Effects of region, soil, land use, and terrain type on fuelwood properties of five tree/shrub species in the Sahelian and Sudanian ecozones of Mali

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Abstract

· **Context** There is little information about inter- and intra-specific variation in fuelwood properties of trees/shrubs in West Africa.

· **Aims** We studied variation in fuelwood properties of *Balanites aegyptiaca*, *Combretum glutinosum*, *Guiera senegalensis*, *Piliostigma reticulatum*, and *Zizyphus mauritiana* in the Sahelian and Sudanian ecozones of Mali.

· **Methods** Trees were sampled on different soil (sandy, sandy/loam, or rocky), land use (parkland agroforest or woodland), and terrain (flat, temporarily flooded, or hill slope) types in five regions extending from the drier eastern to the more humid western parts of Mali. Basic density, volatile matter, fixed carbon, ash content, moisture content, gross calorific value, and fuel value index were measured for each tree and adjusted for tree age.

· **Results** All fuelwood properties differed significantly among species, but there were significant species by region interactions. Most fuelwood properties of four species differed significantly among regions. Soil and/or land use type had significant effects on a few fuelwood properties of four species.

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• **Conclusion** In general, fuelwood production is recommended in all regions for *G. senegalensis*, in drier regions for *B. aegyptiaca* and *C. glutinosum*, in more humid regions for *Z. mauritiana*, and on rocky soils for all species. Fuelwood production of *P. reticulatum* is not recommended.

1 Introduction

Rural communities in the Sahelian and Sudanian ecozones of West Africa use many native tree species for fuelwood (Faye et al. 2011) and demand for fuelwood is increasing (FAO 2011). Environmental conditions can directly or indirectly affect fuelwood properties. For example, ash content of wood may be greater in sites where there is more available calcium and potassium in the soil (Sarmiento et al. 1985); and wood density may be correlated with tree growth rate, which in turn is affected by rainfall, soil fertility, etc. (e.g., Sotelo Montes et al. 2006). There is very little published information about variation in fuelwood properties in natural populations, and this information is needed in order to target species and environments for production of higher quality fuelwood.

Several properties should be considered when assessing the value of wood for fuel. Gross and net calorific values are the amounts of energy per unit mass that are released from the complete combustion of oven-dried and air-dried wood samples, respectively, so wood with high gross and net calorific values is clearly desirable (Nirmal Kumar et al. 2011). Denser wood has more energy per unit volume and burns more slowly (Fuwape and Akindele 1997). High moisture and ash contents reduce gross calorific value because energy is used to evaporate the water and ash is the non-combustible mineral residue in the wood (Shanavas and Mohan Kumar 2003). Volatile matter is released as combustible and non-combustible gasses when the wood is burned; and fixed carbon is the mass, excluding ash and moisture content, remaining after the volatile matter is released (McKendry 2002). Wood with higher volatile matter ignites more rapidly and produces more heat during combustion but it may also produce more smoke, and wood with higher fixed carbon burns longer (Fuwape and Akindele 1997; Kataki and Konwer 2002). Several fuel value indices have been used to quantify the overall quality of fuelwood from different species: the most commonly used index in recent years adjusts gross calorific value for the density, ash, and moisture contents of the wood (e.g., Sotelo Montes et al. 2011).

In this paper, we discuss variation in fuelwood properties of five tree/shrub species in the Sahelian and Sudanian ecozones of Mali. The Sahel is a semi-arid transitional ecozone between the more humid Sudanian ecozone to the south and the Sahara Desert to the north, so there are steep rainfall gradients with latitude and also with longitude. The species [*Balanites aegyptiaca* (L.) Delile (Balanitaceae), *Combretum glutinosum* Perr. ex DC. (Combretaceae), *Guiera senegalensis* J.F. Gmel. (Combretaceae), *Piliostigma reticulatum* (DC.) Hochst. (Caesalpiniaceae), and *Zizyphus mauritiana* Lam. (Rhamnaceae)] are used for fuelwood and also provide additional products and environmental services for rural communities (Faye et al. 2011). They tolerate and/or avoid drought stress during the long dry period (typically from October to June), and are common in woodlands and "parkland" agroforests, which rural communities manage for the production of food crops, tree products, and livestock. *B. aegyptiaca* and *Z. mauritiana* are distributed from the Sahelian to the northern part of the Sudanian ecozone, and *C. glutinosum*, *G. senegalensis*, and *P. reticulatum* are distributed from the Sahelian to the southern part of the Sudanian ecozone (Le Houérou 1980). *B. aegyptiaca* is an evergreen, drought-tolerant tree that produces a deep taproot and grows very slowly above ground (Hall and Walker 1991). *C. glutinosum* is also an evergreen tree, with dense foliage in the crown, but it grows only near available water sources and has active photosynthesis only during the rainy season in the drier north (Berger et al. 1996). *G. senegalensis* is a shrub that produces roots extending at least 4 m in depth, grows quickly above ground and adjusts its leaf surface area to available soil water, thereby allowing active photosynthesis during part of the dry season (Seghieri et al. 2005; Kizito et al. 2006). *P. reticulatum* is a semi-evergreen, leguminous shrub that produces roots extending at least 3 m in depth, does not fix nitrogen, grows well in temporarily flooded sites, and has adventitious shoots that tend to grow at oblique angles rather than vertically, thereby creating a microhabitat favorable for growth (Wezel et al. 2000; Kizito et al. 2006). *Z. mauritiana* is a relatively fast growing tree that produces deep roots, avoids drought by shedding its leaves during the dry season and is common in woodlands and along temporary streams (Berger et al. 1996; Clifford et al. 1998).

The major objective of this research was to determine if fuelwood properties (basic density, volatile matter, fixed carbon, ash content, moisture content, gross calorific value, fuelwood value index) of the species differ among regions, soil types, land use types, and terrain types in Mali. Recommendations are provided regarding the species and sites to target for fuelwood production, and seed sources to use for establishing new fuelwood plantations.

2 Materials and methods

2.1 Study regions, tree sampling, and site variables

B. aegyptiaca, *C. glutinosum*, *G. senegalensis*, *P. reticulatum*, and *Z. mauritiana* were sampled in parklands and
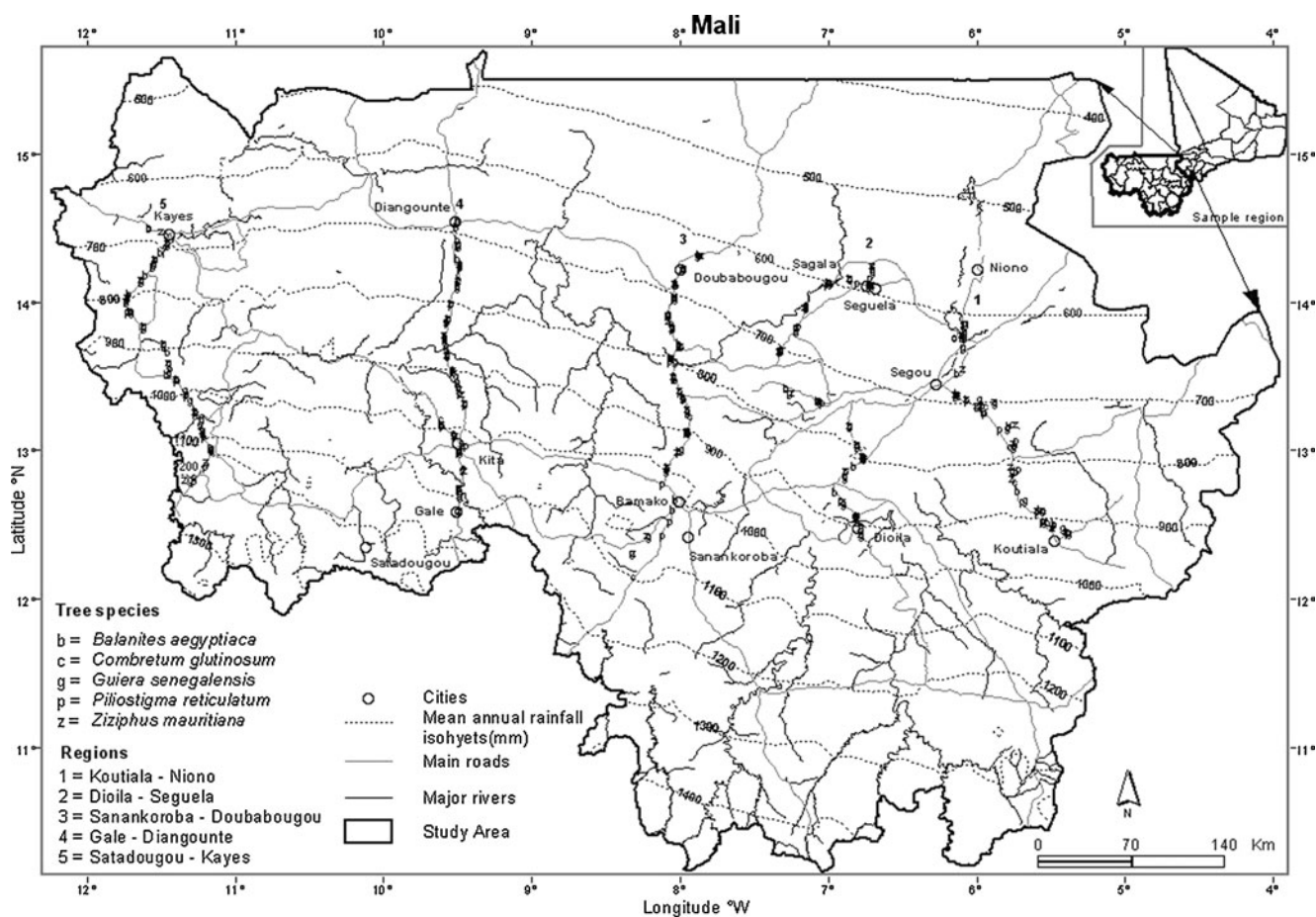
Fig. 1 Geographic location of five tree/shrub species sampled in five regions in Mali, and mean annual rainfall isohyets across the sample regions

woodlands in five regions, extending from southeastern to southwestern Mali (Fig. 1), at the end of the dry season in 2009. For each species, 15–16 trees were sampled roughly along a latitudinal transect in each region, with a minimum distance of 10 km between trees. Trees were selected if they were produced by natural regeneration; the stem was not a coppice shoot, and was undamaged, growing relatively upright and within a predetermined diameter class (4–12 cm at 30 cm above ground). Tree stems in this diameter class are typically cut for firewood. Information about tree age, elevation, annual rainfall and sample sizes in each region is given in Table 1.

Three site variables were visually assessed for each tree: soil type (primarily sand, sand/loam mixture or primarily rocks including laterite), land use type (parkland agroforest or woodland), and terrain type (flat, temporarily flooded, or hill slope). Detailed information about the species composition, etc. of parkland agroforests and woodlands was not recorded. Latitude, longitude, and elevation of each tree were obtained using a GPS receiver, and mean annual rainfall (mm) was obtained from the WorldClim database, described elsewhere (Hijmans et al. 2005), using the trees' geographical coordinates.

2.2 Wood samples and fuelwood variables

The stem of each tree was cut at 30 and 60 cm above ground in the field. The north- and south-facing sides were labeled on the bark and cut surfaces. The bark was removed from each stem sample in a laboratory in Mali, lines were drawn along the north- and south-facing sides of the wood, and the samples were then air-dried for 2 months.

Two disks, without nodes or other defects, were cut from the lower part of the stem sample and used for determination of wood density and tree age. The disks were air-dried for 1 month to obtain equilibrium moisture content (EMC) prior to measurements. Basic density (BDen) of one disk (2 cm thick, generally at 31–33 cm above ground) was measured in kg m^{-3} using the water displacement method (ASTM 1997). The number of annual rings was counted on the second disk (1 cm thick, generally at 33–34 cm above ground) and used as an estimate of tree age. As others have demonstrated, annual rings can be visually distinguished in both deciduous and evergreen tree species in semi-arid zones and used to estimate tree age if there is a distinct dry season to induce cambial dormancy and trigger

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Table 1 Estimated age, elevation, and mean annual rainfall of five tree/shrub species sampled in five regions in Mali

Species[a]	Mean	Mean by region[c]					Minimum–maximum by region[c]				
Variable[b]		R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
Ba											
Age	5.2	5.3	5.6	5.4	4.6	4.9	3–7	4–7	3–8	3–6	3–7
Elevation	280	294	307	385	297	120	260–351	275–364	294–462	217–352	35–209
Rainfall	791	765	730	825	815	815	614–923	577–893	626–1,030	684–1,020	669–1,045
Sample size	79	15	16	16	16	16					
Cg											
Age	5.9	5.2	5.9	6.2	6.0	6.3	4–8	5–8	5–9	5–7	4–9
Elevation	282	303	302	386	298	130	254–365	250–341	280–468	235–355	36–200
Rainfall	831	754	733	827	916	925	623–923	571–914	631–1,094	721–1,130	669–1,207
Sample size	79	16	16	15	16	16					
Gs											
Age	6.2	5.0	7.0	6.3	6.3	6.6	3–8	5–9	4–9	4–8	5–9
Elevation	286	297	312	393	293	134	257–350	284–363	263–463	193–357	50–201
Rainfall	838	765	734	830	923	937	607–923	577–914	631–1,072	711–1,130	687–1,205
Sample size	79	15	16	16	16	16					
Pr											
Age	6.4	6.3	7.1	6.4	6.0	6.4	5–9	5–11	4–8	5–7	5–9
Elevation	286	298	314	386	295	136	277–356	279–380	281–438	233–361	54–214
Rainfall	838	764	732	826	915	950	609–923	585–890	626–1,044	711–1,088	687–1,207
Sample size	79	15	16	16	16	16					
Zm											
Age	5.8	5.3	5.8	5.8	5.7	6.4	4–7	4–9	4–8	4–8	5–8
Elevation	285	302	308	393	302	122	250–352	273–362	292–450	246–355	43–205
Rainfall	835	764	735	829	919	924	614–927	571–942	626–1,072	711–1,130	677–1,208
Sample size	79	15	16	16	16	16					

[a] Species: *Ba Balanites aegyptiaca*, *Cg Combretum glutinosum*, *Gs Guiera senegalensis*, *Pr Piliostigma reticulatum*, *Zm Ziziphus mauritiana*

[b] Variable: Age=estimated age (years), Elevation=estimated elevation (m), Rainfall=estimated mean annual rainfall (mm), and Sample size= number of sampled trees/shrubs

[c] R1 to R5=regions 1 to 5 see Fig. 1

formation of growth boundaries (Gourlay 1995; Tarhule and Hughes 2002; Gebrekirstos et al. 2008); and there is a distinct dry season of approximately 8 months following the rainy season in Mali (Hiernaux and Le Houérou 2006). The lower surface of the second disk was sanded so that the annual rings were clearly visible, and the four cardinal directions (i.e., north, east, south, and west) were labeled on the surface. A digital image of the surface was produced with a scanner. A grid (mm) was overlaid on the image and the annual rings were marked along the four cardinal directions using Adobe® Photoshop CS4 version 11 software. The number of rings was then counted.

Sawdust was prepared from the remaining part of the air-dried stem samples (generally between 36 and 40 cm above ground) and used to measure other fuelwood properties at the Laboratory of Energy of Biomass of the Universidade Federal do Paraná in Brazil. The sawdust samples were

stored under controlled conditions (60% relative humidity, 20°C) for 1 month to attain EMC prior to measurements. Gross calorific value is the total energy available from an oven-dry sample, and net calorific value is the total energy available from an air-dry sample: these are also known as the upper and lower heating values, respectively. Following procedures described elsewhere (ABNT 1984), percent moisture content (MC) was determined from a small sample (0.5 g) of sawdust, and then the oven-dry sample of sawdust was used to determine gross calorific value (GCV) in MJ kg^{-1}. Net calorific value (Net CV) was calculated from GCV: Net CV equals GCV minus the energy needed to evaporate the water (1.36 MJ kg^{-1}). Gross calorific value per cubic meter (GCVm^3) was calculated as the product of BDen and GCV. The percent contents of volatile matter (Vol), fixed carbon (Carb), and ash (Ash) were determined from the mean of two small air-dried samples of sawdust (each about 4 g): Vol and

Ash were measured, and Carb was calculated as 100%−Vol−Ash (ABNT 1986). The fuel value index (FVI) was calculated using the following formula: FVI = [(BDen)(Net CV)]/[(Ash)(MC)] (Sotelo Montes et al. 2011).

2.3 Data analysis

The SAS® statistical package (SAS Institute Inc. 2004) was used for all analyses, and the significance level was $\alpha \leq 0.05$ for all tests. BDen, Vol, Carb, Ash, MC, GCV, GCVm^3, and FVI were analyzed. Data transformations were not necessary as the variables exhibited normal distributions (UNIVARIATE procedure).

Values for all fuelwood variables were adjusted for differences in tree age. In a preliminary analysis of covariance (MIXED procedure, restricted maximum likelihood estimation method), the effects of age (covariate), region, and the age by region interaction were tested for each variable of each species. The effect of age was generally not significant, but the age by region interaction was significant in many cases, indicating that the effect of age depended on the region. Therefore, the analysis of covariance was repeated by region for each species, and data were adjusted using the following formula:

$$Y_{age-adjusted} = Y_{unadjusted} - (Beta_{age-region}) * (Age_{tree} - Age_{species}),$$

where $Y_{age-adjusted}$=the value of the variable adjusted for tree age, $Y_{unadjusted}$=the value of the variable not adjusted for tree age, $Beta_{age-region}$=the effect of age on the variable within the region (i.e., the covariate parameter estimate), Age_{tree}=estimated age of the tree, and $Age_{species}$=mean age of all trees of the species.

Mean age of the sampled trees (with minimum and maximum in parentheses) was 5.2 (3–8), 5.8 (4–9), 5.9 (3–9), 6.2 (4–11), and 6.4 (4–9)years, respectively for *B. aegyptiaca*, *Z. mauritiana*, *C. glutinosum*, *G. senegalensis*, and *P. reticulatum*. The differences in mean age were small but statistically significant in some cases (*B. aegyptiaca* < other species, *Z. mauritiana* and *C. glutinosum* < *P. reticulatum*; Tukey test $P<0.05$), but that would have little if any effect on interspecific differences in fuelwood properties based on previous research (e.g., Lemenih and Bekele 2004; Kumar et al. 2010).

Analysis of variance (ANOVA, MIXED procedure, restricted maximum likelihood estimation method) was used to determine if fuelwood variables differed significantly among species, regions, and site variables. Two ANOVA models were used to test differences among and within species. The model among species included five main effects (species, region, soil type, land use type, terrain type) and the two-way interactions between species and the other main effects (all fixed factors). The model within species included four main effects (region, soil type, land use type, terrain type). Interactions between regions and site variables were not tested because there were not enough observations for some site variables in some regions. Least-squares means were compared using the Tukey HSD (honestly significant difference) test. The Tukey test controls the experiment-wise error so it is very conservative: if the F test is barely significant, then the Tukey test may not detect any significant difference among the means.

Pearson correlation coefficients (Corr procedure) were used to investigate linear relationships among fuelwood properties of the trees for each species.

3 Results

3.1 Differences in fuelwood properties among species

All fuelwood variables differed significantly among species (Table 2). There were no significant interactions between species and site variables. However, the species by region interaction was significant for five variables [Vol, MC, GCV ($P<0.001$); Ash ($P<0.01$); Carb, FVI ($P<0.05$)], indicating that rankings of some species changed in some regions. Differences due to regions and site variables are discussed in the Sections 3.2 and 3.3, respectively.

In general, *G. senegalensis* had better fuelwood properties than the other species (Table 2). Its FVI was high because it had the highest BDen and GCV, the lowest Ash, and moderate MC. It also had the highest GCVm^3 because this is a function of BDen and GCV, and the highest FVI because this is a function of BDen, Net CV, Ash, and MC. *P. reticulatum* had the least desirable fuelwood properties (low BDen and GCV, high Ash and MC).

Judging from the coefficients of variation, there was relatively little variation in BDen, Vol, Carb, MC, GCV, and GCVm^3 (Table 2). Ash and FVI had very large coefficients of variation compared with the other fuelwood properties. The coefficients of variation were generally greater for *C. glutinosum* than for the other species.

3.2 Differences in fuelwood properties among regions

Mean annual rainfall was lower in the eastern and higher in the western regions (Table 1). The range in mean annual rainfall among sample locations was lower for *B. aegyptiaca* (575–1,045 mm) than for the other species (about 575–1,205 mm).

Regional differences were significant for at least four of the eight fuelwood properties of *B. aegyptiaca*, *G. senegalensis*, *P. reticulatum*, and *Z. mauritiana* (Table 3). However, most fuelwood properties of *C. glutinosum* did not differ significantly among regions. BDen did not differ significantly among regions for any species.

Fuelwood properties were better in some regions for some species and in other regions for other species (Table 3).

Table 2 Means and coefficients of variation of fuelwood properties of five tree/shrub species in Mali

Variable[a]	P[b]	Means for species[c]					Coefficient of variation (%)				
		Ba	Cg	Gs	Pr	Zm	Ba	Cg	Gs	Pr	Zm
BDen	***	615c	666d	673d	530a	569b	5.7	7.7	5.1	6.9	7.7
Vol	***	80.20b	79.95b	79.90b	78.45a	80.70b	1.5	2.0	1.0	1.5	1.6
Carb	***	18.55ab	18.84abc	19.47bc	19.63c	18.18a	5.2	8.4	4.1	5.0	6.6
Ash	***	1.25b	1.22b	0.64a	1.93c	1.12b	27.5	39.7	32.7	28.4	32.4
MC	**	11.14ab	10.78a	11.18ab	11.74b	10.80a	11.4	12.8	12.5	9.5	10.9
GCV	***	19.14ab	19.08ab	19.93c	19.03a	19.40b	2.2	2.0	1.3	1.9	1.8
GCVm^3	***	11,783b	12,707c	13,416c	10,076a	11,036b	6.3	8.1	5.1	7.0	7.8
FVI	***	886b	1,020b	2,081c	477a	918b	38.1	42.8	30.2	33.1	36.8

[a] Variable: BDen=wood basic density (kg m^{-3}); Vol, Carb, Ash, and MC=volatile matter, fixed carbon, ash, and moisture, respectively, of wood (%); GCV and GCVm^3 =gross calorific value of wood (MJ kg^{-1} and MJ m^{-3}, respectively); FVI=fuel value index [(net calorific value x BDen)/ (MC x Ash)]

[b] P=probability of F for testing species: ***$P<0.001$; **$P<0.01$; numerator/denominator degrees of freedom=4/344

[c] Species: Ba *Balanites aegyptiaca*, Cg *Combretum glutinosum*, Gs *Guiera senegalensis*, Pr *Piliostigma reticulatum*, Zm *Ziziphus mauritiana*; least squares means with the same letter are not significantly different ($P>0.05$) and those with different letters are significantly different ($P<0.05$) based on Tukey HSD test; sample size=78 for Ba and 79 for other species

For example, FVI tended to be higher in the three eastern-most regions (#1, #2, #3) for *B. aegyptiaca*, but in an eastern and two western regions (#1, #4, #5) for *Z. mauritiana*. These regional differences in FVI reflected the differences in Ash and MC. In addition, MC of *C. glutinosum* and *P. reticulatum* was generally lower in the eastern regions. Fuelwood properties of *G. senegalensis* were generally good in all regions (e.g., high GCV, low Ash).

3.3 Differences in fuelwood properties among soil, land use, and terrain types

Soil and land use types had significant effects on some fuel-wood properties, but the effect of terrain type was not significant for any variable (Table 4). In the analysis among species, MC was greater on sandy and sandy/loam soils than on rocky soils. Since MC is in the denominator of FVI, FVI was greater on rocky and sandy/loam than on sandy soils. Analyses within species gave similar results for *C. glutinosum* (FVI), *B. aegyptiaca*, *G. senegalensis*, and *Z. mauritiana* (MC). The effect of land use was significant for *G. senegalensis* and *Z. mauritiana*: Ash of *G. senegalensis* was greater in parklands than in woodlands; while Vol of *Z. mauritiana* was greater and Carb was lower in parklands than in woodlands.

4 Discussion

4.1 Differences in fuelwood properties among species

There are only a few published reports about fuelwood properties of the five species included in this study. Values

for GCV and BDen of *B. aegyptiaca* in this study were slightly lower than those reported for 13-year-old trees in a genetic evaluation test in Niger (Sotelo Montes et al. 2011). Values for BDen of *B. aegyptiaca*, *C. glutinosum*, *G. sene-galensis*, and *Z. mauritiana* were similar to those observed among 5–14-year-old trees in natural populations in Burkina Faso, but BDen of *P. reticulatum* was higher in the Burkina Faso study (Nygård and Elving 2000). There are no other published reports about fuelwood properties of these species in the region. In India, young trees (<4 years) of *Z. mauritiana* had lower GCV than the trees in this study (Puri et al. 1994).

Coefficients of variation for BDen, Vol, Carb, MC, GCV, and GCVm^3 were very low in this study. This is consistent with studies of BDen in natural populations in Burkina Faso (Nygård and Elving 2000) and of BDen, GCV, and GCVm^3 in genetic evaluation tests (e.g., Sotelo Montes et al. 2003; Sotelo Montes and Weber 2009; Weber and Sotelo Montes 2010; Sotelo Montes et al. 2011). The low coefficients of variation probably reflect the fact that most wood proper-ties are under relatively strong genetic control (i.e., have higher heritability) and are less affected by environmental conditions than traits such as tree height and stem diam-eter (e.g., Sotelo Montes et al. 2006; Sotelo Montes and Weber 2009).

In contrast, the coefficients of variation for Ash and FVI were very large in this study. The large coefficient of vari-ation for Ash suggests that it is more affected by local environmental conditions than the other fuelwood proper-ties. Ash contains calcium and potassium (Ragland et al. 1991), and one would expect higher calcium and potassium contents in plant tissues growing on soils with greater

Table 3 Means of fuelwood properties of five tree/shrub species in five regions in Mali

Species[a]	Variable[b]	P[c]	Means for regions[d] R1	R2	R3	R4	R5
Ba	BDen	ns	605a	632a	613a	610a	616a
Ba	Vol	**	80.48b	80.48b	80.47b	80.49b	79.07a
Ba	Carb	*	18.25a	18.48ab	18.41ab	18.26a	19.37b
Ba	Ash	***	1.28ab	1.04a	1.12a	1.25ab	1.56b
Ba	MC	***	10.35a	9.94a	10.48a	12.19b	12.74b
Ba	GCV	*	18.85a	19.22ab	19.25ab	19.02ab	19.36b
Ba	GCVm^3	ns	11,413a	12,149a	11,814a	11,611a	11,928a
Ba	FVI	***	953bc	1139c	1010bc	749ab	577a
Cg	BDen	ns	691a	681a	655a	655a	651a
Cg	Vol	ns	80.75a	79.65a	79.61a	79.99a	79.73a
Cg	Carb	ns	17.89a	19.11a	19.34a	18.81a	19.06a
Cg	Ash	ns	1.37a	1.25a	1.06a	1.21a	1.22a
Cg	MC	***	9.85a	9.77a	10.20a	11.76b	12.30b
Cg	GCV	ns	18.96a	19.09a	19.13a	19.17a	19.05a
Cg	GCVm^3	ns	13,095a	13,001a	12,519a	12,547a	12,373a
Cg	FVI	ns	1,110a	1,091a	1,199a	866a	833a
Gs	BDen	ns	685a	679a	676a	658a	666a
Gs	Vol	*	80.27b	79.96ab	79.33a	80.15ab	79.80ab
Gs	Carb	**	19.06a	19.50ab	20.06b	19.22ab	19.50ab
Gs	Ash	ns	0.68a	0.54a	0.62a	0.64a	0.71a
Gs	MC	***	10.25a	12.58b	10.51a	11.67ab	10.92a
Gs	GCV	*	19.97ab	19.87ab	20.12b	19.91ab	19.78a
GS	GCVm^3	ns	13,681a	13,501a	13,608a	13,108a	13,180a
Gs	FVI	ns	1,991a	2,340a	2,266a	1,959a	1,847a
Pr	BDen	ns	537a	547a	533a	504a	528a
Pr	Vol	**	79.29b	79.28b	78.23ab	78.00ab	77.44a
Pr	Carb	**	18.86a	18.98ab	20.03c	20.02bc	20.27c
Pr	Ash	ns	1.86a	1.74a	1.75a	1.98a	2.30a
Pr	MC	***	10.81a	11.44ab	12.65c	12.51bc	11.32a
Pr	GCV	*	19.13b	19.09ab	19.06ab	19.11ab	18.74a
Pr	GCVm^3	ns	10,266a	10,440a	10,157a	9,626a	9,889a
Pr	FVI	ns	544a	566a	472a	403a	399a
Zm	BDen	ns	583a	567a	558a	560a	576a
Zm	Vol	***	80.71ab	80.84b	79.54a	81.36b	81.05b
Zm	Carb	***	18.08a	17.79a	19.34b	17.72a	17.97a
Zm	Ash	*	1.21ab	1.37b	1.12ab	0.92a	0.98ab
Zm	MC	***	10.05a	11.26bc	12.03c	10.67ab	10.01a
Zm	GCV	*	19.28a	19.52a	19.20a	19.53a	19.47a
Zm	GCVm^3	ns	11,224a	11,070a	10,721a	10,938a	11,227a
Zm	FVI	**	977ab	698a	785ab	1063b	1067b

[a]Species: *Ba Balanites aegyptiaca*, *Cg Combretum glutinosum*, *Gs Guiera senegalensis*, *Pr Piliostigma reticulatum*, *Zm Ziziphus mauritiana*

[b]Variable: Vol, Carb, Ash, and MC=volatile matter, fixed carbon, ash, and moisture, respectively, of wood (%); GCV and GCVm^3=gross calorific value of wood (MJ kg^{-1} and MJ m^{-3}, respectively); FVI=fuel value index [(net calorific value×BDen)/(MC×Ash)]

[c]P=probability of F for testing regions: ***$P<0.001$, **$P<0.01$, *$P<0.05$, ns $P>0.05$; numerator/denominator degrees of freedom=4/74

[d]R1 to R5=regions 1 to 5 (see Fig. 1); least squares means with the same letter are not significantly different ($P>0.05$) and those with different letters are significantly different ($P<0.05$) based on Tukey HSD test; sample size=78 for Ba and 79 for other species

available calcium and potassium (Sarmiento et al. 1985). The availability of these minerals is affected by many factors such as the bedrock type; soil type, organic matter content, and pH; intensity of rainfall and leaching; land-use history (e.g., number of years under cultivation and fallow, crop species grown) and farmers' soil improvement practices in the parklands (e.g., cutting and burning shrubs, and applying manure before sowing crops); the specific microhabitat created by the tree and neighboring trees; and the amount of potassium- and calcium-rich dust that is transported from the Sahara Desert by the Harmattan winds and deposited on tree leaves and soil during the dry season

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Table 4 Means of fuelwood properties of five tree/shrub species in different soil and land use types in Mali[a]

Species[b]	Variable[c]	P[d]	Means for land use and soil types[e]		
			Soil type		
			Sandy	Sand/Loam	Rocky
All	MC	***	11.41b	11.13ab	10.85a
All	FVI	*	997a	1065ab	1167b
Ba	MC	**	11.51b	10.92a	10.99a
Cg	FVI	**	929ab	870a	1261b
Gs	MC	*	11.67b	11.02ab	10.86a
Zm	MC	*	11.17b	10.90ab	10.34a
			Land use type		
			Parkland	Woodland	
Gs	Ash	**	0.74b	0.54a	
Zm	Vol	**	81.22b	80.18a	
Zm	Carb	*	17.76a	18.60b	

[a] Results shown only for variables with significant difference among soil or land use types

[b] Species: *All* all species; *Ba Balanites aegyptiaca*, *Cg Combretum glutinosum*, *Gs Guiera senegalensis*, *Pr Piliostigma reticulatum*, *Zm Ziziphus mauritiana*

[c] Variable: Vol, Carb, Ash, and MC=volatile matter, fixed carbon, ash, and moisture, respectively, of wood (%); FVI=fuel value index [(net calorific value×BDen)/(MC×Ash)]

[d] P=probability of F for testing means: ***$P<0.001$, **$P<0.01$, *$P<0.05$; numerator/denominator degrees of freedom=2/344 for all species, 2/75 (Ba) or 2/76 (other species) for soil type and 1/77 for land use type

[e] Least squares means with the same letter are not significantly different ($P>0.05$) and those with different letters are significantly different ($P<0.05$) based on Tukey HSD test; sample size=78 for Ba and 79 for other species

(Wezel et al. 2000). Therefore, one would expect considerable spatial variability in available soil calcium and potassium and, as a result, considerable variability in ash content among trees. The large coefficient of variation for FVI reflects the fact that it was derived from four variables (BDen, Net CV, MC, Ash), so the coefficient of variation reflects the combined variation/covariation among these variables.

4.2 Differences in fuelwood properties among regions

Regional differences were significant for the majority of the fuelwood properties of *B. aegyptiaca*, *G senegalensis*, *P. reticulatum*, and *Z. mauritiana*. This reflects in part the fact that several variables were highly correlated (Sotelo Montes et al., unpublished data) due to the way they were measured or derived. Vol and Ash were measured and percent Carb was calculated as the difference: as a result, Vol was negatively correlated with Carb and Ash (mean Pearson r of five species=−0.95 and −0.39, respectively, $P<0.001$, $N=79$ for each species). In addition, GCVm^3 and FVI were correlated

with the variables used to derive them. Therefore, if one variable differs significantly among regions and it is strongly correlated with a second variable, then the second variable also differs significantly among regions.

In contrast to the other species, most fuelwood properties of *C. glutinosum* did not differ significantly among regions. This indicates that the variation among *C. glutinosum* trees within regions was considerably greater than the differences among regions, compared with the other species. This is consistent with the fact that the coefficients of variation for fuelwood properties were generally greater for *C. glutinosum* than for the other species, and suggests that local environmental conditions may have a relatively greater effect on fuelwood properties of *C. glutinosum* trees, compared with the other species.

BDen did not differ significantly among regions for any species in this study, also indicating that the variation within regions was considerably greater than the differences among regions. Small differences in BDen were also observed among natural populations of *B. aegyptiaca*, *C. glutinosum*, and *G. senegalensis* in Burkina Faso (Nygård and Elving 2000), and results from provenance/progeny tests generally show that there is more variation in BDen within populations than among populations (e.g., Sotelo Montes and Weber 2009; Weber and Sotelo Montes 2010).

Mean annual rainfall differed among regions (Table 1) so one might expect that the regional differences in fuelwood properties were due, at least in part, to the regional differences in rainfall (Sotelo Montes et al. 2011). The effect of rainfall on fuelwood properties of the five species was investigated (Sotelo Montes et al., unpublished data): in most cases, regressions of fuelwood properties with rainfall were not significant or they explained very little variation. Therefore, other variables in addition to rainfall are important in explaining the regional differences in fuelwood properties.

4.3 Differences in fuelwood properties among soil, land use, and terrain types

Soil type had a general effect on wood MC and FVI of the five species. MC tended to be higher on sandy soils and lower on rocky soils and, since MC and FVI are inversely related, FVI tended to be higher on rocky soils. This suggests that fuelwood production for these species should be promoted primarily on rocky soils in the study region.

Ash of *G. senegalensis* and Vol of *Z. mauritiana* was greater in parklands than in woodlands. In terms of fuelwood production, these results suggest that woodlands would be better for *G. senegalensis* (lower Ash), but parklands would be better for *Z. mauritiana* (higher Vol, which is positively correlated with FVI: Pearson $r=0.45$, $P<0.001$, $N=79$). Ash is composed primarily of calcium and potassium (Ragland et al. 1991), and the concentration of these

minerals in plant tissues is generally higher in more fertile soils (Sarmiento et al. 1985). Farmers' management practices, such as burning brush and applying organic fertilizer before sowing crops, should increase soil fertility in parklands over time, so the higher Ash of *G. senegalensis* wood in parklands may reflect the more fertile soils. The higher Vol content of *Z. mauritiana* wood in parklands may be due to the production of protective compounds. In theory, one would expect greater production of resins and other protective compounds in the wood in locations with larger populations of wood-boring insects (Zangerl and Bazzaz 1992).

4.4 Recommendations for fuelwood production in the study regions

Based on the results of this study and other considerations, we recommend the following:

- Promote fuelwood production of *G. senegalensis* throughout the study region, *B. aegyptiaca* and *C. glutinosum* in the drier eastern regions, and *Z. mauritiana* in the more humid western regions.
- Promote fuelwood production of these species on sites with rocky, less fertile soils in the study region because the wood's moisture content was lower on rocky soils, and one would expect that the wood's ash content would be lower on less fertile soils. In general, this means targeting sites not considered priority for crop production.
- Conduct research to identify the specific environmental conditions that affect fuelwood properties of these species. This is particularly important for *C. glutinosum*, since local environmental conditions may have a relatively greater effect on fuelwood properties of this species, compared with the other species.
- Collect seed of the recommended species in the driest locations for establishing fuelwood plantations. This is based on climate change models that predict higher temperatures coupled with lower and more variable rainfall in the study region (Buontempo 2010), and the expectation that progeny of trees from drier locations are better adapted to drought (e.g. Sotelo Montes et al. 2011).

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