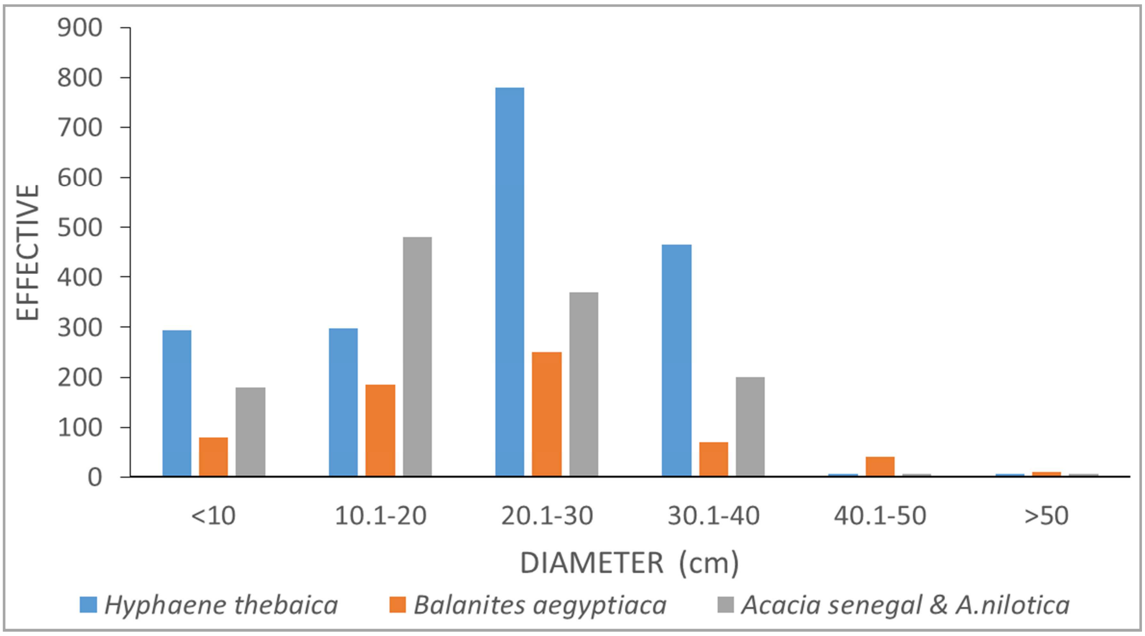

Figure 6. *Repartition of individuals following the diameter.*

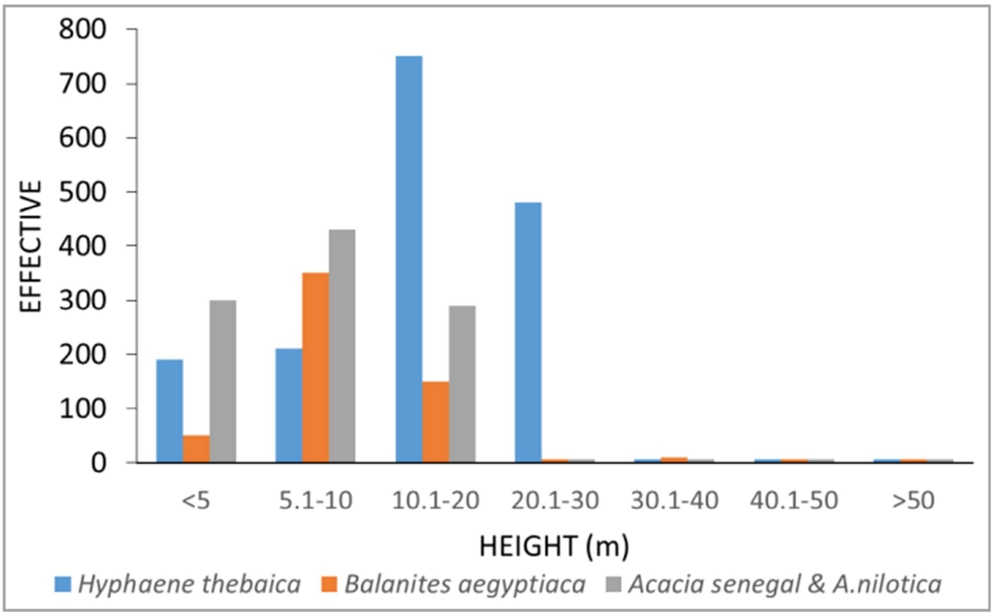

Figure 7. *Repartition of individuals following the height.*

3.6.3. Diameter of the Canopy

The global canopy diameter structure of the *Hyphaene thebaica* parklands follows a «J» distribution with a maximum of trees concentrated in 5.1-10 m as well as in the two other parklands. They show a belt shape (Figure 8). The belt shape is pronounced for *B. aegyptiaca* and mixed *Acacia senegal – A. nilotica* parklands. The number of tree species with a canopy diameter more than 30m is scarce. The number of individuals by diameter reduces with the increasement of canopy diameter. In general, these two sahelian parklands present belt shape suggesting that regeneration of young individuals and maintenance of old trees are difficult.

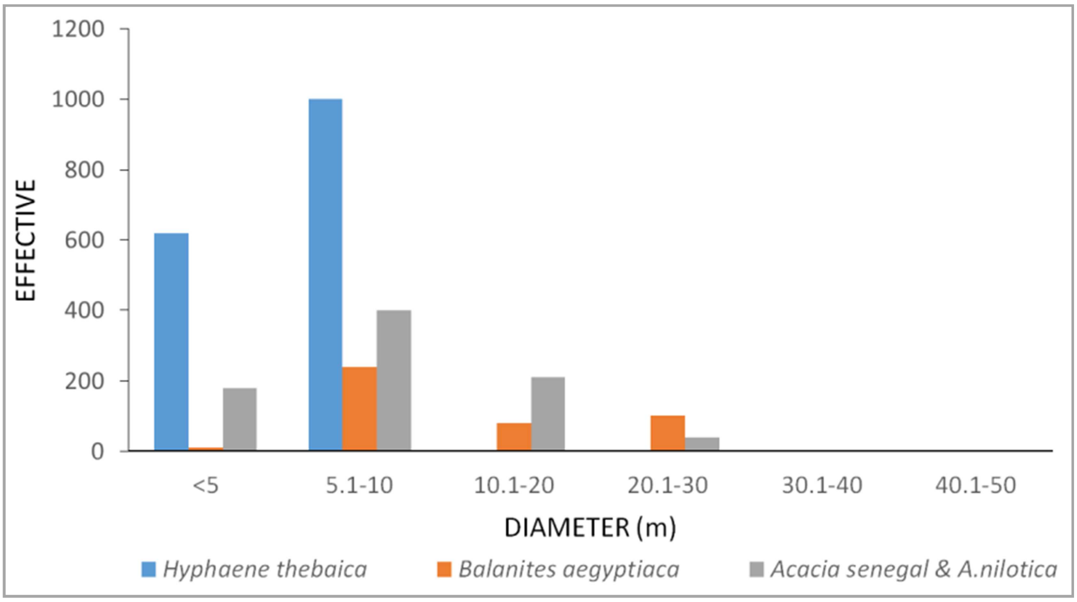

Figure 8. *Repartition of trees according to canopy diameter.*

3.7. Ecological Services and Economic Value

The carbon stock ranges from 5.60 tC/ha in *Balanites aegyptiaca* parkland to 21.10 tC/ha in *Hyphaene thebaica* parkland (Table 3). There is a significant difference among the parklands (0.03<0.05), suggesting that they operate differently. The ecological services of the Chad sahelian parklands fluctuates significantly from 20.25 tCO_2/ha in *Balanites aegyptiaca* parkland to 77.36tCO_2/ha in *Hyphaene thebaica* parkland (0.0005 <0.001), confirming the heterogenous carbon sequestration potential of the parklands. Concerning their economic aspect, farmers of the sahelian parklands of Chad will receive in total 1205.2 $, if carbon credit is paid. The highest economic value is observed in *Hyphaene thebaica* parkland.

Table 3. *Ecological services and economic value of Chad sahelian agroforestry parklands.*

Parkland Types	Total biomass (t/ha)	Total carbon stock (t/ha)	Total Carbon equivalent (tCO_2/ha)	Economic value ($USA)
Hyphaene thebaica	47.9	21.10	77.36	773.6
Balanites aegyptiaca	11.91	5.60	20.25	202.5
Mixed *Acacia nilotica - A. senegal*	13.3	6.25	22.91	229.1
Total	73.11	32.95	120.52	1205.2

4. Discussion

4.1. Typology of Parklands

The three types of agroforestry parklands distinguished are well known in the sahelian zone. Compared to sudanian parklands, those of Chad sahelian zone are less diversified. The specific richness of these parklands is low compared to what have been reported in others tropical ecosystems [20-22]. Nevetheless, this low specific richness value is higher than that registered in parklands reported in Doufelgo - Togo [4] and in Cameroon [2]. However, their density is appreciable because higher than that highlighted in *Prosopis africana* parrklands (7,89 trees/ha) of Niger [23]. The demography analysis has shown that these parklands exhibited a homogenous structure. Companion tree species found are natural except *Azadirachta indica*, *Mangifera indica*, *Moringa oleifera* and *Citrus lemon* introduced by sahelian farmers. Diverse functions are linked to plant species retained deliberately in parklands among which the common are food, regeneration of soil fertility, fodder production for animals, etc. Each of these species presents its proper structure depending to the use made by farmers. The average trees density varies significantly and the recovery flutuates according to the ecoligical requirement of crops (heliophilous, scyaphilous).

4.2. Floristic Diversity and Structural Characteristics

In general sahelian parklands show a low diversity with Shannon index ranges from 1.62 to 2.91 bits with indexes of Simpson and Pielou of the same trend, is a characteristic of the arid zone plant population. This trend express a homogenization or sahelization of the vegetation and mainly of the parklands [9]. Lack of diversity in these parklands is linked to the cultural practices of the area. The spatial structure of parklands is affected by specific crop management [3]. Different types of species are met in sahelian parklands: exotics and naturals. The low floristic richness observed at the level of parklands would be due to the use of species by the human populations for the satisfaction of their daily need as well as the ecology of crops produced.

The demography of sahelian parkland exhibits a normal distribution of diameter independently of the parkland type. As above mentionned, this distribution indicates that young and old trees in the system have difficulties to grow. These findings agree with those reported on *Borassus akeassi* parklands in Benin [24].

4.3. Carbon Sequestration Potential and Economic Value

Several works have shown the function of agroforestry systems as an opportunity to reduce CO_2 concentrations in the atmosphere by increasing carbon stocks in agricultural lands [7, 25-29]. Globally, Chad sahelian parklands store an average of 10.98 tC/ha. This value is low compared to that reported in other tropical’parklands [1, 2, 22]. Nevertheless, *Hyphaene thebaica* parkland showed a leading function in mitigating climate change. Its sequestration potential represents 54.19% of the biomass stored in these parklands. Despite certains phenomenons which destroy agroforestry parklands in general, those of the Chad sahelian zone are economically profitable and appear as an attractive alternative in terms of timber production, household income source and the fight against global warming. The total carbon captured by sahelian parklands is 120.52 tCO_2/ha. This finding disagrees the one reported in Tandjile-Chad [11], in Benin [30] and in northen Cameroon [2, 21, 31]. Chad sahelian parklands have a slip carbon sequestration capacity. In general, parklands play different major functions among which food, soil fertility restoration, fodder production for animals and several others ecological services.

5. Conclusion

Three different physiognomic types of agroforestry parklands existing in the Chad sahelian zone were characterized: *Hyphaene thebaica* parkland, *Balanites aegyptiaca* and mixed *Acacia senegal - A. nilotica* parkland. They are well known, well represented and well structured. Their physiognomy varies according to the specific flora and dominant species as well as objectives of the farmers. Two of them are monospecific (*Hyphaene thebaica,* and *Balanites aegyptiaca* parklands) and the third is mixed (*A. senegal - A. nilotica*). *Hyphaene thebaica* parkland plays a leading role in mitigating climate change by storing 54.19% of the biomass of the Chad sahelian parklands. The economic value is 1205.2 $USA. Valorisation of agroforestry systems will contribute to the biodiversity preservation as well as improving carbon sequestration potential and of cause supply data which will facilitate the Chad access to carbon market. To better know the functionning of the Chad sahelian parklands, the soil, litter and herbaceous species carbon stock needs to be estimated as well as crop production.

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