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Stem basic density and bark proportion of 45 woody species in young savanna coppice forests in Burkina Faso

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Abstract – In total 1287 sample trees were taken from 57 savanna woody species, representing 22 families in 5 stands, 5–14 years old, at 4 sites which has a mean annual precipitation of 620–785 mm in Burkina Faso. Stem discs were taken at one-meter intervals along the tree stem up to a diameter of 3 cm. For 45 of these species, with more than 4 stems sampled, the stem basic density varied between 301–854 kg m^{-3}. Bark proportion of stem biomass varied between 9–53%. Indications of decreased basic density and increased bark proportion with height of the stem and with decreased stem size was found for several species. Data presented provides a basis for the construction of models to convert standing woody volumes over bark to oven-dry mass whereby the bark proportion of the stem biomass can be determined.

specific gravity / humidity content / indigenous species / fuel-wood / biomass

Résumé – Densité basale de tronc et proportion d'écore de 45 espèces ligneuses issues de taillis dans une savane du Burkina Faso. Un échantillon de 1287 individus appartenant à 57 espèces et 22 familles de ligneux de savane a été coupé au Burkina Faso. Ces individus sont issus de 5 populations âgées de 5 à 14 ans provenant de 4 sites dont la pluviométrie est comprise entre 620 et 785 mm. Des disques ont été pris à 1 m d'intervalle le long de la tige jusqu'à un diamètre de 3 cm. Pour 45 de ces espèces comprenant plus de 4 tiges échantillonnées, la densité basale a varié entre 301 et 850 kg m^{-3} et la proportion d'écorce entre 9 et 53 %. Une diminution de la densité basale et une augmentation de la proportion d'écorce en fonction de la hauteur ont été observées pour plusieurs espèces. Les données présentées fournissent une base pour l'élaboration de modèles pour convertir les volumes de bois sur pied avec écorce en matière sèche d'étuve où la proportion d'écorce de la tige peut être déterminée.

gravité spécifique / taux d'humidité / espèces locales / bois de feu / biomasse

ABBREVIATIONS

BD_{ub} Stem Basic Density under bark, kg m^{-3}

BD_{ub}^{height} Disc Basic Density under bark per tree height, kg m^{-3}

BD_{ob} Stem Basic Density over bark, kg m^{-3}

$B_{M\%}$ Stem Bark Mass Proportion on an oven-dry mass basis, %

$B_{W\%}^{height}$ Disc Bark Proportion on an oven-dry mass basis per tree height, %

$B_{V\%}$ Stem Bark Volume Proportion on a green volume basis, %

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$MC_{ob\%}$ Stem Moisture Content over bark on a dry mass basis, %

$D_{ub0.5}$ Stem Diameter under bark at 0.5 m height, mm

$D_{ob0.5}$ Stem Diameter over bark at 0.5 m height, mm

$D_{DRYub0.5}$ Stem Diameter in oven-dry conditions under bark at 0.5 m height, mm

DBH Diameter at breast height

1. INTRODUCTION

In Sahel, fuel-wood has historically been collected from dead trees without bark, whereas today fuel-wood increasingly originates from the cutting of live woody stems [13], particularly in the vicinity of urban areas. In developing silvicultural systems for firewood production in the Sahel, short-rotation coppice silviculture [7, 10] or coppice with standards [5, 11] have been proposed. Rotation periods of at least 5 years and older depending on the woody species and required dimensions for harvesting has been suggested in savanna silviculture [1, 7]. At present, a rotation of 20 years is tested in a large-scale operation at Burkina Faso for the supply of fuel-wood to the capital Ougadougou [5]. In fact, large forest areas in Sahel are now considered to have secondary coppice growth and their accompanying rotation periods are gradually getting shorter [1, 5].

Reliable estimates of the woody oven-dry biomass in coppice forests are needed for analyses of the fuel-wood balance in Sahel. Existing forest inventory data is reported in terms of standing woody volumes over bark but these volumes require basic density of a given species for the conversion to oven-dry mass [8, 10]. However, species composition varies between different forests therefore conversion factors (volume to oven-dry mass) for a forest should be weighted by the frequency of occurrence of each species. At present, the conversion factor of 0.62 ton m^{-3} is used, independently of woody species and tree age, to calculate the woody biomass in Sahel [10]. Furthermore an assumed uniform bark volume proportion of 13%, is used to calculate the available fuel-wood under bark.

Information on species basic density is a key factor for investigating calorific value and thus fuel-wood quality [1]. In general bark is inferior to wood in terms of basic density [8, 10]. Another aspect of fuelwood quality is the unhealthy emission when bark is used for fuel-wood. For instance high nitrogen concentrations in the bark of Acacia species have been reported to give high levels of nitrogen oxides when burning and therefore debarking is suggested [15]. Another argument for debarking is to reduce the nutrient removal from the forest [16]. To analyse the consequences on fuelwood production of debarking there is a need to determine the difference in bark proportion between woody species.

In general, there is a variability of basic density among individuals of a given species, among geographical locations, with age and along stems [8, 17]. Since wood is a hygroscopic material both mass and volume varies with the moisture content**,** and volumes above the fibre saturation point are marginally affected, there are a variety of ways to calculate wood basic densities. The most appropriate measure for assessment of biomass is basic density, or oven-dry mass divided by wet volume [8]. The wet volume usually refers to wood samples soaked in water until saturation in the laboratory, which is relatively equivalent to green volume in standing trees [6, 8, 12, 17].

This study was performed in conjunction with a short-term rotation management for fuel-wood production in natural savanna forests. The aim of this paper was to determine stem wood basic density and bark proportion for woody species in young coppice stands in Burkina Faso. This would provide tools for constructing models that convert green woody stem volume to oven-dry mass with and without bark per species [5, 8, 10]. The data is required in analysis of a regional or national fuel-wood balance to convert existing forest inventory data from woody volumes to oven-dry mass in young coppice stands. Further, data presented could also be used for discussions on the ecological implications of different fuel-wood management strategies.

2. MATERIALS AND METHODS

2.1. Study sites

The study was carried out in Burkina Faso, West Africa, in the tree- and shrub savanna zone [3] in the north Soudanian zone [9]. Mean annual precipitation and temperature, for the period 1983-1996, at the Ougadougou airport located close to the centre of the study area at (12° 25' N, 1° 30' E) was 723 mm and 28 °C, respectively. The dry season lasts for 6 months according to the definition by Bagnouls and Gaussen [4]. Sample trees for determination of basic density were taken from 5 stands located at 4 sites (*figure 1*), all at an altitude of 300 m.a.s.l., and with an annual mean precipitation ranging between 620–785 mm (*table I*). Stands had emerged after clear-cut and varied in ages between 5 to 14 years when they were cut in 1996-97. Stand density varied between 635–1234 stem ha^{-1}. One site, the Sa forest, is situated on a hydromorphic mineral of vertisoil type. The other three sites are located on leached grey ferruginous soils on sandy, sandy-clay or clayey-sand material. Many species sporadically occurred in a patchy spatial structure and it was suggested that vegetative regeneration from stumps, stools and roots dominated on a woody volume basis. Experimental sites of 4 ha were selected in representative areas of each forest and had been protected from fire since the last clear-cut in the early 1980's.

2.2. Sampling procedure

The experiment consisted of 16 adjacent square plots of 2500 m^2 (50×50 m), grouped in 4 square blocks, one plot per block was randomly selected for clear-cutting and split in a grid of 25 m^2 (5×5 m) plots [11]. Sample trees > 3 cm DBH from different species and stands were selected in parity to their occurrence. Within species only one stem was sampled per 25 m^2 plot or per stool and with even distribution of diameters. Sampling was carried out during the midst of the dry season, from February to May, and at this time few species had leaves. Every woody species encountered on each site was represented by at least one sample. Classification of woody plant stature in tree, bush and lianoid growth and identification of species and families follows Guinko [9].

2.3. Mensuration of stem disc samples

Cutting and weighing of tree disc samples were made less than one hour after felling the tree. Stem discs, 10 cm thick, were cut at every meter starting from 0.5 m up the height of the main stem until a diameter of 3 cm over bark was reached. If the sample position on the stem fell on a knot the cutting place was shifted up or down along the stem. Dead stems were not sampled. On discs taken at 0.5 m from the stump, diameter was measured by cross calipering over bark ($D_{ob0.5}$) and under bark ($D_{ub0.5}$) in fresh condition and under bark ($D_{DRYub0.5}$) in oven-dry condition (see abbreviations).

Volume determination was made with a modified version of the water displacement method [12]. After placing 15 litres of water in a container, on an electronic balance (1 g) it was tarred. Immersion of a sample just under the water surface was done by hand with a needle, assumed to have negligible volume, attached to the sample. Dry mass was determined on an electronic balance (1 g) immediately after drying in an oven at 103 ± 2 °C to constant mass, which took 4–5 days. Volume determination is made indoors on a saturated wood sample in Gonse, Tiogo and Yabo whereas in Sa forest volume determination was made with a portable electronic balance (1 g) on fresh disc samples in the forest. About half of all 1287 samples were taken in Sa forest and we

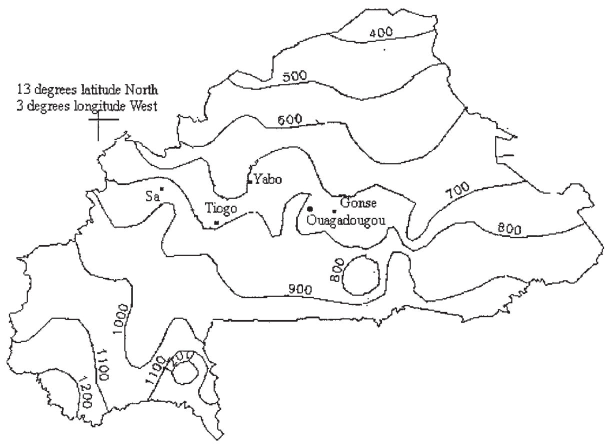

Figure 1. Rainfall patterns in mm per year and the geographical position of four forest stands: Sa, Tiogo, Yabo and Gonse and the capital of Burkina Faso, Ougadougou. Scale 1:5.000.000.

assume these measurement systems gives equivalent result. Restoration of the green volume by saturation of the wood sample is an assumption in most studies determining wood basic density [6, 8, 12, 17].

2.4. Calculations and statistical analysis

For each stem basic density under bark (BD_{ub}) and over bark (BD_{ob}), bark mass percentage on a dry mass basis ($B_{M\%}$), bark volume percentage on a green volume basis ($B_{V\%}$) and moisture content over bark ($MC_{ob\%}$) were calculated by summing disc values taken from each main stem:

$$BD_{ub} = \frac{\sum \text{ovendry disc mass under bark}}{\sum \text{fresh disc volume under bark}} \tag{1}$$

$$BD_{ob} = \frac{\sum \text{ovendry disc mass over bark}}{\sum \text{fresh disc volume over bark}} \tag{2}$$

$$B_{M\%} = \frac{\sum \text{ovendry disc mass over bark} - \sum \text{ovendry disc mass under bark}}{\sum \text{ovendry disc mass over bark}} * 100 \tag{3}$$

$$B_{V\%} = \frac{\sum \text{green disc volume over bark} - \sum \text{green disc volume under bark}}{\sum \text{green disc volume over bark}} * 100 \tag{4}$$

$$MC_{ob\%} = \frac{\sum \text{fresh disc mass over bark} - \sum \text{ovendry disc mass over bark}}{\sum \text{ovendry disc mass under bark}} * 100 . \tag{5}$$

Table I. General data on investigated stands.

	Gonse 10*	Gonse 5*	Site Sa 14*	Tiogo 13*	Yabo 13*
Species encountered	28	34	24	44	19
Total number of sampled trees	129	176	577	278	127
Stand density (stems >3 cm DBH ha^{-1})	779	522	1234	777	655
Annual precipitation mm	735	735	680	785	620

DBH Diameter at Breast Height.
* The figure after the name of the site indicate stand age.

Analysis of covariance [18] was used to test the site effect per species by using BD_{ub} as a linear function of $D_{ub0.5}$ for 11 ubiquitous species. After pooling samples from all stands mean values per species for the 45 species with more than 4 sample trees were calculated for diameter ($D_{ob0.5}$, $D_{ub0.5,}$ and $D_{Dryub0.5}$), basic density (BD_{ub} and BD_{ob}), bark percentage ($B_{M\%}$ and $B_{V\%}$) and moisture content ($MC_{ob\%}$). Simple linear regressions were fit to BD_{ub} on $D_{ub0.5}$ and to $B_{M\%}$ on $D_{ub0.5}$ for 5 species. Mean $MC_{ob\%}$ per species was fitted with a linear regression to the mean BD_{ub} per species for the 45 sampled species.

Mean values per stem height and their standard errors were calculated for basic density under bark (BD_{ub}^{height}) and bark percentage ($B_{W\%}^{height}$). For *Anogeissus leiocarpus* and *Acacia seyal* Restricted Maximum Likelihood (REML) was used for estimation of the variance component of B_{ub}^{height} among trees with the following model;

$$BD_{ub}^{height}{}_{ij} = \beta_0 + \beta_1 * D_{ub0.5\,i} + \beta_2 * \text{height}_{ij} + \alpha_i + \varepsilon_{ij} \quad (6)$$

where β_0, β_1 and β_2 are coefficients, α is a random tree effect and i is the tree number and j is the disc number within the tree. All α_i and ε_{ij} are assumed to be independent and have a normal distribution with mean zero. Discs were numbered starting from $i = 1$ at the 0.5 m-level. The significance level of all statistical tests was 0.05 and the word "mean" was applied for arithmetic mean. Statistical analysis was performed with SPSS 8.0.0 and SAS 6.12.

3. RESULTS

The number of species encountered per stand, varied from 19 to 44 (*table I*), and few species were present on all sites. Out of totally 57 species representing 22 families, 34 had a tree stature, 16 were bushes and 7 had a lianoid growth (*table II*). Species mean $D_{ob0.5}$ ranged from 20 mm to 95 mm indicating a large difference in growth after clear-cutting. No significant site effect on species basic density was found among the 11 ubiquitous species tested (*table II*). For the 45 species with more than 4 sample trees the range of BD_{ub} was 301–854 kg m^{-3} (*table III*). Several species had similar BD_{ub} and within species variation was often larger than the variation between species mean BD_{ub}. The range of BD_{ob} was 253–807 kg m^{-3} and double bark in percentage of $D_{ob0.5}$ ranged from 9% to 37%. Wood shrinkage expressed in terms of percentage contraction of $D_{ub0.5}$ ranged from 2% to 10%. The $B_{M\%}$ ranged from 9% to 53% and $B_{V\%}$ ranged from 11% to 51%. $MC_{ob\%}$ ranged from 34% to 294%.

In general fast-growing species like *Bombax costatum* with a $D_{ob0.5}$ of 85 mm had low BD_{ob} (253 kg m^{-3}) and slow-growing species like *Dicrostachys cinerea* with a $D_{ob0.5}$ of 46 mm had high BD_{ob} (787 kg m^{-3}). Furthermore fast-growing species had large bark thickness ($D_{ob0.5} – D_{ub0.5}$) for instance *Bombax costatum* had 32 mm, or 37% expressed as a percentage of $D_{ob0.5}$ and the opposite was found for species with low $D_{ob0.5}$ like *Dicrostachys cinerea*, which had 7 mm or 17%. BD_{ub} was less than BD_{ob} for fast-growing species like *Lannea sp., Commiphora africana, Detarium microcarpum* and *Entada africana* indicating a higher basic density for bark than for wood. The difference found between species double bark thickness at 0.5 m stem height was also found in the difference between species $B_{M\%}$ and $B_{V\%}$ for the whole stem. There was no pattern found in the wood shrinkage between species with regard to BD_{ub}. Coefficient of determination for species mean $MC_{ob\%}$ for 45 species on species mean BD_{ob} was 83% with intercept = 350.9 and slope = –0.4l7.

For *Anogeissus leiocarpus* and *Acacia seyal*, representing two species with a tree stature, the variance in disc basic density (BD_{ub}^{height}) between trees was larger than the variance within trees, (model 6) 56% and 62%, respectively (*table V*). Estimates of coefficients β_1 and β_2, showed that disc basic density (BD_{ub}^{height}) augmented

Table II. Stem basic density (kg m^{-3}) under bark for 57 savanna woody species on 4 sites in Burkina Faso.

Species	Family	Stature	Gonse10	Gonse5	site Sa14	Tiogo13	Yabo13
Acacia ataxacantha DC.	Mimosaceae	L			694		
Acacia dudgeoni Craib ex. Holl.	Mimosaceae	T	723	768		671	701
Acacia gourmaensis A. Chev.*	Mimosaceae	T	772	713			
Acacia macrostachya Reichenb. ex Benth.	Mimosaceae	B	700	736		761	763
Acacia pennata (Linn.) Willd.	Mimosaceae	L	710		836	712	705
Acacia senegal (Linn.) Willd.	Mimosaceae	T		767			683
Acacia seyal Del.	Mimosaceae	T	728	734	749	711	
Albizzia chevalieri Harms	Mimosaceae	T			642		
Anogeissus leiocarpus (DC.) Guill. et Perr.*	Combretaceae	T	753	708	709	750	785
Balanites aegyptiaca (L.) Del.	Balanitaceae	T	668	636	702	659	695
Bombax costatum Pellegr. et Vuillet	Bombacaceae	T	311	286	305		
Boscia senegalensis (Pers.) Lam. ex Poir.	Capparacea	B			700		
Boswellia dalzielli Hutch.	Burceraceae	T			720		
Butyrospermum paroxum **	Sapotaceae	T	675	686		712	
Capparis sepiaria	Caparacea	L			627		
Cassia sieberiana DC.	Caesalpiniaceae	B	714	744		700	
Cassia singueana Del.	Caesalpiniaceae	B		690			
Combretum aculeatum Vent.	Combretaceae	L		687			683
Combretum fragrans F. Hoffm.	Combretaceae	T				635	
Combretum glutinosum Perr. ex DC.*	Combretaceae	T	694	660		700	720
Combretum micranthum G. Don *	Combretaceae	B		768	707	766	798
Combretum nigricans Lepr. ex Guill. et Perr. *	Combretaceae	T			758	761	746
Commiphora africana (A. Rich.) Engl.*	Burceraceae	T	332	402	367	328	347
Crossopteryx febrifuga (Afzel. ex G. Don) Benth.	Rubiaceae	T	631	620		602	
Dalbergia melanoxylon Guill. et Perr.	Papilionaceae	T			817		804
Detarium microcarpum Guill. et Perr.	Caesalpiniaceae	T		515		582	
Dicrostachys cinerea (L.) Wight et Arn.*	Mimosaceae	T	871	831	844	893	866
Diospyros mespiliformis Hoschst. ex A.DC.	Ebenaceae	T				642	
Entada africana Guill. et Perr.	Mimosaceae	B	513	496		558	
Feretia apodanthera Del.	Rubiaceae	B	686	676	647	695	
Gardenia ternifolia Schum. et Thonn.	Rubiaceae	B				655	
Grewia bicolor Juss.*	Tiliaceae	T	764	789	740	799	799
Grewia flavescens Juss.	Tiliaceae	L			654	720	
Grewia mollis Juss.	Tiliaceae	B			716	714	
Guiera senegalensis J. F. Gmel. in L.	Combretaceae	B	656	636	609	692	695
Lannea acida A. Rich.*	Anacardiaceae	T	463	463	463	471	462
Lannea microcarpa Engl. et Krause	Anacardiaceae	T				464	464
Mitragyna inermis (Willd.) O. Kotze.	Rubiaceae	T			600	563	
Piliostigma reticulatum (DC.)	Caesalpiniaceae	B	671	642		628	
Piliostigma thonningii (Schum.) Miln-Red.	Caesalpiniaceae	B		705		655	
Prosopis africana Taub.	Mimosaceae	T				687	
Pterocarpus lucens Lepr. ex Guill. et Perr.*	Papilionaceae	T			805		866
Pterocarpus erinaceus Poir.	Papilionaceae	T	657	620		672	
Saba senegalensis (A. DC.) Pichon	Apocynaceae	L				523	
Sclerocarya birrea (A. Rich.) Hoschst.*	Anacardiaceae	T	503	461	496	535	550
Securinega virosa (Roxb. Ex Willd.) Baill.	Euphorbiaceae	B		680		688	
Sterculia setigera Del.	Sterculiaceae	T	322			292	
Stereospermum kunthianum Cham.	Bignoniaceae	T	595	622		693	
Strychnos spinosa Lam.	Loganiaceae	B				693	
Tamarindus indica L.	Caesalpiniaceae	T	772	750		769	
Terminalia avicennioides Guill. et Perr.	Combretaceae	T	648	631		636	
Terminalia laxiflora Engl.	Combretaceae	T		655		663	
Terminalia macroptera Guill. et Perr.	Combretaceae	T		590		622	
Xeroderris stuhlmannii (Taub.) Mendonca et E. P. Sousa	Papilionaceae	T				565	
Ximenia americana L.	Olacacea	B	623	644	651	654	
Ziziphus mauritiana Lam.	Rhamnacea	B	517				
Ziziphus mucronata Willd.	Rhamnacea	B				645	

* Tested for stand effect.
** Synonomous Vittelaria paradoxa C.F. Gaertn.
T: Tree.
B: Bush.
L: Lianoid growth.

Table III. Mean dendrological parameters for 45 savanna woody species in the age 5-14 years in Burkina Faso.

Species	N	BD_{ub} kg m^{-3}	BD_{ob} kg m^{-3}	$D_{ob0.5}$ mm	B_{thick}	shrinkage	$B_{M\%}$ percentage	$B_{V\%}$	MC_{ob}
Acacia ataxacantha	29	694 (33)	707	39	14	4	18 (7)	18	34
Acacia dudgeoni	6	728 (33)	701	51	25	5	33 (5)	35	78
Acacia gourmaensis	27	748 (57)	624	57	29	4	31 (8)	42	72
Acacia macrostachya	33	759 (40)	727	60	21	4	28 (4)	31	60
Acacia pennata	11	744 (75)	728	39	13	3	13 (4)	14	50
Acacia senegal	6	738 (67)	671	46	25	2	31 (6)	37	86
Acacia seyal	85	751 (37)	702	67	17	3	24 (5)	29	68
Albizzia chevalieri	8	642 (46)	574	47	23	3	26 (9)	34	80
Anogeissus leiocarpus	151	720 (45)	721	65	14	4	21 (5)	21	53
Balanites aegyptiaca	17	677 (50)	651	80	18	3	33 (9)	35	67
Bombax costatum	19	306 (35)	253	87	37	6	41 (7)	51	237
Boscia senegalensis	12	700 (56)	682	**	**	**	31 (4)	33	62
Boswellia dalzielli	16	719 (51)	730	20	23	7	35 (6)	34	52
Butyrospermum paradoxum	20	696 (56)	639	72	22	4	32 (5)	37	89
Capparis sepiaria	12	636 (54)	683	**	**	**	22 (8)	17	83
Cassia siberiana	5	720 (25)	721	69	10	2	17 (1)	17	59
Combretum fragrans	5	635 (21)	642	49	19	2	26 (1)	25	84
Combretum glutinosum	49	686 (41)	674	56	14	3	21 (6)	23	74
Combretum mircathum	78	736 (54)	730	43	11	3	15 (3)	16	41
Combretum nigricans	43	751 (34)	751	62	9	2	17 (4)	17	55
Commiphora africana	80	365 (29)	381	56	19	3	33 (6)	30	164
Crossopteryx febrifuga	10	610 (16)	623	63	16	4	27 (6)	26	81
Dalbergia melanoxylon	36	819 (25)	794	48	15	5	18 (3)	21	48
Detarium microcarpum	8	565 (38)	614	75	25	4	44 (12)	39	95
Dicrostachys cinerea	72	854 (35)	787	46	17	5	18 (4)	25	39
Entada africana	16	517 (46)	537	64	23	3	37 (8)	35	128
Feretia apodanthera	40	671 (33)	661	34	15	5	21 (4)	23	57
Grewia bicolor	45	780 (46)	761	52	20	7	24 (4)	26	40
Grewia flavescens	12	671 (106)	621	21	18	10	22 (11)	29	44
Grewia mollis	13	715 (31)	719	48	22	6	29 (4)	29	43
Guiera senegalensis	20	681 (34)	669	55	10	6	9 (2)	11	46
Lannea acida	31	465 (25)	545	75	30	4	53 (9)	46	141
Lannea mirocarpa	6	468 (10)	510	73	27	4	40 (3)	35	153
Piliostigma reticulatum	18	641 (48)	612	57	23	3	29 (8)	32	97
Piliostigma thonningii	6	664 (37)	616	60	27	3	35 (6)	40	95
Prosopis africana	6	687 (13)	650	93	15	4	25 (3)	29	83
Pterocarpus lucens	42	830 (45)	807	59	11	4	15 (3)	18	37
Pterocarpus erinaceus	11	656 (41)	623	61	17	2	36 (10)	39	88
Sclerocarya birrea	49	509 (45)	500	77	20	3	30 (4)	31	145
Securinega virosa	7	684 (33)	673	40	9	5	12 (3)	14	55
Sterculia setigera	7	301 (58)	347	95	21	5	36 (7)	23	294
Strychnos spinosa	6	693 (31)	629	60	12	2	20(3)	27	73
Tamarindus indica	12	767 (25)	699	52	20	4	24 (5)	30	50
Terminalia avicennoides	6	638 (18)	617	61	24	4	39 (6)	41	73
Ximenia americana	12	646 (22)	614	53	26	5	38 (7)	41	67

N	Number of stems sampled.
BD_{ub} (st. dev.)	Stem Basic Density under bark in kg m^{-3}, standard deviation in brackets.
BD_{ob}	Stem Basic Density over bark in kg m^{-3}.
$D_{ob0.5}$	Stem Diameter over bark in mm at 0.5 meter height.
B_{thick}	Double bark thickness ($D_{ob0.5}$–$D_{ub0.5}$) expressed as a percetage of $D_{ob0.5}$.
Shrinkage	Radial wood shrinkage ($D_{ub0.5}$–$D_{DRYub0.5}$) expressed as percentage of $D_{ub0.5}$.
$B_{M\%}$ (st. dev.)	Stem Bark Weight Proportion (%) on a dry weight basis, standard deviation in brackets.
$B_{V\%}$	Stem Bark Volume Proportion (%) on a green volume basis.
MC_{ob}	Stem Moisture Content over bark (%) on a dry weight basis.
**	Missing values.

Table IV. Stem basic density under bark (BD_{ub}) and stem bark proportion ($B_{M\%}$) as function of tree size ($D_{ub0.5}$) for 5 savanna woody species.

Species	Parameter estimates	r^2	p-value
Anogeissus leiocarpus	$BD_{ub} = 663 + 1.0*D_{ub0.5}$	16	0,000
Anogeissus leiocarpus	$B_{M\%} = 0.28 - 0.0011*D_{ub0.5}$	21	0,000
Acacia seyal	$BD_{ub} = 705 + 0.7*D_{ub0.5}$	6	0,018
Acacia seyal	$B_{M\%} = 0.36 - 0.0021*D_{ub0.5}$	54	0,000
Combrethum glutinosum	$BD_{ub} = 637 + 1.0*D_{ub0.5}$	17	0,003
Combrethum glutinosum	$B_{M\%} = 0.31 - 0.0019*D_{ub0.5}$	28	0,000
Combrethum micranthum	$BD_{ub} = 610 + 3.2*D_{ub0.5}$	24	0,481
Combrethum micranthum	$B_{M\%} = 0.22 - 0.0018*D_{ub0.5}$	23	0,000
Dicrostachys cinerea	$BD_{ub} = 820 + 0.7*D_{ub0.5}$	5	0,058
Dicrostachys cinerea	$B_{M\%} = 0.25 - 0.0017*D_{ub0.5}$	32	0,000

Table V. Variation in disc basic density within and between trees.

	Anogeissus leiocarpus				*Acacia seyal*			
	Variance	%			Variance	%		
between trees	1350	56			2226	62		
within trees and error	1070	44			1346	38		
variation with fixed effects	2420	100			3572	100		
variation without fixed effects	3089				3776			
Fixed effects	Coefficient	SE	DF	p-values	Coefficient	SE	DF	p-values
intercept	696,72	12,12	133	0,0001	734,76	14,74	113	0,0001
tree size ($D_{0.5}$)	0,81	0,21	328	0,0001	0,48	0,25	288	0,0616
height level (i = 0.5 – 6.5)	–23,51	1,48	328	0,0001	–10,21	1,58	288	0,0001

with tree size ($D_{ub0.5}$) and declined with height along the stem (*table V*). No interaction effect between tree size ($D_{ub0.5}$) and height was found. Significant differences in mean BD_{ub}^{height} with height along the stem between the first two or three meters up the stem were also found for several species in *table VI*. The r^2 for fitting BD_{ub} on $D_{ub0.5}$ was low and ranged from 5–28% for the 5 species tested (*table IV*), however the tendency was clear with increasing BD_{ub} with increased tree size. Corresponding r^2 for $B_{M\%}$ was also low and ranged from 24–54% but with decreasing $B_{M\%}$ with increased tree size.

4. DISCUSSION

During the 1980's, the Ministry of Forestry in Burkina Faso established plots on several sites that were representative forests in the country to analyse the production in short-term rotations with clear-cutting methods. The four sites in this study were selected to cover the range of site conditions in the north Soudanian zone. Yabo is the most arid site, situated at the border to the bush steppe in the south Sahel zone while Tiogo is the least arid close to the south Soudanian zone (*table I, figure 1*). Sa is bordering the tree savanna and situated on a vertisol with a stand density about twice as high compared the other stands. Given the difference in site conditions we wanted to check for variation in BD_{ub} between sites within species before pooling samples from all sites, but no stand effects on BD_{ub} were found. The test was made for 11 more ubiquitous species, sufficiently represented in more than one stand.

If studies would be made to closer examine site effects on species BD_{ub}, very large samples are needed, since the variation between trees is large as indicated in this study e.g. *Anogeissus leiocarpus* and *Acacia seyal*. These two species were selected, for the analyses of variance components (model 6), because they were frequently sampled and had long stems providing several samples per tree. The parameter estimate for stem height (β_2 in model 6) was –23.51 kg m^{-3} m^{-1} for *Anogeissus leiocarpus* (*table V*). In the case of *Anogeissus leiocarpus* this represents about a 10% decrease in BD_{ub} on four meters and this was also evident in *table VI*. However,

Table VI. Basic density (kg m^{-3}) under bark per tree height in meter starting at stump for a savanna coppice forest in the age 5–14 years in Burkina Faso.

	tree height in meter													
	0,5		1,5		2,5		3,5		4,5		5,5		6,5	
species	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Acacia ataxacantha	732	8	699	12	673	14	625	33	633	33	.	.	.	.
Acacia dudgeoni	725	14	701	17	.	.	.	.	.	.	.	.	.	.
Acacia gourmaensis	746	15	731	16	708	31	667	.	676	.	.	.	.	.
Acacia macrostachya	782	8	726	8	703	11	664	22	659	.	.	.	.	.
Acacia pennata	756	22	694	19	660	.	.	.	.	.	.	.	.	.
Acacia senegal	750	23	723	37	792	37	.	.	.	.	.	.	.	.
Acacia seyal	753	5	741	5	737	7	733	11	705	25	718	37	690	30
Albizzia chevalieri	649	20	639	13	600	0	571	.	.	.	.	.	.	.
Anogeissus leiocarpus	738	4	704	4	684	5	667	10	686	18	704	4	.	.
Balanites aegyptiaca	682	12	671	15	687	17	659	.	623	.	.	.	.	.
Bombax costatum	319	8	295	10	281	9	281	7	.	.	.	.	.	.
Boscia senegalensis	675	29	.	.	.	.	.	.	.	.	.	.	.	.
Boswellia dalzielli	720	13	.	.	.	.	.	.	.	.	.	.	.	.
Butyrospermum paradoxum	722	12	681	14	692	18	663	13	640	32	.	.	.	.
Capparis sepiaria	627	25	.	.	.	.	.	.	.	.	.	.	.	.
Cassia siberiana	744	11	700	17	699	16	625	.	.	.	.	.	.	.
Combretum fragrans	671	32	643	13	579	40	.	.	.	.	.	.	.	.
Combretum glutinosum	697	6	674	7	675	11	629	16	.	.	.	.	.	.
Combretum mircathum	746	6	722	6	701	10	740	19	.	.	.	.	.	.
Combretum nigricans	776	6	725	6	698	10	688	15	.	.	.	.	.	.
Commiphora africana	359	4	364	4	382	5	402	17	.	.	.	.	.	.
Crossopteryx febrifuga	624	9	589	9	584	11	556	.	.	.	.	.	.	.
Dalbergia melanoxylon	826	7	798	12	799	9	809	17	847	28	.	.	.	.
Detarium microcarpum	582	15	551	16	533	16	531	13	.	.	.	.	.	.
Dicrostachys cinerea	866	6	831	6	806	14	810	.	.	.	.	.	.	.
Entada africana	518	13	521	12	551	15	563	40	508	.	.	.	.	.
Feretia apodanthera	666	8	659	9	625	29	672	.	691	.	.	.	.	.
Grewia bicolor	788	10	752	8	725	20	697	52	.	.	.	.	.	.
Grewia flavescens	677	32	655	29	600	.	.	.	.	.	.	.	.	.
Grewia mollis	729	12	703	15	669	23	733	.	.	.	.	.	.	.
Guiera senegalensis	697	8	668	8	635	7	629	.	.	.	.	.	.	.
Lannea acida	456	6	464	8	452	14	462	13	417	83	.	.	.	.
Lannea mirocarpa	475	4	461	8	441	11	444	.	.	.	.	.	.	.
Piliostigma reticulatum	655	11	628	10	590	17	580	11	.	.	.	.	.	.
Piliostigma thonningii	680	16	637	19	642	.	.	.	.	.	.	.	.	.
Prosopis africana	716	9	662	11	636	8	632	3	673	31	.	.	.	.
Pterocarpus lucens	835	8	823	8	795	12	780	15	794	34	730	3	.	.
Pterocarpus erinaceus	688	17	624	15	618	6	603	27	621	24	.	.	.	.
Sclerocarya birrea	519	8	509	7	497	8	490	12	467	21	.	.	.	.
Securinega virosa	674	24	687	9	.	.	.	.	.	.	.	.	.	.
Sterculia setigera	308	24	291	19	262	19	306	23	.	.	.	.	.	.
Strychnos spinosa	711	15	669	11	639	12	.	.	.	.	.	.	.	.
Tamarindus indica	783	7	744	8	731	20	.	.	.	.	.	.	.	.
Terminalia avicennoides	635	11	619	13	.	.	.	.	.	.	.	.	.	.
Ximenia americana	668	9	641	9	664	20	.	.	.	.	.	.	.	.

M: Mean.
SE: Standard error.

with increased tree height above 4.5 m the average BD_{ub} for discs per height increased for *Anogeissus leiocarpus* (*table VI*) which we believe was due to the need for structural stability in branches in the crown. Our results indicate that an increase in BD_{ub} occurred in the top of the stem for several other species i.e. *Acacia seyal*, *Dalbergia melanoxylon*, *Prosopis africana* and *Pterocarpus erinaceus* (*table VI*).

The sampling system applied on each tree individual assumed an apical dominance with a clear main stem where discs values are given equal weights. For species with a bush stature bifurcating branches constitute a larger part of the total biomass than for species with a tree stature having a distinct main stem. Therefore increased weight for disc values up along the stem should be given depending on the amount of bifurcation for species with a bush stature. In this study no correction have been made for stem BD_{ub} for speciemens with more ramification. Less than a third of the 57 species in this study have a bush stature and six species in this study had a lianoid growth pattern with few major branches (*table II*).

Extraction of wood cores is a common procedure for determining the basic density. In this study wood cores would not be an option because of the small dimensions and, for many species, hard wood making extraction of good cores difficult. Moreover this would not provide an accurate assessment of the bark proportion because many savanna woody species having an irregular bark and wood surface. Therefore we believe that stem discs is an adequate sampling procedure for these conditions. Volume measurement under bark was made after debarking and this was difficult to make after the samples had dried whereas it was easy to debark freshly cut disc. Therefore volume determination was made in the forest on the site called Sa 14.

In this study the time since the stands were cut was known and this is an advantage given the difficulty to determine age, by counting year rings, in tropical trees. However, within each stand, age was not homogeneous because stems continuously emerge and die. Therefore there is an age variation among sampled stems and we assume that the younger stems have smaller diameters. To examine the change in BD_{ub} and $B_{M\%}$ with $SD_{\mathrm{ub0.5}}$ regression analyses were performed (*table IV*). For five species investigated there were indications of increased BD_{ub} and decreased $B_{M\%}$ with increased $SD_{\mathrm{ub0.5}}$. Thus for these 5 species there were some evidence of juvenile wood and this has been reported in a previous study where density increased from pith to bark for 11 out of 18 dry Costa Rican forest species [17]. The order of magnitude of this change in bark and wood parameters can be exemplified with *Anogeissus leiocarpus* where the range of tree size ($D_{\mathrm{ub0.5}}$) in this study was about 100 mm (30–128). This corresponds to an increase of the BD_{ub} of 17% (663 to 773) and a decrease of $B_{M\%}$ with 39% (28 to 17). However, this is clearly higher than what was estimated in a similar study in Ghana where bark proportion was only 7% in a 34 years old plantation of *Anogeissus leiocarpus* with a mean diameter at breast height of 9.8 cm [2].

In an analysis of the fuel-wood balance in Sahel, Jensen [10] used the same conversion factor for all species to obtain the oven-dry mass under bark from green woody volume over bark. Nevertheless, more accurate conversion factors can be obtained through weighting with the species-wise representation. Species-specific BD_{ob} information allows correcting for any bias due to the relative abundance of trees with different BD_{ob} and $B_{V\%}$ [8]. In this study a conversion figure has been calculated by weighting with the actual woody volume per species in the five stands (Nygård in prep.) and this resulted in a BD_{ob} of 0.68 ton m^{-3} (0.66–0.69) and a $B_{M\%}$ of 24% (20–25). Differences between sites representing different species composition appear to be small but when multiplied with the standing volume on a large scale the corrections can be considerable. Moreover we believe the BD_{ob} of 0.62 ton m^{-3} used by Jensen [10] is grossly underestimated considering it has been used also for old forests and data in this study indicates that BD_{ob} increase with dimension.

Data presented in this study could be used for discussions on ecological implications of rotation periods, silviculture and fuel-wood management. From a silviculture perspective, intensification of fuel-wood production should consider selective thinning of species with low BD_{ub} to improve the production of the remaining stand. There were indications within a given species that BD_{ub} increased and $B_{M\%}$ decreased with increased tree size ($D_{\mathrm{ub0.5}}$). Hence, longer rotation periods would produce a better fuel-wood quality. Another reason for increasing the rotation period would be to reduce the bark proportion of the total biomass in order to reduce nutrient removal from the forest. According to Wang et al. [16] it is better to remove stem-wood > branches > bark to minimise nutrient removal from the forest. In this study $B_{M\%}$ of commonly used fuel-wood species in a young coppice forest constitute about a fourth of the total stem oven-dry mass and if bark is systematically harvested in large scale there is a risk of reduced long term site fertility. Could debarking of fuel-wood be a realistic silviculture option? According to Peltier et al. [13] a fuel-wood harvesting system is already in place in Niger to produce debarked fuel-wood, which is in fact demanded by the urban market [13]. By selecting the appropriate seasonal time of the year for cutting and storing the wood, debarking can be facilitated. Debarking could be considered a value adding processing of fuel-wood in rural areas where there is a lack of job opportunities. In this study the difference between BD_{ob} and BD_{ub} varied between species was indicating a higher bark basic density for some species (*table III*). Furthermore there were large variations between species in bark thickness and $MC_{\mathrm{ob\%}}$. High bark basic density, bark thickness and

Table VII. Bark proportion, in percentage, on an ovendry matter basis, in percentage, per tree height in meter starting at stump for a savanna coppice forest in the age 5–14 years in Burkina Faso.

	tree height in meter													
	0,5		1,5		2,5		3,5		4,5		5,5		6,5	
species	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Acacia ataxacantha	14	1	18	1	22	1	24	1	22	1				
Acacia dudgeoni	32	1	34	1										
Acacia gourmaensis	30	1	31	2	24	7	9		12					
Acacia macrostachya	27	1	30	1	33	1	37	2	30					
Acacia pennata	13	1	16	1	16									
Acacia senegal	30	2	33	3	33	2								
Acacia seyal	23	1	25	1	26	1	27	1	30	2	31	3	35	2
Albizzia chevalieri	25	3	27	3	38	5	46							
Anogeissus leiocarpus	21	0	21	0	23	1	24	1	26	2	35	5		
Balanites aegyptiaca	33	2	32	2	30	2	22		26					
Bombax costatum	40	2	43	2	39	2	36	1						
Boscia senegalensis	31	1												
Boswellia dalzielli	35	2												
Butyrospermum paradoxum	30	1	32	1	35	2	36	2	36	0				
Capparis sepiaria	21	2												
Cassia siberiana	17	1	17	1	17	0	18							
Combretum fragrans	24	2	26	1	24	2								
Combretum glutinosum	21	1	22	1	20	1	19	1						
Combretum mircathum	14	0	16	0	18	1	16	4						
Combretum nigricans	15	1	17	1	18	1	16	2						
Commiphora africana	35	1	32	1	32	1	39	3						
Crossopteryx febrifuga	25	2	29	2	29	3	31							
Dalbergia melanoxylon	17	1	20	1	22	1	21	1	22	2				
Detarium microcarpum	42	5	47	4	46	4	44	1						
Dicrostachys cinerea	16	0	21	1	24	1	23							
Entada africana	37	2	37	2	33	2	34	1	40					
Feretia apodanthera	21	1	22	1	23	1	21		24					
Grewia bicolor	23	1	26	1	29	1	39	5						
Grewia flavescens	21	3	17	1	19									
Grewia mollis	28	1	32	1	32	4	22							
Guiera senegalensis	8	0	9	1	10	1	10							
Lannea acida	53	2	54	1	53	2	54	5	49	13				
Lannea mirocarpa	39	1	41	1	39	1	40							
Piliostigma reticulatum	28	2	29	2	34	2	36	3						
Piliostigma thonningii	35	2	35	2	35									
Prosopis africana	24	2	26	1	27	1	25	1	28	2				
Pterocarpus lucens	14	1	17	1	18	1	20	1	14	10	24	1		
Pterocarpus erinaceus	34	3	37	3	27	1	30	2	28	1				
Sclerocarya birrea	28	1	31	1	33	1	34	2	37	1				
Securinega virosa	12	1	13	1										
Sterculia setigera	35	3	40	4	40	4	39	3						
Strychnos spinosa	19	2	22	1	24	0								
Tamarindus indica	22	1	25	2	29	5								
Terminalia avicennoides	38	3	39	2										
Ximenia americana	37	2	38	2	45	3								

M: Mean.
SE: Standard error.

$MC_{ob\%}$ are essential for assessment of stem sensitivity to ground fire [14]. In Bolivia a bark thickness of 18 mm [14] at breast height was required to withstand lethal cambial temperatures in experimental low intensity fires.

5. CONCLUSIONS

There is a large variation in basic density between species in this study and the species composition varies strongly from one forest to another. Therefore conversion factors from standing woody volume to ovendry woody mass should be weighted with the species-wise representation. There were indications within a given species that basic density increased, and bark proportion decreased with increased tree size. This indicates that longer rotation periods will produce a woody biomass with higher basic density and lover bark proportion. Thus when evaluating fuel-wood production in a coppice forest, variations in species composition and tree age in a savanna forest must be considered.

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