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Firewood yield and profitability of a traditional *Daniellia oliveri* short-rotation coppice on fallow lands in Benin

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ABSTRACT

Sub-Saharan Africa has a great diversity of local coppicing species which are exploited in traditional short coppice systems for firewood. Biomass yield and profitability of these systems as well as their responses to silvicultural improvement are little known. This study evaluated the firewood yield and the profitability of a traditional *Daniellia oliveri* short-rotation coppice on fallow lands in central Benin. Two weed management options were considered: (1) the weedy option, usually practiced by locals, which experienced grass competition and bushfires, and (2) the weed-free option, which consisted in periodic removal of grasses and other species. Destructive measurements and allometric equations were used to estimate biomass yield in 12 plots over 42 months. A cost-benefit analysis model based on the net present value and the benefit-cost ratio was used to compare the profitability of the two management options. Biomass accumulation rate averaged 1.08 ± 0.20 tonnes of dry matter ha^{-1} $year^{-1}$ (t DM ha^{-1} $year^{-1}$) in weedy conditions. Weed removal improved 3.5 times this rate in weed-free plots (3.83 ± 0.47 t DM ha^{-1} $year^{-1}$). After 42 months, total biomass reached 3.67 ± 0.65 t DM ha^{-1} in weedy plots and 11.63 ± 0.76 t DM ha^{-1} in weed-free plots. Most of the biomass (≥88%) was marketable in local markets. Coppice exploitation was profitable after 24 months for both management options. Weed removal improved the profits three times. A sensitivity analysis showed that both options were still profitable with up to 25% increase of labour and transport costs, 25% decrease of biomass price and 12% increase of the discount rate.

1. Introduction

Short-rotation coppice on agricultural lands is a promising option to increase firewood supply in the context of the search for alternatives of sustainable energy sources in Sub-Saharan Africa [1,2]. Firewood is the major source of energy in the region and its demand is expected to increase in the next decades [3,4]. Firewood resources from natural forests are decreasing. Today firewood harvesting practice consists in cutting green coppices of a wide range of indigenous species while the productivity of fallow lands which supply the bulk of the coppices is decreasing [1,5–8]. At present, long-rotation management of forests and available lands with slow-growing indigenous species to meet firewood demand would not be accepted by farmers and local communities [8,9]. Short-rotation coppice with high use potential indigenous coppicing species has been proposed as an alternative to improve firewood supply and livelihoods of smallholder farmers [1,9].

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Short-rotation coppice consists in growing pioneer trees with rapid biomass growth rates and abilities to resprout after cutting [10,11]. The suitable species for short-rotation coppice must be of: (1) fast growth, (2) good coppicing abilities, (3) high survival rate and good resistance against pests, diseases and fires in tropical regions, (4) good wood combustion characteristics [10,12]. When managed in a sustainable and economic way, short-rotation coppice has a great potential to partly meet energy demand and generate incomes and other environmental benefits [10,13,14].

Managing and promoting short-rotation coppice in an ecologically and economically sustainable manner requires as for any silvicultural system, basic knowledge on the growth and silviculture of the targeted species, and the profitability and ecological sustainability of the production systems [10,15–17]. The first key steps are the estimation of potential biomass productivity, identification of effective silvicultural treatments (e.g. thinning, weeding) for improved yields and cost-effectiveness of production options [10,15]. Especially, economic considerations from the viewpoint of farmers must be taken into account in research on biomass plantations on agricultural lands [10]. This kind of information is essential to prove the feasibility of any silvicultural intervention and understand the influential factors of its adoption and upscaling [10,13].

In Sub-Saharan Africa, these basic data are unfortunately limited or missing for most of the indigenous firewood species [18,19]. The potential of the great diversity of local trees of the region for short-rotation coppice for firewood production has been little explored [19,20]. Most forestry studies have focused for decades on large-scale plantations with exotic fast-growing tree species such as *Acacia* spp., *Eucalyptus* spp. and *Senna siamea* [21]. Bellefontaine [20] has provided a provisional inventory of indigenous woody species, which have coppicing abilities in the Sudanian and Sahelian zone. Evidence from past research has also revealed that local communities are exploiting many of the species in traditional short coppice systems for firewood, and their productivity may increase substantially if suitable and cost-effective improved silvicultural practices are performed. This is the case for pioneer species such as *Guiera senegalensis* and *Combretum glutinosum* in the Sahel [6,22–24], *Daniellia oliveri* in the Sudano-Guinean zone [25–27], and *Markhamia lutea* in East Africa [28]. Many of these species such as *G. senegalensis* and *D. oliveri* have high natural densities and relatively rapid growth forming monospecific stands [23,24,27,29]. However, the biomass yield and economic benefits of these traditional systems as well as their responses to silvicultural improvements (e.g. weeding, thinning) are little known. Even if existing literature reported a few data on the yield abilities of mixed-species stands in fallows and savannas [17,18], data on the silvicultural behaviour of individual species and the financial performance of short coppice systems with those species are still lacking.

This study integrates both ecological and economic approaches to investigate the biomass production and profitability of a *D. oliveri* traditional short coppice system for firewood production on fallow lands in the Guinean and Sudanian zone of Benin. Specifically, we estimate total and marketable biomass productivity and related profits of the system over 42 months. We also tested the effects of a simple silvicultural improvement consisting in periodic weed removal on the biomass yield and profitability of the system.

Weed control is a key factor in coppice management and may improve substantially tree growth [10,27,30,31]. In grassland of the Sudanian and Guinean zone, grasses represent 80–90% of weed biomass and their interactions with trees may result in three major limiting effects [32]. First, grasses may compete with trees for soil nutrients [31]. Second, frequent and intensive fires favoured by grass necromass may impede tree growth [31–33]. Third, fires may burn weed biomass in fallows and inhibit organic matter accumulation in the soil [31,34]. We hypothesized that weed removal and fire prevention practices would overcome all these limiting factors and improve the growth rate of the total and marketable aboveground woody biomass. The improvement of the biomass growth rate would increase the profitability of the system for smallholder farmers, so that the system would be more attractive to them.

2. Material and methods

2.1. Study area

The study area covers the Sudano-Guinean transition zone of Benin, a country located in the Dahomey Gap of West Africa between 6°20′–12°25′ N and 1°–3°40′ E. Annual average rainfalls range between 900 and 1200 mm, and occur mostly during the rainy season from April to October. Major soil types encountered in this region include alluvial clay soils, lateritic soils, ferruginous sandy soils and ferralitic soils [35]. Vegetation consists of woodlands, tree and shrub savannas, and fallows with abundance of *D. oliveri* and *Andropogon gayanus*, the dominant grass species [36]. The monthly herbaceous biomass growth rate of these grasslands averages 0.8–1.5 tonnes of dry matter per hectare (t DM ha^{-1}) during the rainy season and the annual biomass may reach 4–8 t DM ha^{-1} [37,38]. Because of accumulation of grass necromass the area experiences frequent bushfires during the dry season from December to April. Beside the expansion of croplands, the traditional exploitation of woodfuel from fallows and savannas to meet nearest cities' demand is a widespread activity [36].

2.2. Study species and its exploitation in traditional short-rotation coppice

D. oliveri (Rolfe) Hutch. & Dalz. is widespread in Sudano-Guinean savannas up to Gambia and Uganda [29]. It is a multipurpose tree species belonging to the sub-family of Caesalpiniaceae. It has generally a single stem, which may grow 2–3.5 m high in less than three year [27] and reach 30 m at adult stage [29]. It has vigorous stump sprouting and root suckering abilities, tends to invade forest fallows and usually forms monospecific stands with up to 2500–7500 stems ha^{-1} [19,27,29]. It is found on various types of soil, even on marginal agricultural lands, which characteristic may be a great asset for short coppice. Its wood is well appreciated as fuel in the Sudanian and Sahelian region [25–27]. Its wood specific

gravity is 0.64 ± 0.03 Mg m^{-3} and the net calorific value is 16–17 MJ kg^{-1} [26].

Local smallholders' management practices in the study area consist in land abandonment after the cropping period (generally 2–3 years). Then, the species resprouts intensively and forms almost pure stands [27]. Rotation cycles practiced by farmers depend on the region, on the acuity of firewood problems and on the purpose of production. When farmers manage the coppice for self-consumption, they may harvest coppices at any time during the fallow period to satisfy domestic firewood needs. On the contrary, when it is about commercial purpose, they leave the coppice until it reaches a suitable age before cutting (a minimum of two to eight years). Farmers harvest coppices manually and following that the species resprouts again. Usually, they do not control weeds and bush fires during the fallow period. Harvested coppices are sold in bundles of 30–40 sticks on local markets, generally located along main roads to cities [27].

2.3. *Study design and data collection*

2.3.1. *Size and price of marketed firewood and definition of marketable size criteria*

We conducted a market survey in October 2005 to define the criteria for marketable firewood size and estimate the biomass weight and prices of marketed bundles for further estimation of biomass prices. The survey was conducted during the dry season because in the rainy season, *D. oliveri* firewood is marketed in mixed bundles with other species. Indeed, during the rainy season, natural stands of the species are bushy and quite impenetrable making cutting difficult and harvest costs too high. Thus, farmers prefer mixing *D. oliveri* with any other species they may find to make bundles. Three local markets namely Abomey (7°11′ N, 1°59′ E), Agbangnizoun (7°4′ N, 1°57′ E) and Zogbodomey (6°58′ N, 2°10′ E), were selected. Ten bundles of firewood were sampled randomly, each from one vendor in each market. The number of sticks of firewood in each bundle was counted and the length and butt diameter of each stick were measured. The 10% quantiles of the distributions that best fit the length and butt diameter of the sticks was used as reference sizes on the field to decide if a coppice met local market requirements. The length of firewood sticks fitted a normal distribution of mean and standard deviation equal to 98 and 14 cm respectively, while the butt diameter fitted a gamma distribution of shape 5.3 and rate 1.6 (Fig. 1). The 10% quantiles of the length and diameter distributions were 80 cm and 2 cm respectively (Fig. 1). Thus, a stem should have a height and a basal diameter superior to 80 and 2 cm respectively to be considered marketable.

Each bundle was weighted to determine its total air-dried weight. Five 15 cm-long stick cookies were sampled for each market and oven-dried at 80 °C for 15 days for determination of the dry matter content. The estimated dry matter content was 73% in the market of Abomey, 62% in the market of Zogbodomey and 88% in the market of Agbangnizoum. The total dry weight of bundles was estimated by multiplying their air-dried weight by their dry matter content.

2.3.2. *Estimation of total and marketable biomass*

To measure periodic variations of total and marketable biomass and test whether they were improved by weed removal, we established twelve 10 m × 5 m-size plots in village fallows one year after field abandonment in October 2005, far from forest stands to avoid seeds from mature trees

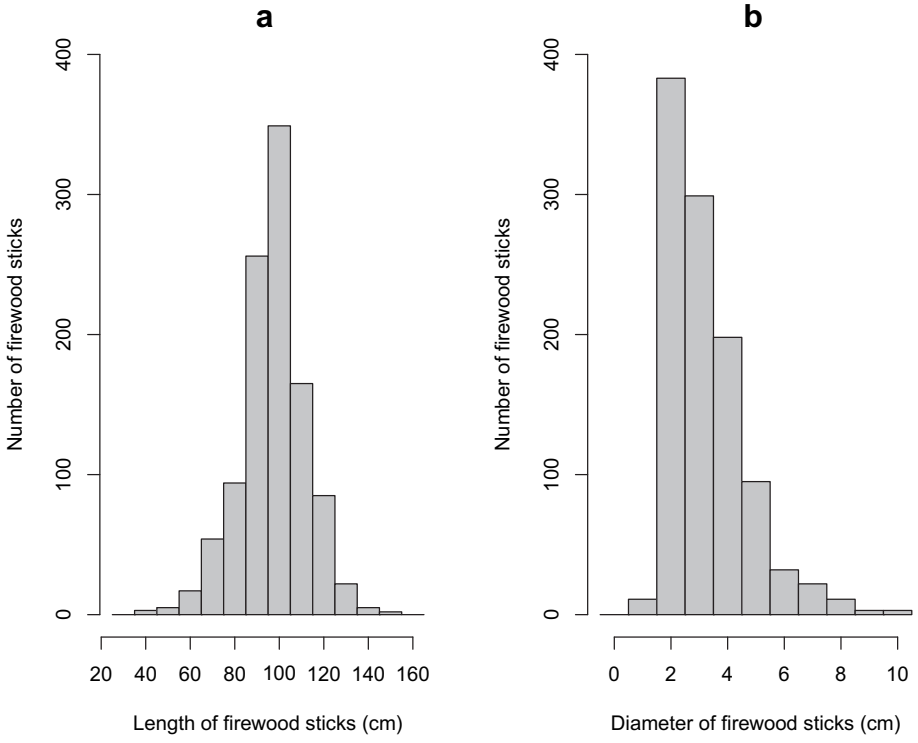

Fig. 1 – Size distribution of *D. oliveri* marketable firewood sticks from three local markets (a) length of firewood sticks, (b) butt diameter of firewood sticks.

to be dispersed onto the plots. Three of the major soil types of the study area were considered for plots' establishment: (1) alluvial heavy clay soil in the area of Zogbodomey, (2) ferruginous sandy soil in the area of Abomey, (3) lateritic soil in the area of Agbangnizoun. Two sites at least 5 km distant and as homogenous as possible with respect to their history of cultivation were selected on each soil type. In each site, we set up two plots 50 m apart and applied one of the two weed management treatments to each plot: (1) the weedy control treatment which is usually practiced by farmers and consisted in leaving weeds on the plots and, (2) the weed-free treatment which consisted in hoeing and mulching all weeds including grasses and other species in the plots twice a year (in June three months after the beginning of rains, and in October at the end of rains) until canopy is closed, 24 months later. Because of grass biomass accumulation in the weedy plots, they practiced bushfires during the dry season (January to March). During weed-freeing operations, we made firebreaks around all weed-free plots to prevent tree vegetation from burning.

At the inception of the experiment after plots' establishment, we cleared land in all plots. We removed any vegetation and cut down *D. oliveri* shrubs at ground level [19]. We estimated total and marketable woody biomass through a combination of destructive and non-destructive measurements 6, 12, 18, 24, 36 and the 42 months after land clearance.

Destructive measurements were performed only after 42 months. We felled all trees within each plot and sorted the wet stem and branches of each felled tree into marketable and non-marketable parts depending on whether their sizes were superior to the reference sizes defined with the size distributions of marketed firewood. We then sectioned them into 0.5–1-m long segments of regular form. We measured the butt, median and end diameters and length of each segment and estimated its volume with the Smallian formulae $V = \pi/4 \cdot (d_1^2 + d_2^2) \cdot l/2$ where V is the volume, l is the length, d_1 is the butt diameter and d_2 the end diameter of the segment. We calculated the total volume of each tree by summing its entire stem and branch segments' volumes, and its marketable volume by summing the volumes of its marketable parts (stem and branches).

Five 15 cm-long cookies were also sampled from each plot and oven-dried at 80 °C for 15 days for wood density determination. Their oven-dried weight was measured and their volumes were approximated with the Smallian formulae. The wood density values calculated were 0.61 Mg m^{-3} in the area of clay soil and 0.55 Mg m^{-3} in the areas of lateritic and sandy soils. Total and marketable biomass was determined for each tree by multiplying the wood density by the total and marketable volume and for each plot by summing the total and marketable biomass of all trees in the plot.

Total and marketable biomass of individual tree at 6, 12, 18, 24 and 36 months was estimated through non-destructive measurements based on allometric equations derived from the biomass data of 42 months. We grouped all felled trees into four height classes (Table 1). Total and marketable biomass of individual trees in each class was regressed against basal diameter and total height using equations of the form $B = a \times d^b$ [16] or $B = a + b \times h \times d^2$ [39] where B is the oven-dried weight of the tree, h is the total height, d is the basal diameter, a and b are regression coefficients (Table 1). We used the equation with the best R^2 for each height class to estimate individual trees' biomass (Table 1).

2.3.3. *Evaluation of profitability*

To evaluate the profitability of the traditional coppice system and test whether weeding improved it, we performed a cost-benefit analysis for each of the six coppice ages, i.e. 6, 12, 18, 24, 36, 42 months. We considered each of the two coppice management practices, namely coppicing in weedy or weed-free conditions, as a production option. Input costs and output values were estimated for each plot at 6, 12, 18, 24, 36 and 42 months after land clearance. We calculated the net present value (*NPV*) for each period as follows: $NPV = \sum_{t=1}^{t=n}(R_t - C_t)/(1-r)^t$ where R_t is the expected benefits from biomass selling, C_t is the values of production costs, t is the time in years and r is the annual discount rate [40]. The annual discount rate r applied by the microfinance structures of the study area is equal to 3%.

We calculated the benefit-cost ratio for each period by dividing the net present value by the present worth of the costs stream for the six coppice ages.

$NPV > 0$ means that the production system is economically profitable, and then farmers may accept it. $NPV < 0$ means that the production system is not economically profitable, and then farmers may reject it. We compared the net present value and the benefit-cost ratio for the two coppice management options to determine the effects of weeding operations on the profitability of the coppice system through time. In the absence of funding constraints, the most acceptable system is the one with the highest net present value. The benefit-cost ratio helps to further evaluate the profitability of production

Table 1 – Total and marketable tree biomass estimation equations for 6, 12, 18, 24 and 36 months-aged coppices.

Height classes	Total biomass		Marketable biomass	
	Equation	R^2	Equation	R^2
≤75 cm	$B = -4.91636 + 0.3011 \times h \times d^2$	0.99	$B = 21.89 \times d^{2.11}$	0.99
76–115 cm	$B = 10.38 + 0.27 \times h \times d^2$	0.99	$B = 30.79 \times d^{1.87}$	0.96
116–200 cm	$B = 43.56 + 0.21 \times h \times d^2$	0.98	$B = 17.43 \times d^{2.55}$	0.90
200–400 cm	$B = 79.75 + 0.19 \times h \times d^2$	0.98	$B = 13.86 \times d^{2.75}$	0.96

B = tree oven-dried biomass in g.
h: total plant height (cm).
d: basal diameter (cm).

Table 2 – Unit costs of wood biomass production in traditional *D. oliveri* short-rotation coppice in three different areas in March 2005.

Field operations	Weed management option	Coppice age (months)	Units[a]	Unit costs		
				Abomey (sandy soil)	Agbangnizoun (lateritic soil)	Zogbodomey (clay soil)
Land clearance	Weed-free	0	XOF ha^{-1}	8000	6000	6000
	Weedy	0	XOF ha^{-1}	0	0	0
Weeding[b]	Weed-free	n.a	XOF ha^{-1}	8000	8000	8000
	Weedy	n.a	XOF ha^{-1}	0	0	0
Harvest	Weed-free	6	XOF ha^{-1}	5000	4000	4000
		12	XOF ha^{-1}	8000	6000	6000
		18	XOF ha^{-1}	12000	9600	9600
		24	XOF ha^{-1}	16000	12800	12800
		36	XOF ha^{-1}	16000	16000	16000
		42	XOF ha^{-1}	16000	16000	16000
	Weedy	6	XOF ha^{-1}	3000	2000	2000
		12	XOF ha^{-1}	6000	5000	5000
		18	XOF ha^{-1}	8000	6000	6000
		24	XOF ha^{-1}	10000	8000	8000
		36	XOF ha^{-1}	10000	8000	8000
		42	XOF ha^{-1}	10000	8000	8000
Transport	n.a[c]	n.a	XOF kg DM^{-1} km^{-1}	0.21	0.13	0.13

a XOF: local currency, 1 USD ≈ 435–512 XOF, 2009 United Nations rates.
b Two weeding operations were performed per year on weed-free plots until the end of the second year.
c n.a. = not applicable.

options. It provides a means of selecting the most cost-effective option. The higher the benefit-cost ratio, the better the value of the production option is.

The major costs during the traditional production cycle were labour (land clearance, weeding, and harvest) and transport costs (Table 2). We considered no cost for land rental. We estimated all unit costs based on data of focus groups surveys we conducted in the nearest villages to our experimental sites in March 2005. All unit costs were generally standard for the same market area. We estimated weeding costs in XOF ha^{-1} per operation. Two weeding operations per year were performed on weed-free plots for two years. Harvest costs estimated in XOF ha^{-1} depended on the stand density, which in turn depended on the coppice age and weed management options (Table 2). Farmers usually transport firewood to markets with local transportation means (motorcycles or small vans). We estimated unit transport costs by recording the costs for one bundle and the distance to nearest markets from each plot site and then converting these data to unit costs in XOF kg DM^{-1} km^{-1} by dividing the recorded costs by the bundle dry weights and the distance to the markets. To estimate total transport costs in the net present value model, we considered an average distance of 15 km for all sites (mean distance farmers considered too far to reach a market). We considered no cost for planting material as the species regenerates naturally [27,29].

To estimate biomass selling-prices, we converted the selling prices of bundles obtained during the 2005 market survey to unit prices in XOF kg DM^{-1} by dividing the price of each bundle by its oven-dried weight. We then estimated an average price for each market (Table 3). We multiplied the unit prices by the marketable biomass at each period for each plot to estimate total benefits.

2.3.4. *Sensitivity analysis*

To take into account uncertainties due to changes in production costs and market conditions, we performed a sensitivity analysis of the profitability model [40]. We varied one at a time the selling prices, transport and labour costs (land clearance, weeding and harvest) by ± 25% and the discount rate by +6% and +12% and estimated the resulting changes on the net present value and benefit-cost ratio [40].

2.4. *Statistical analysis*

We used the linear mixed model with the first-order autoregressive within-subject error variance–covariance matrix to compare the two coppice management options with respect to the growth rates of total and marketable biomass, production costs, net present value and benefit-cost ratio. We considered

Table 3 – *D. oliveri* biomass selling-prices in three local markets in October 2005.

Markets	Price (XOF kg DM^{-1})[a]		
	Mean ± SD[b]	Minimum	Maximum
Abomey (sandy soil)	11.75 ± 1.85	8.75	14.75
Agangnizoun (lateritic soil)	25.50 ± 3.60	18.25	30.05
Zogbodomey (clayey soil)	15.5 ± 2.25	12.95	20.25
Mean ± 1 SD	17.50 ± 4.60	13.30 ± 4.75	21.70 ± 7.75

a XOF: local currency, 1 USD ≈ 435–512 XOF, 2009 United Nations rates.
b SD: standard deviation.

the coppice management option as the fixed-factor, plots as subjects (random) nested in sites (random), and the variance–covariance matrices were grouped by treatment and soil type, the coppice age being the repeated factor.

We used a mixed model in a split plot design to compare the total and marketable biomass, the net present value and the benefit-cost ratio of the two coppice management options at the end of the experiment (42 months), with weeding treatment (sub-plot factor) nested in soil type (whole-plot factor) and sites as random replicates. All biomass, net present value and benefit-cost ratio data were log-transformed to stabilize variances. We assessed all effects at 0.05 significance level.

3. Results

3.1. Total and marketable wood biomass yield

Total and marketable biomass increased significantly with the age of the coppice in weedy plots (1.08 ± 0.20 t DM ha^{-1} $year^{-1}$, $p < 0.0001$ for total biomass, and 1.05 ± 0.20 t DM ha^{-1} $year^{-1}$, $p < 0.0001$ for marketable biomass, Fig. 2). The biomass growth rate was improved 3.5 times for total biomass (3.83 ± 0.47 t DM ha^{-1} $year^{-1}$, $p < 0.0001$) and 3.6 times for marketable biomass (3.77 ± 0.45 t DM ha^{-1} $year^{-1}$, $p < 0.0001$), by weed removals in weed-free plots (Fig. 2). After 42 months, total biomass was 3.2 times higher in weed-free plots (11.63 ± 0.76 t DM ha^{-1}) than in weedy plots (3.67 ± 0.65 t DM ha^{-1}, $p = 0.0002$). Likewise, marketable biomass in weed-free plots (10.96 ± 0.61 t DM ha^{-1}) averaged 7.70 t DM ha^{-1} higher than in weedy plots (3.26 ± 0.64 t DM ha^{-1}, $p = 0.0002$). Marketable wood biomass represented 95 ± 2 and 88 ± 4% of the total biomass respectively on weed-free and weedy plots after 42 months. The non-marketable parts included mostly small branches which were more important in weedy plots (12 ± 4%) than in weed-free plots (5 ± 2%). The shape of growth curves showed that biomass might continue increasing significantly for both treatments if the experiment duration was extended (Fig. 2).

3.2. Production costs

Production costs increased significantly with the age of the coppice for both treatments ($p < 0.0001$, Fig. 3) and were correlated with the quantity of biomass (Pearson's correlation, $R^2 = 0.730$, $p < 0.0001$). The incremental rate was 4.5 times higher for the weed-free option (1415 ± 115 XOF ha^{-1} $month^{-1}$, approximately 16980 ± 1380 XOF ha^{-1} $year^{-1}$) than the weedy option (310 ± 250 XOF ha^{-1} $month^{-1}$, approximately 3720 ± 3000 XOF ha^{-1} $year^{-1}$, $p < 0.0001$, Fig. 3). It drops however for the weed-free option after 24 months. After 42 months, total costs were five times higher for the weed-free option (72980 ± 3760 XOF ha^{-1}) than the weedy option (14550 ± 1315 XOF ha^{-1}, $p < 0.0001$). Weeding, transport and harvest costs represented the major costs for the weed-free option (respectively 40, 32 and 20% of total costs), while harvest and transport costs were the highest costs for the weedy option (respectively 55 and 45% of the total costs).

3.3. Net present value

The net present value increased significantly with the age of the coppice and exceeded zero between 18 and 24 months for

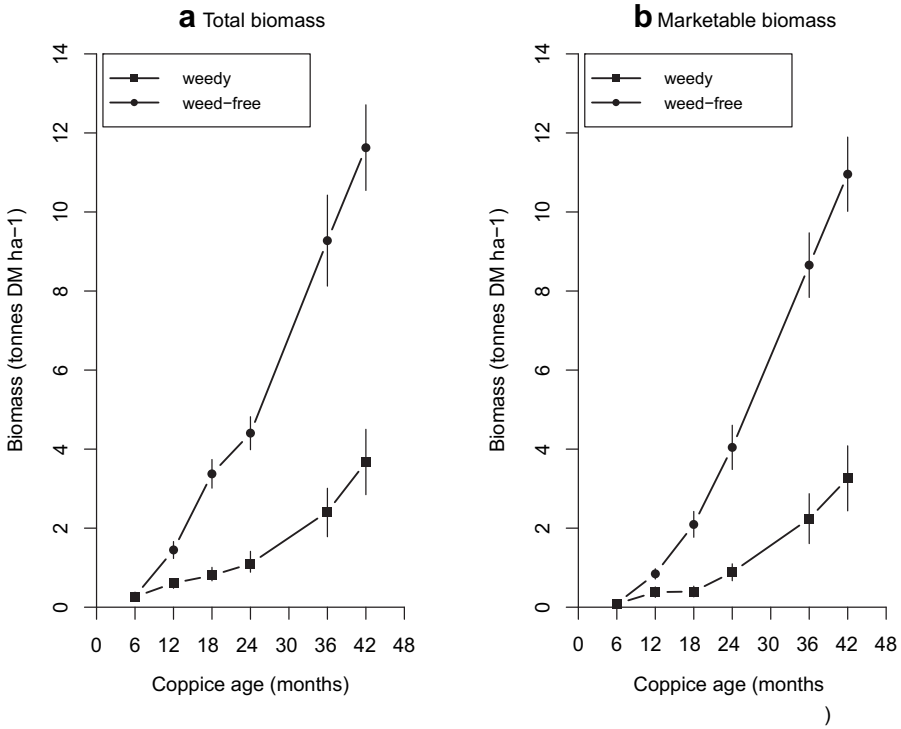

Fig. 2 – Total and marketable wood biomass (mean ± SE) evolution of *D. oliveri* following short coppice ages in weedy and weed-free conditions (DM = Dry Matter).

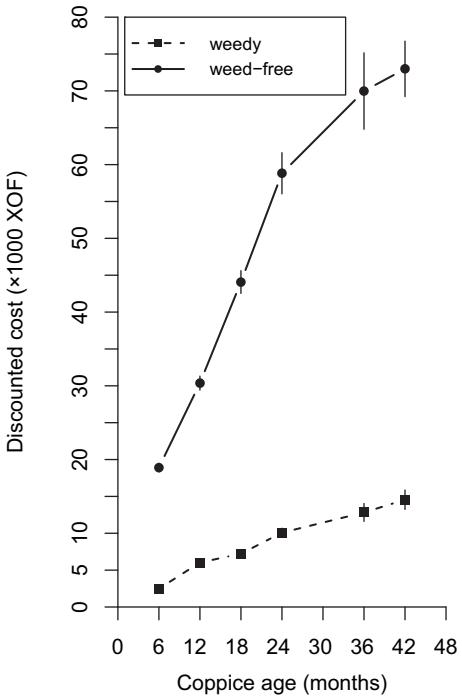

Fig. 3 – Discounted production costs (mean ± SE) of *D. oliveri* short ages coppice management in weedy and weed-free conditions (XOF: local currency, 1 USD = 435–512 XOF, 2009 United Nations rates).

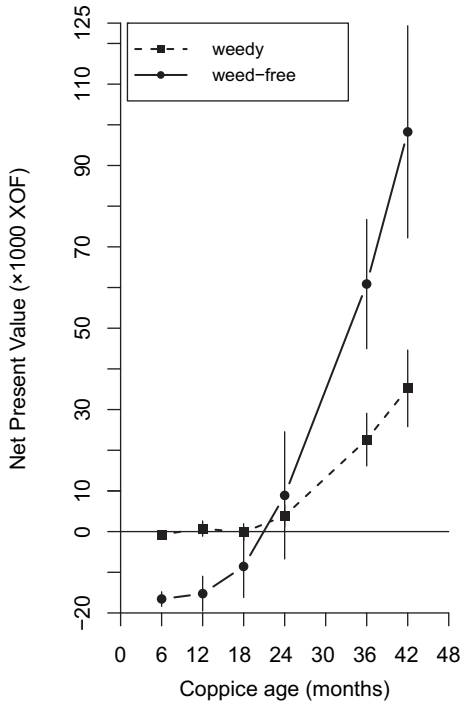

Fig. 4 – Net present value (mean ± SE) of *D. oliveri* short ages coppice management in weedy and weed-free conditions (XOF: local currency, 1 USD = 435–512 XOF, 2009 United Nations rates).

the weedy option ($p < 0.0001$, Fig. 4). The rate of increase was improved by weed removals in the weed-free plots ($p < 0.0001$, Fig. 4). During earlier coppice stage (0–6 months), the net present value was higher for the weedy option ($\leq -615 \pm 845$ XOF ha^{-1}) than the weed-free option ($\leq -16580 \pm 1780$ XOF ha^{-1}, $p < 0.0001$, Fig. 4), though none of the two options was profitable. Then, it increased more rapidly for the weed-free option (3270 ± 850 XOF ha^{-1} month^{-1}, approximately 40.000 ± 10200 XOF ha^{-1} year^{-1}) than the weedy option (1010 ± 352 XOF ha^{-1} month^{-1}, approximately 12000 ± 4250 XOF ha^{-1} year^{-1}). Between 18 and 24 months, the profit of the weed-free option exceeded the profit of the weedy option. Weed removals did not however shorten the minimum time for the net present value to exceed zero (Fig. 4). At 42 months, the net present value of the weed-free option (98250 ± 26075 XOF ha^{-1}) averaged 63035 XOF ha^{-1} more than the weedy option (35215 ± 9420 XOF ha^{-1}, $p = 0.0024$).

3.4. *Benefit-cost ratio*

The benefit-cost ratio increased significantly with the coppice age for both management options ($p < 0.0001$, Fig. 5). Periodic weed removal did not improve the rate of increase. Instead, the rate was similar for both treatments during the first 24 months, then it increased for the weedy option ($p = 0.0148$, Fig. 5). It exceeded the value of one earlier for the weedy option (24–30 months) than the weed-free option (after 36 months, Fig. 5). After 42 months, the net profit generated by the weedy option was 2.5 times higher than the investments costs, while this ratio was only 1.41 for the weed-free option (Fig. 5).

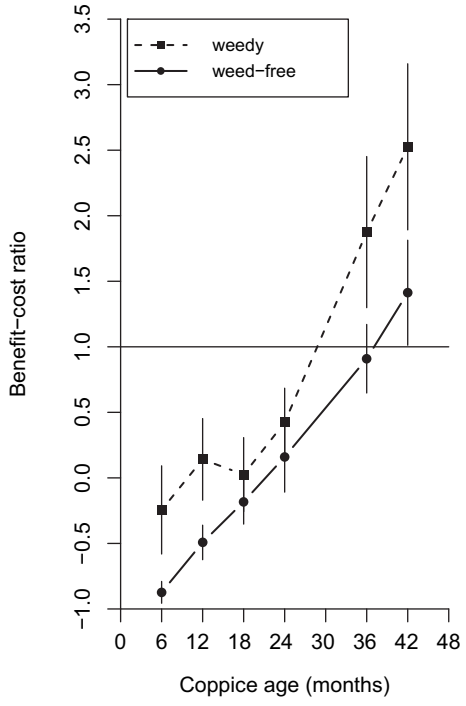

Fig. 5 – Benefit-cost ratio (mean ± SE) of *D. oliveri* short ages coppice management in weedy and weed-free conditions.

3.5. Sensitivity analysis

The sensitivity analysis showed that both management options were still profitable though labour and transport costs increased by 25%, the discount rate increased by 6 and 12% and selling prices decreased by 25% (Table 4). In these circumstances, the weed-free option still yielded 2.5–3 times more profit than the weedy option depending on the changes in prices, costs or discount rate ($p < 0.0001$ for each changing parameters, Table 4). Similarly, the benefit-cost ratio was still 1.5–2 times higher in weedy conditions than in weed-free conditions, ($p < 0.0001$ for all changing parameters, Table 4).

Though still profitable, both management options were highly sensitive to variations of price and discount rate with important falls in the net present value and benefit-cost ratio. The drops in net present values and benefit-cost ratios resulting from a 25% decrease in price were higher for the weed-free option (−43% both variables) than the weedy option (−35% for both variables). A discount rate of 9% yielded a loss of 18% in the profit while a discount rate of 15% resulted in a loss of 32% of the profit for both options.

The net preset value was less sensitive to the labour and transport costs' changes (less than 15% of variation). The benefit-cost ratio was less sensitive to the discount rate and transport costs' changes. In all cases, an increase in the price would be an advantage for the profitability of both production options with up to 35% increase for the weedy option and 43% increase for the weed-free option for both net present value and benefit-cost ratio.

4. Discussion

4.1. Biomass yield of D. oliveri traditional short coppice in weedy and weed-free conditions

This study estimated the growth rate of the aboveground woody biomass of a traditional *D. oliveri* short-rotation coppice for firewood production and investigated whether periodic weeding improves it. The results suggest that *D. oliveri* traditional short coppice may yield up to 1.08 t DM ha^{-1} $year^{-1}$ in weedy conditions. The important root and stump masses of the species in the soil [22,27] may explain this coppicing and biomass production habit. Thus, the sustainability of biomass production may depend on the quantity and quality of root and stump masses in the soil [41]. Shortening of fallow cycles associated with extended cropping periods may thus damage root masses, limit resprouting and reduce firewood yields [31,41].

Weeding improves the rate of woody biomass accumulation 3.5 times (3.83 t DM ha^{-1} $year^{-1}$ and approximately 12 t DM ha^{-1} in 3.5 years) compared with the traditional weedy option. Consequently, total and marketable firewood biomass after 42 months was 3–3.5 times higher on weed-free plots than on weedy plots. This improvement in biomass production is attributed first to a higher coppice density on weed-free plots (approximately 7500 stems ha^{-1}) compared with the weedy plots (approximately 2500 stems ha^{-1}), and second to an improvement in tree height growth in weed-free plots [27]. Trees in weed-free plots benefited from the elimination of grasses and other herbaceous species. In weedy plots in contrast, grasses and other species' competition for soil nutrients and light associated with destructive effects of dry season's fires have reduced the coppice density and growth, thus limiting biomass production [27,32,33].

Despite the substantial improvement in biomass yield through weeding, biomass production of the coppice system was relatively modest compared with exotic species such as *Eucalyptus camaldulensis* promoted in the area as firewood species with a yield of 5.73 t DM ha^{-1} $year^{-1}$ in weed-free conditions and under 1050 mm $year^{-1}$ of rainfalls [42]. However, the coppice may yield biomass as much as *S. siamea* also promoted in the area, with 3.81 t DM ha^{-1} $year^{-1}$ in similar rainfalls and in weed-free conditions [42].

Biomass data on indigenous species in pure stands are almost inexistent for the Sudano-Guinean area, not permitting valuable comparisons. Moreover, data available for mixed-species coppices are limited to stands in weedy conditions. Nonetheless, comparisons with data existing on mixed-species stands suggest that the productivity of *D. oliveri* short coppice in weedy conditions compares well with that of fallows and savannas in the humid and subhumid tropics. For example, Rutherford [43] found 0.9 t DM ha^{-1} $year^{-1}$ in Botswana savannas with approximately 1000 mm $year^{-1}$ of

Table 4 – Sensitivity analysis – Effects of changes in profitability parameters on net present value and benefit-cost ratio of *D. oliveri* short coppice in weedy and weed-free conditions after 42 months.

Paremeters	Net present value (XOF ha^{-1})[a,b]		Benefit-cost ratio	
	Weedy	Weed-free	Weedy	Weed-free
Base analysis	35216	98256	2.52	1.41
Discount rate = 9%	28885 (−18%)	80593 (−18%)	2.52 (0%)	1.41 (0%)
Discount rate = 15%	23946 (−32%)	66811 (−32%)	2.52 (0%)	1.41 (0%)
Price + 25%	47659 (+35%)	141065 (+43%)	3.40 (+35%)	2.01 (+43)
Price − 25%	22774 (−35%)	55447 (−43%)	1.64 (−35%)	0.80 (−43%)
Labour costs + 25%	33263 (−6%)	85933 (+12%)	2.09 (−17%)	1.05 (−25%)
Labour costs − 25%	37170 (+6%)	110580 (−12%)	3.09 (+22%)	1.92 (+36%)
Transport costs + 25%	33532 (−5%)	92335 (−6%)	2.17 (−13%)	1.24 (−12%)
Transport costs − 25%	36901 (+5%)	104178 (+6%)	2.97 (+17%)	1.61 (+14%)

a XOF: local currency, 1 USD ≈ 435–512 XOF, 2009 United Nations rates.
b Figures in parentheses represent the percent variation of the net present value or benefit-cost ratio compared with the base analysis.

rainfalls and Menaut and Cesar [44] obtained 1.4 t DM ha^{-1} $year^{-1}$ in shrub savannas in Lamto, Ivory Coast with 1300 mm $year^{-1}$. Nygard et al. [17] found a biomass yield of 1.1 t DM ha^{-1} $year^{-1}$ in areas of 900 mm $year^{-1}$ of rainfall in Burkina Faso. However, many of the species in these stands are unsuitable for commercial firewood because of their low basic density (≤50 Mg m^{-3}) and commercial biomass may be reduced by up to 31% of the stand yields [17]. This emphasizes the advantage of growing pure stands or selected species by removing low-quality species to improve the yields of good quality firewood species in naturally regenerating coppice stands.

The relatively modest biomass yield of *D. oliveri* short-rotation coppice suggests that it may not be suitable for large-scale industrial plantations, but rather for local plantations to meet domestic firewood consumption. Moreover, after the coppice period trees are not too large (4–8 cm of diameter and 2.5–4 m of height) [27], and land clearing and tree roots' removal may not be a major constraint for land reuse for agricultural purposes. This has been one of the major constraints of biomass plantations using exotic species that forestry programmes have promoted in the area for years. Furthermore, the small-sized firewood produced [27], may be more suitable for women and children who are the main firewood harvesters [1,9]. Naughton-Treves et al. [8] suggested a strategy that combines large-scale plantations with exotic species to meet industrial firewood demands, with short coppice for indigenous species for meeting domestic firewood needs.

The wood specific density used in this study to convert volume to biomass (0.55–0.61 Mg m^{-3}) was slightly lower than the value found by Erakhrumen [45], 0.58–0.7 Mg m^{-3}, using the mercury displacement method at 25 °C. However, the tree samples used by Erakhrumen [45] originated from trees older than young coppices used in our study.

4.2. *Profitability of D. oliveri traditional short coppice in weedy and weed-free conditions*

From an economic perspective, the study evaluated the profitability of the traditional coppice system and tested whether the expected improvement in biomass yields through weeding would result in an improvement of the financial gain of the system. The results suggest that the *D. oliveri* traditional short coppice may be profitable to farmers even in weedy conditions from 36 to 42 months. Weeding treatment improves the net benefits of the coppice system three times. This improvement is attributed to the increase of marketable biomass yield in weed-free plots. However, in the earlier stages (0–24 months), none of the management options was profitable because of the high costs of labour necessary to increase biomass, which were not compensated by the low returns of those earlier stages. This result supports the observed common practices in the area that consists in harvesting coppices from 2 to 3 years [27], that is the approximate minimum age when the coppice system may be profitable.

Considering the benefit-cost ratio, the weedy option is by far more advantageous to farmers with net benefits 2.5 times higher than input costs, compared with the weed-free option with net benefits 1.4 times higher than input costs at the end of the experiments. This may lead many farmers to prefer the weedy option though the weed-free option yields higher profits. Indeed, if farmers were constrained by financial means to bear high labour or transport costs, they may prefer the weedy option. The increase in the benefit-cost ratio with the age of the coppice for both options suggests that it might be more advantageous to farmers to harvest woodfuel at later coppice ages.

4.3. *Conclusion and implications for coppice management in rural communities*

This study has provided an estimation of biomass yield and profit that can be expected from a traditional short-rotation coppice with an indigenous species in the Sudano-Guinean zone of West Africa. Moreover it demonstrated that weed removal in traditional fallows, the major sources of firewood in most rural communities, is a mean to improve substantially firewood yields and livelihoods of farmers. Weed control in traditional fallow system is not a common practice in rural communities for which coppice management generally consists in abandoning fields after the cultivation period with no maintenance or improvement [7,9,31,46]. Grass removal, selective cutting of undesired woody species and fire prevention are practices that should be encouraged to increase firewood production of preferred species and economic outcomes of traditional coppices on fallow lands. As suggested by the financial analysis, this practice may require high initial labour costs. It may also be difficult to implement it especially in fallows with a mixture of species [31].

This study is limited in time (three years) and six months and weeding is the only applied silvicultural treatment. However, if thinning treatments were applied and rotation cycle extended to five or seven years as suggested by the biomass and the net benefits' growth curves, it may be possible to achieve larger firewood products and profits.

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