

# **Managing woodland development stages in Sudanian dry woodlands to meet local demand in fuelwood**

Eméline Sèssi Pélagie Assèdé <sup>a\*</sup>, Fortuné Akomian Azihou <sup>b</sup>, Samadori Sorotori Honoré Biauou <sup>a</sup>, Sayuni B. Mariki <sup>c</sup>, Coert Johannes Geldenhuys <sup>d</sup>, Brice Sinsin <sup>b</sup>

<sup>a</sup> Laboratoire d'Ecologie, de Botanique et de Biologie végétale, Faculté d'Agronomie, Université de Parakou, 03 BP 125, Parakou, Bénin.

<sup>b</sup> Laboratoire d'Ecologie Appliquée, Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, 03 PO Box 1974, Cotonou, Benin.

<sup>c</sup> Department of Wildlife Management, Sokoine University of Agriculture, P.O. Box 3073, Morogoro, Tanzania

<sup>d</sup> Department of Plant and Soil Sciences, University of Pretoria, 1121 South Street, Pretoria 0028, Republic of South Africa.

\* Corresponding author: tel: 0022997613829; email: [assedeemeline@gmail.com](mailto:assedeemeline@gmail.com)

## **Highlights**

- Selective thinning and pruning increase the biomass production.
- The best biomass production was obtained with 60% thinning and pruning.
- There is no significant correlation between household size and fuelwood demand.

## Abstract

Woodlands in the Sudanian zone are under different management regimes, including total protection and controlled use mainly for feeding livestock and collecting fuelwood. This study conducted in Sudanian woodlands of Benin, around the Biosphere Reserve of Pendjari (BRP) aimed to: (i) determine the effect of selective stem thinning and branch pruning on the production of standing biomass of the woodlands; and (ii) assess the effectiveness of Sudanian woodlands to meet the fuelwood demand of the local population. Three vegetation units of about 80 m × 80 m each were identified, relatively uniform floristically and structurally, and representing three woodland development stages in Sudanian woodlands. Three random blocks (replications) of 20 m × 20 m each were demarcated within each vegetation unit. Each block was then divided into four treatment plots of 10 m × 10 m each. Treatments were randomly allocated and consisted of i) no thinning (T1), ii) 30% thinning (T2), iii) 60% thinning (T3), and iv) 100% thinning (T4). Standard branch pruning was applied to all remaining stems. The species name, diameter and/or height of the remaining stems  $\geq 1$  m height were recorded twice during the year period between 2015 and 2016. A semi-structured questionnaire was randomly applied to 150 households to record detailed information on the tree species as well as the quantity of fuelwood used or sold each day. Thinning and pruning had a positive effect on biomass production. The best biomass production (0.88 t/ha/year or 15,028.5 t/year for an area of 16,938.7 ha) was obtained with 60% thinning and pruning. Whatever the treatment, the biomass production did not meet the demand for fuelwood of the local population around the BRP. A deficit between 69.5% (T1) and 64.6% (T3) was observed. The mean per capita fuelwood needs of the households was 1.3 kg/day, and decreased with increasing household size. Extending the experimentation over a longer period (at least ten years), and establishing and using the allometric equations of recorded tree species will improve the estimation of the biomass production of these woodlands.

**Key words:** Sudanian Woodland, tree growth, thinning, pruning, Benin.

## **Introduction**

Firewood is a vital bio-energy resource for the majority of low-income households in Sub-Saharan Africa (Bryceson and Howe 1993). The collection of firewood should therefore be regarded as an important subsistence task that complements the production or acquisition of food in the provision of adequate nutrition. Although seen as an important source of income, the African fuelwood trade is widely considered as having a negative impact. The third world-wide “fuelwood crisis” announced for the 2000s established the link between fuelwood use, deforestation and energy poverty, amplifying the von Thunen-esque “ripples” or “waves” of deforestation (de Montalembert and Clément 1983; Leach 1988; Cline-Cole et al. 1990; Sankhayan and Hofstad 2001). Ultimately, as wood stocks are progressively depleted, collection costs and fuel wood prices are increasing (Aron et al. 1991; Dang 1993). Based on theories of demand-supply and resource-advantage, the scarcity of the resource was identified as a key factor that influences the value assigned to the resource by local populations (Lawrence et al. 2005; Bell et al. 2012). The relationship between demand and supply underlines the forces behind the allocation of resources. Increased resource consumption can cause resource scarcities followed by environmental cost on natural resources (Homer-Dixon 1995; Ghermandi et al. 2010). This reality is increasingly important around protected areas in a context of high human population growth rate where communities are generally poor and depend directly on resource harvesting (Witemyer et al. 2008).

Whatever the resource, its’ sustainable use depends on how human needs are balanced with the long-term sustainability of the ecosystem processes. Fuelwood harvesting rates need to be

balanced with wood production rates in the woodland system for maintaining ecosystem functioning. Thus, the only way to achieve this objective is the development of adapted management strategies aligned with the ecology of these woodland systems. Managing woodlands in the Sudanian zone is of global concern (Dixon and Sherman 1990) and its sustainable use requires improved fuelwood productivity in terms of dry biomass production rates. Different management regimes have been developed in Sudanian woodlands, including total protection and controlled use, mainly for feeding livestock and for collecting fuelwood. Annual early dry season fires, selective tree cutting, and grazing exclusion were formally adopted to improve pasture and fuelwood production (Kaboré 2004; Laris and Wardell 2006; Savadogo et al. 2007; Sawadogo 2007; Dayamba et al. 2011). Their strategy was to exclude fire and grazing by livestock from the harvested plots for three to five years. Although an increase in biomass was observed, subsequent fires following three years of protection had a detrimental effect on woody regeneration due to the accumulation of grass biomass (fuel load) and more intense fires (Manaute 1996). Likewise, natural regeneration through direct seeding has produced unsatisfactory results, with survival rates of as low as 6% and 2% after the first and second year, respectively (Kaboré 2004; Sawadogo 2007). Conversely, tree diversity and subsequent standing biomass increased in fallow systems of Sudanian woodlands after five years (Assede et al. 2012). However, in old fallows (after 8 years), the woodland system showed a depletion in tree species due to competition for soil nutrients, and light (Assede et al. 2012).

The concerns around perceived degradation and loss of Sudanian woodland in terms of species diversity, wood production and use value of the woodlands for diverse user needs, could be addressed through selective stem thinning and branch pruning. As recently demonstrated through an experiment in Miombo woodlands (Geldenhuys et al. 2017), the implementation of selective stem thinning and branch pruning of woodland in different stand development stages

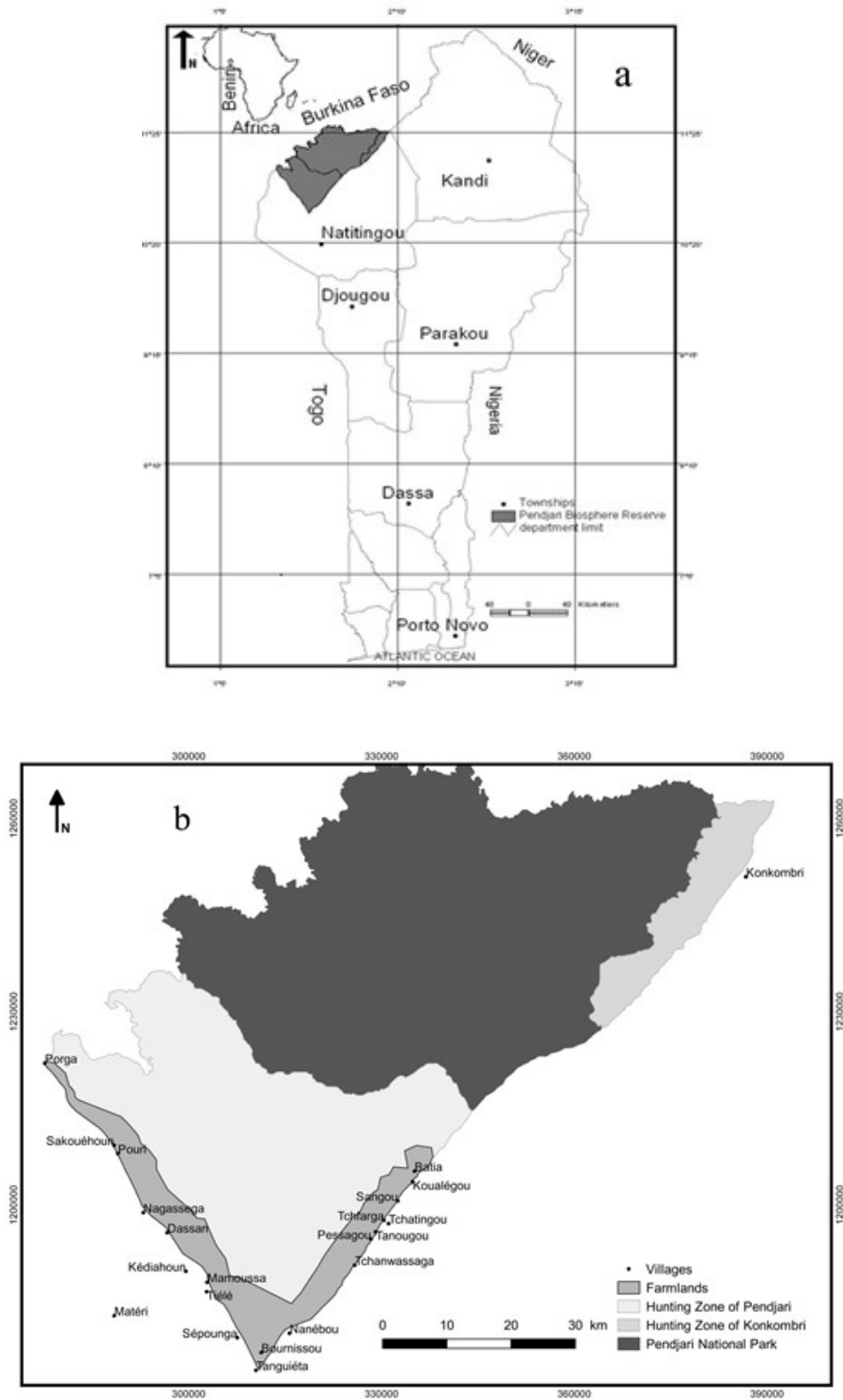
(Geldenhuys 2014) could maintain and improve woodland condition in terms of biodiversity and productivity. This was also shown in two time-series studies by Syampungani et al. (2010) and Chichinye et al. (2020) for different land use practices in Zambezian woodlands.

This study assessed the effect of selective stem thinning and branch pruning on biomass production of Sudanian woodland stands. It aimed to: (i) determine the effect of selective stem thinning and branch pruning on the productivity of standing biomass of the woodlands; and (ii) assess the effectiveness of Sudanian woodlands to meet the fuelwood demand of the local population. We hypothesized that: (i) an increased intensity in selective stem thinning and branch pruning will decrease the potential production of fuelwood in terms of standing biomass of Sudanian woodland stands; (ii) an increase in household size translates in proportionally lower increase in fuelwood demand.

## **Material and Methods**

### *Study area*

The study was conducted in the Biosphere Reserve of Pendjari (BRP), located in the Sudanian woodlands of Benin (10°30' to 11°30'N, 0°50' to 2°00'E) (Fig 1a) and covering 4806 km<sup>2</sup> (CENAGREF 2015). The reserve is comprised of a National Park (2761.23 km<sup>2</sup>) and two adjacent hunting zones (2001 km<sup>2</sup>) surrounded by a Controlled Area (CA) of mainly farmlands (Fig 1b), covering around 300 km<sup>2</sup> (CENAGREF 2015). The experimentation took place in the CA. This area is subject to anthropogenic activities with a vegetation composed of different woodland stand development stages (Assede et al. 2012).



**Figure 1.** Study area. a): map of Benin showing the location of the Biosphere Reserve of Pendjari; b): map of the Biosphere reserve of Pendjari showing the different components.

The BRP is bordered by the foothills of the Atacora Mountain in the east and the Pendjari River in the North and the West. It is characterized by one rainy season (mid-March to mid-September). The annual rainfall averages 1000 mm with 60% falling from July to September. The mean annual daily temperature is 27°C.

The vegetation comprises 802 plant species, distributed amongst 428 genera and 102 families. It is a mosaic of grassland, savanna and woodland, with gallery forest alongside water courses (Assede et al. 2012; CENAGREF 2015). The BRP encompasses 28% of the national flora of Benin (Assédé et al. 2012). The presence of endemic plant species (*Ipomoea beninensis* Akoègninou, Lisowski and Sinsin and *Cissus kouandeensis* A. Chev.) highlights the importance of the reserve for biodiversity conservation.

The local population, largely composed of farmers (96%), is estimated at 283 049, with an annual population growth rate of 3.16% (INSAE 2013). The main activities of the local population around the reserve are crop cultivation and livestock farming. Cultivated crops include rice, yam, maize and cotton, with the latter requiring intense use of pesticides (CENAGREF 2015). The savanna in the CA of the reserve is also intensively harvested for fuelwood, the main source of domestic energy for the local population (Tiomoko 2014).

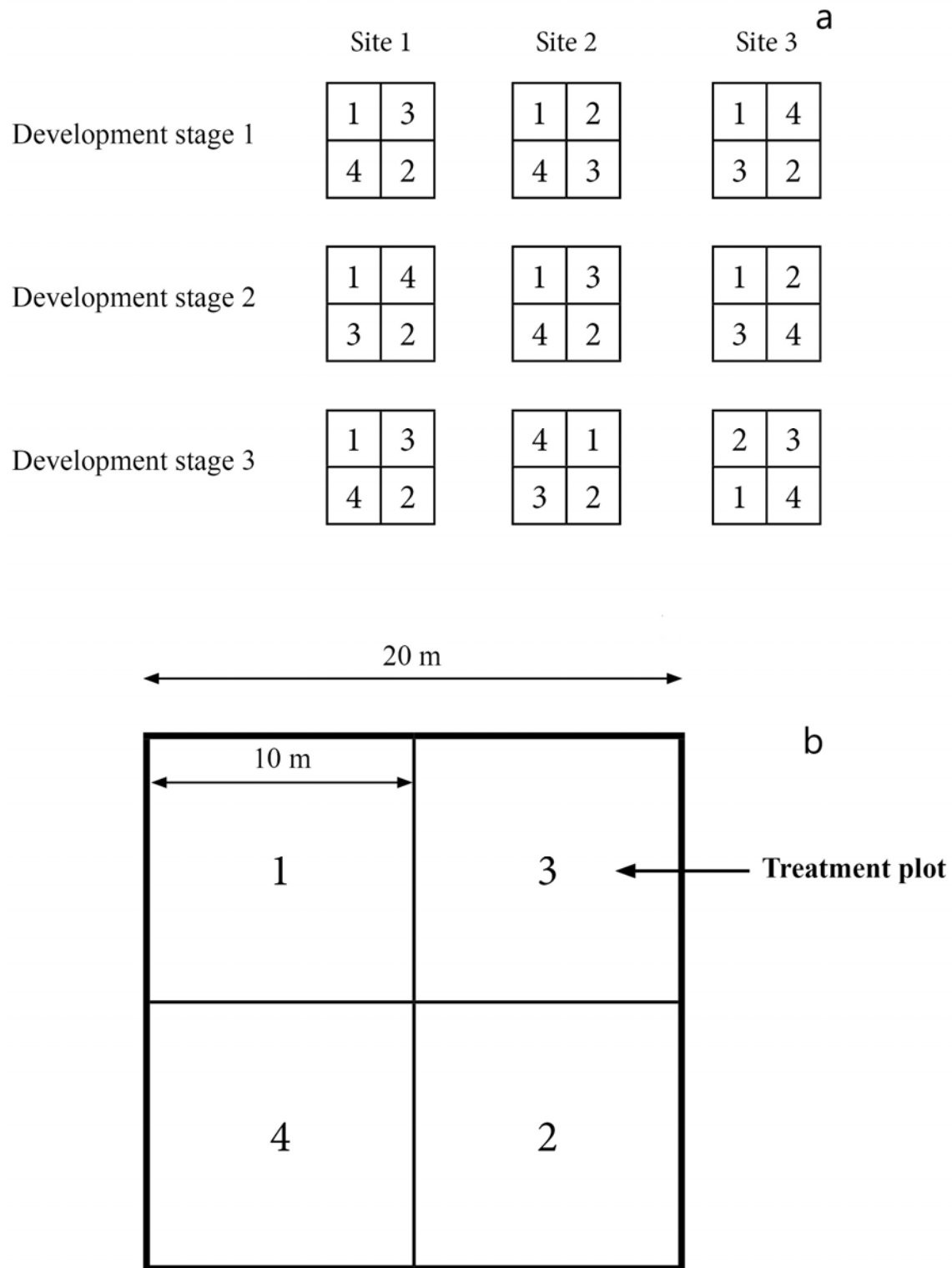
## Data collection

### *Woodland productivity under selective thinning and pruning*

An agreement and collaboration of stakeholders (forest authorities, reserve managers, farmers and herders) around the Biosphere Reserve of Pendjari were obtained for the successful implementation of the experiment. Three vegetation units of about 80 m x 80 m each were identified, representing the three main woodland stand development stages in the study area (Assede et al. 2012; Geldenhuys et al. 2013, 2017): (i) development stage 1: woodland fallow of less than three years with multiple small stems <2 m height; (ii) development stage 2: young woodland fallow of 3-5 years old with fewer stems of 2 to 4 m tall; (iii) development stage 3: advanced to mature secondary woodland fallow of 6-9 years with stems more than 4 m tall. Each unit was relatively uniform floristically and structurally. Three random blocks (replications) of 20 m x 20 m each were demarcated within each vegetation unit (Fig. 2a). Each block was subdivided into four treatment plots of 10 m x 10 m (0.01 ha) each (Fig. 2b). Four silvicultural treatments of stem thinning intensities (% thinning was based on number of stems  $\geq 1$  m height) were randomly allocated to each of the treatment plots:

- T1: no thinning and pruning, as control. All stems  $\geq 1$  m height were measured.
- T2: 30% stem thinning
- T3: 60% stem thinning
- T4: 100% cutting of all stems  $\geq 1$  m height.





**Figure 2.** Sampling design. a: Experimental design and layout; b: Layout of treatment plot.

1 = no thinning; 2 = 30% thinning; 3 = 60% thinning; 4 = 100% cutting of all stems

Branch pruning was applied to all remaining stems on the treatment plots, except Treatment T1, to improve stem form.

The stems of poorest quality, i.e. bent, poor growth, diseased and damaged were targeted for removal (depending on percentage thinning). The stems were cut as low as possible to the ground with a suitable pruning saw, to ensure good establishment of sprouting stems, and to prevent damage to other stems of the same plant, or any other stems in close proximity (Photo 1).



**Photo 1.** Thinning (a) and pruning (b) of stems in an experimental plot

The thinning intensities of T1 and T4 could be considered as control for the approach suggested by conservationists and the normal practices of small-scale farmers respectively, while T2 and T3 are experimental rates (Geldenhuys et al. 2017). Each treatment (observation) plot had a buffer zone of 5 m wide. Plots were not fenced but an agreement was obtained with the local people from the nearby villages to prevent any tree cutting during the experiment.

The species name, stem diameter at 1.3 m above ground level (dbh) and height of the remaining stems  $\geq 1$  m were twice recorded on the observation plots over the 1-year period between 2015 and 2016.

### *Assessment of local demand in fuelwood*

The local demand in fuelwood was estimated in terms of biomass. Considering the three most important ethnic groups (Gourmantché, Waaba and Berba) in terms of population around the BRP, five villages (Fig. 1) were sampled (Batia, Tchanwassaga, Bourignissou, Tiélé, Dassari). The villages were selected based on their closeness to the reserve (the closest) and their dependence on fuelwood. The assumption was that the closer to the reserve and the poorer the villagers are, the most likely they depend on fuelwood as source of domestic energy. Only women were interviewed because firewood collection in Sub-Saharan Africa is done by women (Bryceson and Howe 1993). Two survey methods were used to get as close as possible to the real daily fuelwood consumption pattern from the woodland by each household: a semi-structured survey coupled with a participatory observation.

A semi-structured questionnaire was randomly applied to 30 households (women) per village for a total of 150 households. Detailed information was recorded on household size, tree species collected, quantity of fuelwood used and sold each day. Three households from each village, randomly sampled per ethnic group, were monitored for seven days. Each woman was interviewed each day in the evening at the end of the meal preparation during the seven days. The amount of fuelwood (tree species name, average diameter and height of all stems) consumed was recorded daily. The purpose of this participatory observation method was to confirm the data recorded from the semi-structured survey.

Three samples of various sizes of each recorded tree species (Photo 2) during the survey were collected from the field to determine the wood density of tree species used for fuelwood. The wet mass of each sample was recorded in the field. The 89 samples were then oven-dried and weighed in the “Laboratoire de Production Animale” at the University of Abomey-Calavi.



**Photo 2.** A wood sample collected to determine the wood density of different tree species.

## Data analysis

### *Woodland production under selective stem thinning*

Stem wood volume (m<sup>3</sup>) of each remaining stem per tree species per treatment plot was calculated using stem dbh (cm), stem height (m), and a form factor of 0.496 (Deleuze et al. 2014) to correct for stem tapering, using:

$$V1 = 0.496 * (\pi * (\frac{d1^2}{40000})) * h1 \quad \text{Eq.1}$$

Where V1 = Stem wood volume in m<sup>3</sup>; d1 = stem dbh (m) and h1 = stem height (m) during first recording; The same formula was used with V2, d2 and h2 for the second recording of stem data, during the second measuring period. The stem wood volume of individual stems per 0.01 ha treatment sub-plot was summed to give a total stem wood volume (V1<sub>tot</sub>) per tree species per 0.01 ha treatment sub-plot. This value was converted to stem wood volume per ha using V1<sub>ha</sub> = 100\*V1<sub>tot</sub>. The increase in stem wood volume between the first (V1<sub>ha</sub>) and second (V2<sub>ha</sub>) measurement periods was calculated per tree species and per treatment subplot per stand development stage as:

$$Vj' = V2_{ha} - V1_{ha} \quad \text{Eq.2}$$

The total dry biomass per ha for each thinning treatment  $Pj'$  was determined for each species  $j$  per treatment sub-plot as:

$$Pj' = Vj' * \theta_j \quad \text{Eq.3}$$

With  $\theta$  representing the wood density per species determined with the wood samples.

To study the relationship between the average biomass production ( $y$ ) and the treatment (thinning intensity), the structure of the optimal random model was first examined. A linear model (LM)  $m0$ , and three linear mixed-effect models (LMMs)  $m1$  to  $m3$ , were fitted with the package nlme in R (R Development Core Team 2017) and compared to identify the most suitable model. Production data were  $\log(y)$  transformed to satisfy the requirements of these models.

The specifications of the models compared to identify the structure of the optimal random model were as follows:

$m0$ : linear model with no random effect (null model)

$m1$ : linear mixed-effect model with site as random factor

$m2$ : linear mixed-effect model with woodland development stage as random factor

$m3$ : linear mixed-effect model with site nested within stand development stage as random factor

The optimal model was  $m2$ , a mixed-effect model with only stand development as random variable, with the lowest Akaike Information Criterion (AIC) and Bayesian Information Criteria (BIC) (Table 1). There was no random effect of site ( $p=0.99$ ) on the productivity of biomass.

**Table 1.** Comparison of Linear and mixed-effect candidate models for woodland biomass productivity

Model	df	AIC	BIC	Test	p-value
Random models compared					
m0	2	85.23695	87.82862	m0 vs m1	0.99ns
m1	3	87.23695	91.12446	m1 vs m3	5 e <sup>-2**</sup>
m2	3	80.49163	84.37914	m0 vs m2	9.4 e <sup>-2**</sup>
	-	-	-	m2 vs m1	-
m3	4	81.35658	86.53993	m3 vs m0	0.02*
	-	-	-	m3vs m2	0.28ns
Models including explanatory variables					
m2.1	11	80.04563	94.29983	-	-
m2.2	7	73.28764	82.25850	m2.1 vs m2.2	0.87ns
m2.3	5	78.64074	85.11993	m2.2 vs m2.3	9.3 e <sup>-2**</sup>
m2.4	5	75.86988	82.34907	m2.2 vs m2.4	0.037*

ns=not significant; \*=significant à 5%; vs=versus; \*\*=Significant at 1%; LMs=Linear models; LMMs= Linear mixed-effect models; df=degree of freedom; AIC=Akaike Information Criterion; BIC=Bayesian Information Criteria; P-value=Probability value.

The optimal random model determined previously was subsequently used to assess the effect of the explanatory variables (i.e. woodland development stage and treatment) on biomass production. Linear mixed-effect models (LMMs) (m2.1 to m2.4) were fitted by inclusion of different combinations of the explanatory variables and compared in R 3.6.1.

The specifications of the models compared to assess the effect of the explanatory variables were as follows:

m2.1: optimal random model selected previously and inclusion of the Treatment, Stand development and their interaction as explanatory variables

m2.2: optimal random model selected previously and inclusion of the Treatment and Stand development as explanatory variables, with no interaction

m2.3: optimal random model selected previously and inclusion of the Treatment as the unique explanatory variable

m2.4: optimal random model selected previously and inclusion of the Stand development as the unique explanatory variable

The comparison used a built-in ANOVA function to evaluate whether the candidate models were significantly different based on the probability “p” of the test. Where  $p \leq 5\%$ , the more complex model was selected whereas for  $p > 5\%$ , the simplest model was preferred. The model selection criteria were also based on the AIC and BIC – the smaller their value, the better the fit (Zuur, 2009).

The best LMM with the lowest AIC and BIC was represented by the model m2.2 (Table 1). Pairwise comparison was eventually used to compare modalities of the significant explanatory variables with the package lsmeans in R 3.5.2 (R Development Core Team 2017).

Due to the absence of a random effect of site, biomass was averaged per treatment between the three blocks (Fig. 2) of each stand development stage. The production  $P_t$  in fuelwood, estimated in terms of total dry biomass in kg per year was calculated for each treatment using:

$$Pr = \sum_{j=1}^{n'} Pj' \quad \text{Eq.4}$$

$$Pt = \frac{1}{3} \sum_{k=1}^t Pr \quad \text{Eq.5}$$

where  $Pj'$  and  $Pr$  were the total dry mass of biomass production per species  $j$  and per treatment sub-plot respectively;  $n'$  the number of species per treatment sub-plot;  $t$  the number of treatment sub-plots.

Tree harvesting for fuelwood essentially occurs in woodland, which is the dominant ecosystem in the controlled area (Assede et al. 2012; CENAGREF 2015). The estimation of the initial woodland production  $P'$  around the BRP was based on the total surface of the controlled area

(the area where tree harvesting occurred in the BRP) without the cultivated lands estimated at 16938.7 ha (CENAGREF 2015). We assumed that proper woodland management should be sufficient for meeting the local demand in fuelwood.

The total biomass production  $P'$  of the controlled area around the Biosphere Reserve of Pendjari was estimated considering the production  $Pt$  of each treatment:

$$Pt' = Pt * S' \quad \text{Eq.6}$$

Where  $Pt$  (ha) and  $S'$ (ha) are the biomass production of the woodland per year and total surface of the controlled area without the cultivated lands, respectively.

#### *Assessment of local demand in fuelwood*

Average fuelwood consumption per capita ( $I$ ) – individual person in terms of dry biomass was estimated in kg per year using:

$$I = \sum_{k=1}^N Phk / N \quad \text{Eq.7}$$

With  $Phk$ : the total fuelwood needs for the surveyed household  $k$ ;  $N$ : the total number of individuals (size) of the household.

We used 2016 as reference to calculate local demand in fuelwood considering the period of data collection (2015-2016). The population of the villages around the BRP in 2016 was estimated from the results of the most recent population survey in Benin, and a yearly increment of 3% to account for the annual population growth since the last census (INSAE, 2013). The two main communes around the BRP: Tanguiéta and Matéri (Tiomoko 2014) and population data of their localities (INSAE 2013) were used. The closest villages (less than 2 km) to the reserve (33



villages) with direct influence on the woodland productivity in fuelwood (Table 4) were considered (CENAGREF 2015).

The total demand in fuelwood of each village per year ( $P_v$ ) estimated in kg (biomass) is determined as:

$$P_v = N' * I \quad \text{Eq.8}$$

Where  $N'$ : total number of individuals in the village;  $I$ : Average fuelwood consumption per capita per year.

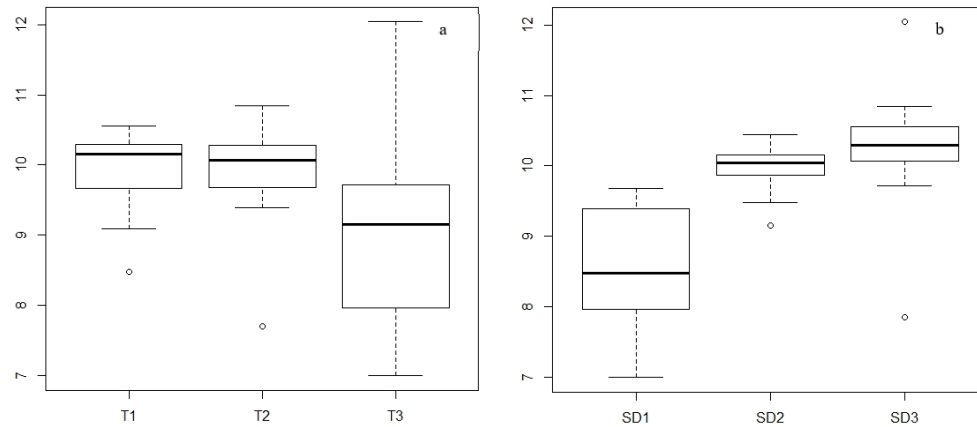
The fuelwood needs of the local population estimated in total biomass per year was compared to the production of woodland development stages with different intensities of thinning.

To assess the relation between household size and fuelwood demand, we modeled fuelwood consumption per capita of the households as a nonlinear function of the household's size (number of persons). The exponential decay function was selected for this purpose based on a preliminary visual inspection of the data.

## **Results**

### *Woodland production under selective stem thinning*

The mean, and range in biomass production varied between thinning intensities (T1 to T3) and between stand development stages (SD1 to SD3) (Fig.3). However, the differences in biomass production between stand development stages were not significant (Table 2).



**Figure 3.** Boxplot of the relation between biomass productivity and treatment (a) and stand development (b).

*T=treatment; SD=stand development*

**Table 2.** Result of the mixed effect model with treatment and stand development variables

	Coefficient	Std.Error	df	t-value	p-value
(Intercept)	8.87	0.79	22	11.17	0.00
Treatment 2	-0.03	0.38	22	-0.08	0.93ns
Treatment 3	-0.82	0.37	22	-2.17	0.04*
Stand development 2	1.35	1.08	0	1.25	NaN
Stand development 3	1.65	1.07	0	1.53	NaN

Std.Error=Standard Error; df=degree of freedom; t-value= Student t test value; ns= not significant; \*=significant à 5%; NaN=impossibility to run the analyses.

Regarding the treatment effect on the biomass production, only treatment 3 (60% thinning and pruning) is clearly demarcated, showing the convergence of both the boxplot in figure 3a, and the results in Table 2.

**Table 3.** Biomass production of woodland development stages with thinning intensity and pruning.

Intensity of Thinning	Sampled Area (m2)	Productivity (t/ha/year)	Total Productivity of CA (t/year)	Total need of the population (t/ year)	Production deficit (%)
Treatment 1	900	0.76	12944.0	42498.6	69.5
Treatment 2	900	0.79	13533.0	42498.6	68.1
Treatment 3	900	0.88	15028.5	42498.6	64.6

CA: Controlled Area of the Biosphere Reserve of Pendjari where people can harvest fuel wood. Total productivity of Controlled Area of BRP was extrapolated from the production measured on experimental plots and based on the total area. Total need of the population per year was extrapolated from surveyed households' consumption of fuel wood and based on the total population in the survey area.

The biomass production of Sudanian woodland stands varied with thinning and pruning intensity. The influence of thinning and pruning on biomass production was positive (Table 3). The best biomass production (0.88 t/ha/year or 15028.5 t/year for the 16,938.7 ha control area) was obtained with 60% thinning and pruning (treatment 3) and was the lowest with Treatment 1 (control, no harvesting).

#### *Local population demand for fuelwood*

In total, fuelwood demand for the closest villages to the Biosphere Reserve of Pendjari (BRP) was 42498.6 t/year (Table 4). Yearly, the average demand in fuelwood biomass varied between villages from 327.4 t to 3940.2 t with an average of 1.3 kg/day per capita. (Table 4).

**Table 4.** Average fuel wood biomass consumption of the local population per village

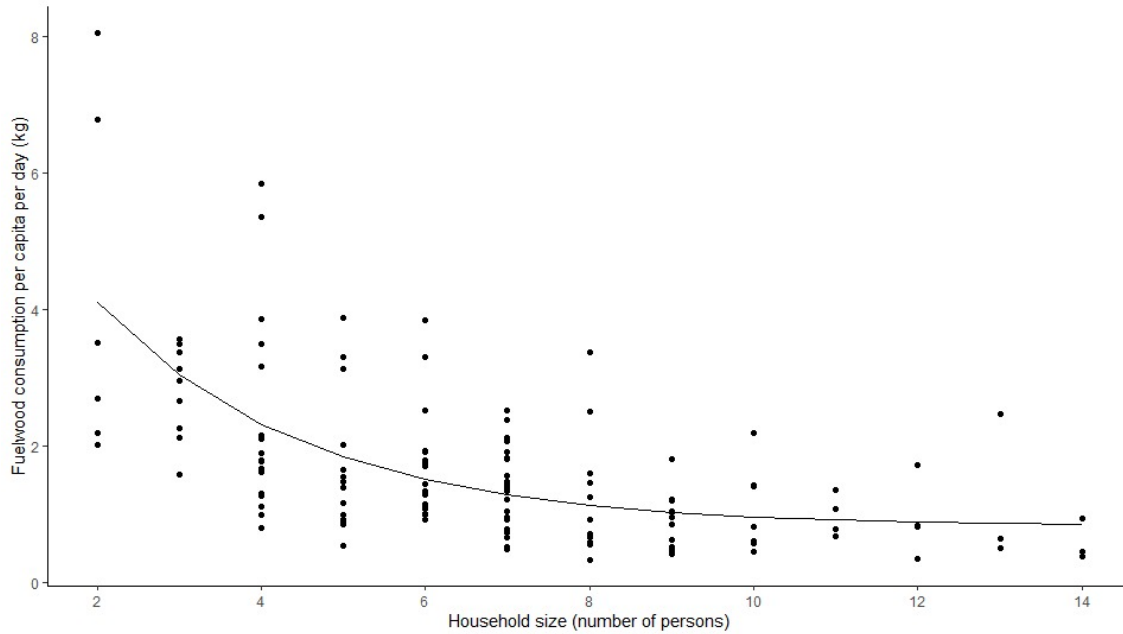
District	Villages	Population size (2016)	P (kg/day)	P (kg)/year	P (t)/year
Tanguiéta	Tchoutchoubou	8304	10795.2	3940248.0	3940.2
	Yarka	4145	5388.5	1966803.0	1967.0
	Porka	2734	3554.2	1297283.0	1297.2
	Bourniessou	3553	4618.9	1685899.0	1686.0
	Goro Bani	2767	3597.1	1312942.0	1313.0
	Djidjire Beri	2728	3546.4	1294436.0	1294.4
	Mamoussa	2755	3581.5	1307248.0	1307.2
	Tchanwassaga	2365	3074.5	1122193.0	1122.2
	Tchatingou	2301	2991.3	1091825.0	1091.8
	Batia	1786	2321.8	847457.0	847.4
	Tanongou	1868	2428.4	886366.0	886.3
	Nanébou	1338	1739.4	634881.0	634.8
	Tiélé	1277	1660.1	605936.5	606.0
	Tchafarga	1742	2264.6	826579.0	826.6
Matéri	Dassari	8164	10613.2	3873818.0	3873.8
	Pingou	4575	5947.5	2170838.0	2170.8
	Porga	4102	5332.6	1946399.0	1946.4
	Nagassega-Kani	3751	4876.3	1779850.0	1780.0
	Nodi	2955	3841.5	1402148.0	1402.1
	Pouri	3188	4144.4	1512706.0	1512.7
	Firihun	2865	3724.5	1359443.0	1359.4
	Satchndiga	2487	3233.1	1180082.0	1180.1
	Tétonga	2347	3051.1	1113652.0	1113.6

Daga	2006	2607.8	951847.0	952.0
Nagasséga	1961	2549.3	930494.5	930.5
Tihoun	1811	2354.3	859319.5	859.3
Kotari	1404	1825.2	666198.0	666.2
Borifieri	1310	1703.0	621595.0	621.6
Tigniga	1106	1437.8	524797.0	524.8
Ouriyori	1112	1445.6	527644.0	527.6
Tankouari	1064	1383.2	504868.0	504.8
Holli	3004	3905.2	1425398.0	1425.4
Kouarihoun	690	897.0	327405.0	327.4
Total	89565	116434.5	42498593.0	42498.6

P: Average biomass expressed in kilograms (kg) or in tonnes (t)

Whatever the treatment applied, the biomass produced did not meet the need of the local population around the BRP (Table 3). A deficit between 69.5 % (treatment 1: no thinning and pruning) and 64.6 % (treatment 3: 60% thinning) was observed. Compared to 30% thinning (T2) and 0% thinning (T1), the deficit in biomass produced with 60% thinning decreased by 4.9 % and 3.5 %, respectively.

The relation between household' size and per capita fuelwood need was nonlinear (Fig. 3) and the exponential decay function parameters were all significant (p value < 0.001). The per capita fuelwood need of the households starts at  $y_0=8.0$  and decays towards  $y_f=0.8$  at a rate  $\alpha=0.39$ . This indicates that larger households ( $\geq 8$  persons) tend to consume much less fuelwood per capita than smaller households. Yet, the moderate correlation ( $r=0.64$ ; p-value < 0.001) between the measured fuelwood need and the values predicted by the model suggests that other potentially important factors are not accounted for in the model.



**Figure 4.** Relation between the per capita fuelwood need of the households and the household's size (number of persons).

## Discussion

Although maintaining the complexity of ecosystems is an intermediate goal for sustainability, the implementation requires a good knowledge of existing resources. The first step for undertaking effective conservation action is to maintain the existing ecological processes and ecosystem services through the maintenance of the initial woodland stock in terms of biomass while satisfying the need of the local population in fuelwood.

In the Sudanian zone of Benin, the demand for fuelwood around the Biosphere Reserve of Pendjari (BRP) varies between localities as a function of the number of households per village. A high population causes a high pressure on the woodland. Thus, the high demand in biomass of some villages is directly related to their high number of households. However, this method to estimate local demand in fuelwood did not consider some of the use aspects. A village with a low number of households can consume more fuelwood than the largest one because of the

differences in uses and household size. For instance, Rudel (2017) demonstrated that a great part of the fuelwood harvested from the forest is sold in markets. A village specialized in trade of fuelwood directly harvested from the woodland will consume more fuelwood compared to the one only focused on domestic uses. As hypothesized, the per capita fuelwood needs of the households decrease with an increase in household size, but not proportionally. This result also suggests that there would probably be more fuelwood waste in cooking for smaller households. Uses also refer to the preferred tree species and diameters for fuelwood. Whatever the focus, woodland-logging often targets different cohorts of tree species, especially the most valuable (Kwashirai 2009; Bouriaud et al. 2013). It is important to improve this method by including donations between households and preferred tree species.

The intensity of woodland use can compromise the effectiveness of its valuable role in maintaining biological diversity (Dixon and Sherman 1990; Assede et al. 2012) and ecosystem services provision. The post-harvesting dynamics in woodland would relate to change in light intensity, soil nutrient redistribution and growth rates of remaining tree stock (Souza *et al.*, 2015). In the context of the study area, post tree-harvesting conditions allowed subsequent biomass productivity, whatever the intensity of thinning and the development stage, to meet local demand, with a positive influence of thinning and pruning. However, the question is how long this positive effect would last. Globally, increasing growth in human population has caused rapid degradation of the woodland ecosystems, resulting in excessive exploitation of tree species for fuelwood and construction material (Stephene and Lambin 2001; FAO 2010; Chirwa et al. 2014). In the Sudanian zone, land use change was strongly accelerated during the last 30 years due to an increase in population. The population growth rate (3% in average) around the BRP (INSAE 2013; Tiomoko 2014) requires an adapted and sustainable management plan of the woodland. Yet, woodland productivity in CA of the BRP did not meet

local need in fuelwood whatever the treatment. The continual increase of the human population around the BRP would probably exacerbate the gap in fuelwood need in the absence of an adapted alternative. Several studies pointed out that Protected Areas (PAs) are the most threatened ecosystems, under increasing pressure mainly because of the expansion in human demand on the environment, exponential population growth and excessive consumptions (Wittemyer et al. 2008; DeFries et al. 2010; Karanth and DeFries 2010; Laurance et al. 2012). Humans get attracted to PAs especially around the BRP because their surroundings abound in ecosystem services (Binlinla et al. 2014). Local populations in the vicinity of the BRP are reported as part of the poorest of the country and strongly relying on firewood as the main source of domestic energy (Tiomoko 2014). A large number of rural households is strongly dependent on these reserve resources for their livelihoods (Vodouhê et al. 2009, 2010; Vodouhê and Dansi 2012), thereby threatening biodiversity (Lambin et al. 2003).

The general perception is that wood production rates in the woodlands of Africa are slow. However, Syampungani et al. (2010) and Chichinye et al. (2020) showed relatively fast rates of 0.5 to 1.0 cm/year and more in stem diameter growth in natural stands of Zambezian woodlands, without any stem thinning. Most woodland species are intolerant of shade and develop even-aged stands. Interestingly, great floristic similarity was demonstrated between Sudanian and Zambezian woodland (Assédé et al. 2020). The theory of light demand or relative shade tolerance of species, often documented in plant ecology (Brokaw and Busing 2000), suggest an intense competition between stems in the stands. Protection and single tree harvesting, as is often advocated, do not contribute to maintaining biodiversity and productivity of such stands (Syampungani et al. 2010; Chichinye et al. 2020). Selective removal of suppressed, deformed and damaged stems could reduce such competition and provide more growing space for the better stems to grow faster. Thus, from this study, the best biomass

production is obtained with 60% thinning and pruning probably because of a combined effect of increased light incidence, reduced tree density and thus competition for nutrients. The intensity of tree thinning and pruning can be seen as modelling of light penetration which directly or indirectly influence woodland productivity. In the theory of recruitment limitation (Muller-Landau et al. 2002), the biomass production releases on the establishment of tree species limitation. An increasing biomass production would reflect a positive post-logging recruitment. Several scientists have long recognized the implications of these factors in post-logging dynamic (Geldenhuys 2014; Syampungani et al. 2016; Chichinye et al. 2019; Nyirenda et al. 2019; Assédé et al. 2020). However, most plant ecological theories were applied to forest tree species and their application in savanna ecosystems is questionable. In the condition of Sudanian woodland, canopy cover did not really affect light penetration, except in woodland development stage four (Geldenhuys et al. 2017) characterized by an almost close canopy (Assede et al. 2012). Variation in the recruitment limitation (Hubbell et al. 1999) and resource heterogeneity across a range of ecosystems is highlighted as an important factor determining tree growth and woodland productivity. The estimated biomass would probably change depending on whether the estimation of woodland production include other vegetation types. It also has to be considered that this study was done over 1 year, which is a very short period, but yet it showed positive growth rates. If the system can be managed over a longer period, then the total biomass will increase as more trees will grow from stand development stage 1 to 3. Daily wood consumption for household use could be obtained through regular stem thinning and branch pruning as a silvicultural management system. Local households need to be assisted to change their resource use practices from regular cutting of all stems (with only small stems remaining) towards selective cutting of suppressed and deformed stems to accumulate biomass in larger stems to eventually supply in the demand for household consumption.



How species composition impacts the response of woodlands to thinning and pruning intensity is not investigated in this study, though it would probably affect the results. A long-term experimentation with a clearly separated measure of thinning and pruning effect could show stand development effects as well as site effects and provide more complete understanding and models of woodland productivity.

## **Conclusion**

Woodland management with selective thinning and pruning was shown to have a positive influence on biomass production. The best production was obtained with 60% thinning and pruning. However, whatever the treatment, the productivity of the Sudanian woodland in biomass did not yet meet the demand of the local population around the Biosphere Reserve of Pendjari. Extending the experimentation over a long period (at least ten years) in correlation with local population growth and a separated measure of thinning and pruning effect can improve the results. Also, the establishment and use of allometric equations of recorded tree species is necessary for a better estimation of the biomass production of woodlands. Moreover, there was an exponential relation between the per capita fuelwood need and the household size. The per capita fuelwood needs of the households decreased with increasing household size, suggesting that smaller households might be responsible for larger consumption of fuelwood due to potential wastes. The inclusion of information on the cooking devices used by the households in future surveys would help in interpreting these patterns and in identifying appropriate measures to mitigate households' impact on woodlands.

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