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Abstract: Information about variation and correlations of fuelwood properties and growth is needed in order to recommend species and sites for fuelwood production in a changing climate in Africa. We investigated effects of site variables (land use, soil, terrain) geographical coordinates and mean annual rainfall on fuelwood properties (volatile matter, fixed carbon, ash content, moisture content, gross calorific value, gross calorific value per m³, fuel value index) of *Combretum glutinosum*, *Combretum micranthum*, *Combretum nigricans*, *Guiera senegalensis* and *Piliostigma reticulatum*, and correlations of fuelwood properties with wood density and growth (height, stem diameter, ring width) in Niger. We hypothesized that wood density, fixed carbon and gross calorific value were positively correlated, and fixed carbon and gross calorific value were positively correlated with growth. Most effects of site variables, geographical coordinates and mean annual rainfall on fuelwood properties differed among species. Fuel value index was greater on rocky than on sandy soils. Wood moisture content of three species was greater in drier than in more humid locations. Correlations of fuelwood properties with wood density and growth differed among species. Based on this research and previous research, we recommend parkland agroforests and sites with rocky soils and higher mean annual rainfall for fuelwood production.

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Key words: geographic variation, mean annual rainfall, land use type, soil type, terrain type

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Résumé: Des informations sur les variations et les corrélations des propriétés du bois de feu et de la croissance sont nécessaires afin de recommander des espèces et sites pour la production de bois de feu dans un contexte de changement climatique en Afrique. Nous avons étudié les effets des variables des sites (utilisation des terres, sol, terrain), des coordonnées géographiques et des précipitations annuelles moyennes sur les propriétés du bois de feu (matières volatiles, carbone fixe, teneur en cendres, teneur en humidité, pouvoir calorifique supérieur, pouvoir calorifique supérieur par m³, indice de valeur du

49 bois de feu) de *Combretum glutinosum*, *Combretum micranthum*, *Combretum nigricans*, *Guiera*
50 *senegalensis* et *Piliostigma reticulatum*, et des corrélations des propriétés du bois de feu avec la
51 densité du bois et la croissance (hauteur, diamètre de la tige, largeur des anneaux) au Niger. Nous
52 avons émis l'hypothèse que la densité du bois, le carbone fixe et le pouvoir calorifique supérieur
53 étaient corrélés positivement, et le carbone fixe et la valeur calorifique supérieur étaient positivement
54 corrélés à la croissance. La plupart des effets des variables du site, des coordonnées géographiques et
55 des précipitations moyennes annuelles sur les propriétés du bois de feu différent d'une espèce à l'autre.
56 L'indice de valeur de feu était plus élevé sur les sols rocheux que sur les sols sablonneux. La teneur en
57 humidité du bois de trois espèces était plus élevée en localités plus sèches que dans les localités plus
58 humides. Les corrélations entre les propriétés du bois de feu avec la densité du bois et la croissance
59 diffèrent selon les espèces. Sur la base de ces résultats obtenus et ceux des recherches antérieures, nous
60 recommandons des parcs agroforestiers et des sites à sols rocheux et des précipitations moyennes
61 annuelles plus élevées pour la production de bois de feu.

62

63 *Mots-clés:* variation géographique, précipitations annuelles moyennes, type d'utilisation des terres,
64 type de sol, type de terrain

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66 Introduction

67

68 Africa is the second largest continent with the largest land area in the tropics, and growing demand
69 for fuelwood is leading to degradation of many natural forests, especially in semi-arid regions and near
70 large urban centers (FAO 2016). Promoting woodlots and management of natural regeneration of
71 species with desirable fuelwood properties could help to reduce woodcutting and the resulting forest
72 degradation. There is very little published information, however, about inter- and intra-specific
73 variation in fuelwood properties and correlations between growth and fuelwood properties of native
74 tree and shrub species in Africa (Erakhrumen 2009; Sotelo Montes et al. 2011, 2012, 2014). Forestry
75 and natural resource policy institutions in Africa, and in other regions where demand for fuelwood is
76 growing, need this information in order to recommend species and sites for production of higher
77 quality fuelwood in a changing climate. In this paper, we discuss variation in fuelwood properties and
78 correlations of fuelwood properties with wood density and growth in five native tree and shrub species
79 in the Sahelian and Sudanian ecozones of Niger. The Sahel is a semi-arid transitional ecozone between
80 the more humid Sudanian ecozone to the south and the Sahara Desert to the north, so there are steep
81 rainfall gradients (Buontempo 2010). The rainy season lasts only 3-4 months per year, and the climate
82 is becoming hotter and drier with more variability in rainfall (Buontempo 2010). Rural and urban
83 communities use many native tree and shrub species for fuelwood (Faye et al. 2011) but some of these
84 species are disappearing locally due to climate change and unsustainable natural resource practices
85 (Larwanou 2008; Gonzalez et al. 2012), and this may create a challenge for fuelwood production in the
86 future.

87 Several properties should be considered when assessing the value of species and sites for fuelwood
88 production. Growth rates of stems and coppice shoots are important because they determine the
89 volume of wood produced over time. Gross and net calorific values are the amounts of energy per unit

90 mass that are released from the complete combustion of oven-dried and air-dried wood samples,
91 respectively, so wood with high gross and net calorific values is desirable (Nirmal Kumar et al. 2011).
92 Denser wood has more energy per unit volume and burns more slowly (Fuwape and Akindele 1997).
93 High moisture and ash contents reduce gross calorific value because energy is used to evaporate the
94 water and ash is the non-combustible mineral residue in the wood (Shanavas and Mohan Kumar 2003).
95 Volatile matter is released as combustible and non-combustible gasses when the wood is burned, and
96 fixed carbon is the mass, excluding ash, remaining after the volatile matter is released (McKendry
97 2002). Wood with higher volatile matter ignites more rapidly and produces more heat during
98 combustion, but it may also produce more smoke; and wood with higher fixed carbon burns longer
99 (Fuwape and Akindele 1997; Kataki and Konwer 2002). Several fuel value indices have been used to
100 quantify the overall quality of fuelwood from different species. The most commonly used index in
101 recent years adjusts net gross calorific value for the density, ash and moisture contents of the wood
102 (e.g., Sotelo Montes et al. 2011).

103 We selected five tree and shrub species for this study: *Combretum glutinosum* Perr., *Combretum*
104 *micranthum* G. Don., *Combretum nigricans* Lepr. ex Guill. & Perr., *Guiera senegalensis* J.F. Gmel.
105 (Combretaceae family), and *Piliostigma reticulatum* (DC.) Hochst. (Caesalpiniaceae family). They are
106 priority species for rural communities in Niger, so farmers want to maintain them in the landscape
107 (Faye et al. 2011). They are used primarily for fuel, but also for construction poles, fodder, medicines
108 and environmental services, such as soil fertility improvement and soil/water conservation. They are
109 commonly found in tropical dry forests (referred to below as woodlands) and in parkland agroforests.
110 Parkland agroforests are the major agricultural production systems in Niger and neighboring countries:
111 essentially they are croplands in which farmers maintain priority tree and shrub species at relatively
112 low density (Boffa 1999). Farmers manage the parkland agroforests for the production of staple food
113 crops (pearl millet and sorghum) during the rainy season, and for products from tree and shrub species

(mainly wood, food, fodder, medicines and fibers) throughout the year. *Combretum glutinosum* and *C. nigricans* are small trees, while the other species are shrubs. *Combretum glutinosum* and *P. reticulatum* are semi-evergreen, while the other species are deciduous during the dry season.

Research on *C. glutinosum*, *G. senegalensis*, *P. reticulatum* and two other species (*Balanites aegyptiaca*, *Ziziphus mauritiana*) in Mali showed that growth and fuelwood properties differed among species; intra-specific variation in growth and fuelwood properties was related to land use type, terrain type, soil type, latitude, longitude, elevation and/or mean annual rainfall; and correlations between growth and fuelwood properties differed in strength among species (Sotelo Montes et. al. 2012, 2014, 2016). Based on the inter- and intra-specific variation and correlations between growth and fuelwood properties, we recommended that national forestry institutes in Mali promote the use of *C. glutinosum* and *G. senegalensis* for fuelwood production, especially in drier locations (Sotelo Montes et al. 2014).

The objectives of this study were to determine (1) if fuelwood properties (volatile matter, fixed carbon, ash and moisture contents, gross calorific value, gross calorific value per m³ and fuel value index) varied due to species, land use type (parkland agroforest or woodland), soil type (primarily sand or primarily rocks), terrain type (flat, temporarily flooded or hill slope), geographical coordinates (latitude, longitude, elevation) and mean annual rainfall in Niger; and (2) if fuelwood properties were correlated with growth variables (height, stem diameter under bark, mean ring width) and wood density of the five species.

We have two working hypotheses based on previous research. (1) Wood density, fixed carbon and gross calorific value are positively correlated (Sotelo Montes et al. 2014). Wood density increases with an increase in vessel wall thickness and a decrease in vessel lumen diameter (Lachenbruch and McCulloh 2014). Thicker vessel walls have a higher carbon concentration than narrower vessel walls (Martin and Thomas 2011), so denser wood should have higher carbon concentration and gross calorific value (Fuwape and Akindele 1997; Kataki and Konwer 2002). (2) Fixed carbon and gross

calorific value are positively correlated with growth variables (Sotelo Montes et al. 2011, 2014; Weber et al. unpublished data). Taller trees tend to have higher carbon concentration in the wood compared with smaller trees (Thomas and Malczewski 2007; Castaño-Santamaría and Bravo 2012), so gross calorific value should be greater in the wood of taller trees compared with smaller trees. Mean height across the five species in this study increased with mean annual rainfall in Niger (Weber et al. unpublished data), so we expect greater fixed carbon and gross calorific value in more humid locations.

Materials and methods

Study region, tree sampling and site variables

We sampled trees of the five species roughly along latitudinal transects in four regions extending from southwestern to southeastern Niger (Fig. 1) at the end of the dry season in 2011. We planned to sample 80 trees of each species (20 per region), but we could not find trees of *C. nigricans* in regions #3 and #4, and we found only 10 trees of *C. micranthum* in region #4. We maintained a minimum distance of 10 km between trees of the same species in order to ensure a broad geographic sampling. Trees were selected if they were produced by natural regeneration, and if the stem was not a coppice shoot, was undamaged, was growing relatively upright, and was within a predetermined diameter class (4–12 cm at 30 cm above ground). We selected this diameter class because these stems are typically cut for fuelwood or construction poles so trees with larger stem diameters are relatively rare. It was not possible to sample trees of all five species at the same sample points due to differences in species' distribution and difficulty in finding trees that satisfied the selection criteria.

We recorded three qualitative site variables and geographical coordinates at the location of each sampled tree. Site variables included land use type (parkland agroforest or woodland), soil type

(primarily sand or primarily rocks including laterite) and terrain type (flat, temporarily flooded or hill slope). Latitude, longitude and elevation were recorded with a GPS receiver, and used to obtain estimates of mean annual rainfall (mm) from the WorldClim database (www.worldclim.org). Minimum and maximum values for latitude, longitude, elevation and mean annual rainfall at locations of sampled trees of each species are given in Appendix 1 (part B). Mean annual temperature is approximately 29 °C (Sivakumar et al. 1993). Soils are generally very sandy and infertile, and are classified as arenosols throughout most of the study region (FAO 2007).

Estimated mean annual rainfall at the location of the sampled trees decreased from south to north, west to east and from low to high elevation (Pearson r of mean annual rainfall with latitude, longitude and elevation, respectively = -0.920 , -0.688 and -0.633 ; $P < 0.001$, $N = 350$). Elevation at the location of the sampled trees increased from south to north and from west to east (Pearson r of elevation with latitude and longitude, respectively = 0.646 and 0.794 ; $P < 0.001$, $N = 350$).

Sample size, mean elevation and mean annual rainfall by species, land use, soil and terrain types are given in Appendix 1 (part A). *Guiera senegalensis* and *P. reticulatum* were sampled mainly in parkland agroforests, while *C. micranthum* and *C. nigricans* were sampled mainly in woodlands. Mean elevation was higher and mean annual rainfall was lower in parkland agroforests than in woodlands, i.e., parkland agroforests were more common in the north and east, while woodlands were more common in the south and west. The majority of trees were sampled on sandy rather than on rocky soils, and on flat terrain rather than on temporarily flooded sites and hill slopes. Trees were not sampled in all combinations of land use, soil and terrain types for all species.

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183 **Measurements of tree growth and fuelwood properties**

184 In the field, we measured height of each tree in cm with a telescopic measuring pole. The tree was
185 then cut down and a sample of the stem (30 cm long) was obtained between 30 and 60 cm above

186 ground. We labeled the north- and south-facing sides of the stem for reasons explained below. In a
187 laboratory, the bark was removed from the stem samples, and lines were drawn on the north and south-
188 facing sides of the wood. Two disks, without nodes or defects, were cut from the lower part of the stem
189 sample (31-34 cm above ground). Disks were air-dried for one month to attain equilibrium moisture
190 content prior to measurements.

191 One disk (1 cm thick) was used to determine the number and width of the annual rings at 33 cm
192 above ground. Annual rings can be visually distinguished in deciduous and evergreen tree species in
193 semi-arid zones in Africa and used to estimate tree age if there is a distinct dry season to induce
194 cambial dormancy and trigger formation of growth boundaries (Gourlay 1995; Gebrekirstos et al.
195 2008), and there is a distinct dry season of 7- 8 months in Niger. We measured the width of annual
196 rings in the four cardinal directions (i.e., north, east, south and west) in order to sample intra-ring
197 variation. The lower surface of the disk was sanded so that the annual rings were clearly visible and
198 the four cardinal directions were labeled on the sanded surface. A digital image of the surface was
199 produced, a grid was overlaid on the image using software and the annual rings were marked on the
200 image along the four cardinal directions. The number of rings was counted and used as an estimate of
201 the tree's age. The width of each ring was measured in mm along each cardinal direction, and the mean
202 width of each annual ring was calculated from the four values. The mean width of all the annual rings
203 was then calculated (referred to below as mean ring width).

204 The other disk (2 cm thick) was used to measure stem diameter under bark and basic density of the
205 wood. Diameter was measured in mm with a diameter tape at 31 cm above ground. Basic density
206 (oven-dry weight/green volume) was measured in kg m^{-3} using the water displacement method (ASTM
207 1997).

208 Sawdust was prepared from the remaining part of the air-dried stem samples (generally between 36
209 and 40 cm above ground) and used to measure other fuelwood properties for each tree. The sawdust

was sieved through a screen (2 mm mesh) to remove particles larger than 2 mm in length or diameter. The sawdust samples were stored under controlled conditions (60% relative humidity, 20°C) for one month to attain equilibrium moisture content prior to measurements. Following procedures described elsewhere (ABNT 1984), percent moisture content (MC) of the air-dried sawdust was determined from a small sample (0.5 g) that was completely dried in a laboratory muffle oven, and then the oven-dried sample was used to determine gross calorific value (GCV) in MJ kg⁻¹ in an adiabatic bomb calorimeter. Net calorific value (net CV) was calculated from GCV, where net CV equals GCV minus the energy needed to evaporate the water (1.36 MJ kg⁻¹). The percent contents of volatile matter (Vol), fixed carbon (Carb) and ash (Ash) were determined from the mean of two small air-dried sawdust samples (each about 4 g), following procedures described elsewhere and using a laboratory muffle oven (ABNT 1986). Vol and Ash were measured, and Carb was calculated from the difference (100% – Vol – Ash) for each sample. Since the sum of Vol, Carb and Ash equals 100% for each sample, Vol is negatively correlated with Carb and Ash. The correlations of Vol with Carb and Ash were –0.921 and –0.597, respectively, and the correlation between Carb and Ash was 0.237 ($P < 0.001$, $N = 344$).

Stem samples of some trees were damaged by wood-boring beetles, so we could not obtain all data from these trees. If we could not estimate the tree's age, then the tree was excluded from the analyses.

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. The following procedures were used: Univariate to assess normality of residuals, Mixed (restricted maximum likelihood estimation method) for analysis of covariance and variance, Corr for Pearson correlations, and Reg for linear regressions. Data transformations were not considered necessary because the residuals from the analyses of variance and regressions exhibited normal distributions.

Values for growth and wood variables were adjusted for differences in tree age separately for each species. The effect of age on each dependent variable of each species was determined using analysis of covariance (with only age as a covariate in the model). Data were then adjusted using the following formula: $Z_{i(jk)} = Y_{i(jk)} - \beta_{i(k)}(X_{j(k)} - X_k)$, where $Z_{i(jk)}$ = adjusted value of variable_{*i*} of tree_{*j*} of species_{*k*}, $Y_{i(jk)}$ = unadjusted value of variable_{*i*} of tree_{*j*} of species_{*k*}, $\beta_{i(k)}$ = effect of age on variable_{*i*} of species_{*k*}, $X_{j(k)}$ = age of tree_{*j*} of species_{*k*}, and X_k = mean age of species_{*k*}. Adjusted data were used for all calculations and analyses described below. Because data were adjusted separately for each species, trees with greater adjusted values for growth variables can be considered faster-growing trees within their particular species.

Age had a significant negative effect on mean ring width of all five species ($P < 0.001$) and a significant positive effect on stem diameter under bark of three species (*G. senegalensis* and *C. micranthum* $P < 0.001$, *C. nigricans* $P < 0.05$). Age did not have a significant effect on height of any species ($P > 0.05$). Age had a significant positive effect on GCV and basic density of *G. senegalensis* wood ($P < 0.05$) but the effect of age on fuelwood properties was not significant in the other species.

Mean age of sampled trees was 8.7, 9.2, 8.9, 8.0 and 7.5 years, respectively for *C. glutinosum*, *C. micranthum*, *C. nigricans*, *G. senegalensis* and *P. reticulatum*. Mean age was significantly greater for the three *Combretum* species compared with the other two species (Tukey HSD, $P < 0.001$). These small differences in mean age probably had little if any effect on inter-specific differences in fuelwood properties, based on previous research (Lemenih and Bekele 2004; Kumar et al. 2010).

Two derived fuelwood properties were calculated from the adjusted data. Gross calorific value per m^3 (GCVm^3) was calculated as the product of basic wood density and GCV. The fuel value index (FVI) was calculated using the following formula: $\text{FVI} = [(\text{basic density})(\text{net CV})]/[(\text{Ash})(\text{MC})]$.

Analysis of variance (ANOVA) was used to determine if Vol, Carb, Ash, MC, GCV, GCVm^3 and FVI differed significantly among species and site variables. Regions were treated as blocks. The

ANOVA model was: $Y_{ijklmn} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \eta_m + \theta_{ij} + \lambda_{ik} + \Omega_{il} + \psi_{im} + \varepsilon_{ijklmn}$, where Y_{ijklmn} = tree_n in treatment combination_{ijklm}, μ = the grand mean, α_i = species_i, β_j = block_j, γ_k = soil type_k, δ_l = land use type_l, η_m = terrain type_m, θ_{ij} = interaction between species_i and block_j, λ_{ik} = interaction between species_i and soil type_k, Ω_{il} = interaction between species_i and land use type_l, ψ_{im} = interaction between species_i and terrain type_m, and ε_{ijklmn} = residual error. Main effects (species, soil, land use, terrain), blocks and interactions were treated as fixed factors. Interactions between blocks and site variables were not tested because there were no observations for some site variables of some species in some blocks (Appendix 1, part A). Least-squares means for main effects were compared using the Tukey HSD (honestly significant difference) test.

Based on previous research in Mali (Sotelo Montes et al. 2012), we expected that the effects of site variables on fuelwood properties would differ among species. For this reason, we also did the ANOVA separately for each species. The ANOVA model was: $Y_{jklmn} = \mu + \beta_j + \gamma_k + \delta_l + \eta_m + \varepsilon_{jklmn}$, where Y_{jklmn} = tree_n in treatment combination_{jklm}, μ = the grand mean, β_j = block_j, γ_k = soil type_k, δ_l = land use type_l, η_m = terrain type_m, and ε_{jklmn} = residual error.

Linear regression analysis was used to determine if geographical coordinates and mean annual rainfall had significant effects on Vol, Carb, Ash, MC, GCV, GCVm³ and FVI of each species. Two sets of regressions were carried out for each species: multiple linear regression (forward selection) with latitude, longitude and elevation as independent variables; and simple linear regression with mean annual rainfall as the independent variable. Only significant terms ($P < 0.05$) were retained in the final regression equations.

Values for mean annual rainfall were estimated from the geographical coordinates of the trees, so the geographical coordinates are proxy variables for mean annual rainfall. If a geographical coordinate has a significant effect on a dependent variable, then mean annual rainfall should have a similar effect. If the effect of a geographical coordinate is significant but the effect of mean annual rainfall is not

significant, then the effect of the geographical coordinate does not reflect mean annual rainfall. These expectations assume that the estimates of mean annual rainfall are accurate.

Pearson correlation coefficients were used to investigate linear relationships between growth variables and Vol, Carb, Ash, MC, GCV, GCVm³ and FVI; and between basic density and Vol, Carb, Ash, MC and GCV. Basic density was used to calculate GCVm³ and FVI, so we were not interested in the correlations between basic density and these variables.

Results

Variation in fuelwood properties among species, land use types, soil types and terrain types

Coefficients of variation were greater for Ash and FVI than for the other fuelwood properties in all five species (Table 1). The FVI had the largest coefficient of variation because it was derived from basic density, net calorific value, ash content and moisture content.

All fuelwood properties differed significantly among species (Table 1: Tukey test). Based on FVI, *G. senegalensis* had the best fuelwood properties and *P. reticulatum* had the worst fuelwood properties. The FVI of *G. senegalensis* was 3.7 times higher than that of *P. reticulatum*. This reflected differences in Ash, net CV (i.e., GCV – 1.36 MJ kg⁻¹) and basic density between the two species. GCV was highest in *G. senegalensis*, while Ash was lowest in *G. senegalensis* and highest in *P. reticulatum*. Basic density was lowest in *P. reticulatum*: mean basic density of *C. glutinosum*, *C. micranthum*, *C. nigricans*, *G. senegalensis* and *P. reticulatum* wood, respectively, were 695, 758, 756, 690 and 581 kg m⁻³ (Weber et al. unpublished data)

There was no relationship between mean basic density and mean GCV of the species. For example, *C. micranthum* had significantly denser wood than *G. senegalensis* and especially *P. reticulatum* (Weber et al. unpublished data), but there was no significant difference in GCV between *C.*

306 *micranthum* and *P. reticulatum*, and *G. senegalensis* had significantly greater GCV than *C. micranthum*
307 (Table 1: Tukey test).

308 Site variables (land use, soil and terrain types) generally did not have significant effects on
309 fuelwood properties in the analysis across species (Table 2: Tukey test results shown only for variables
310 with a significant difference due to site variables). Soil type had a significant effect on FVI: mean FVI
311 across species was greater on rocky than on sandy soils. Interactions between species and site variables
312 were not significant for any fuelwood property (not tabled, $P > 0.05$).

313 Site variables had significant effects on some fuelwood properties of three species (Table 2: Tukey
314 test). The effect of soil type on FVI was significant only in *G. senegalensis*: greater FVI on rocky than
315 on sandy soils. Land use type had significant effects on MC of *C. glutinosum* and $GCVm^3$ of *G.*
316 *senegalensis*: greater MC of *C. glutinosum* in parkland agroforests than in woodlands, and greater
317 $GCVm^3$ of *G. senegalensis* in woodlands than in parkland agroforests. Terrain type had significant
318 effects on Ash and FVI of *C. micranthum*: Ash was highest and FVI was lowest on hill slopes.

319

320 **Variation in fuelwood properties related to geographical coordinates and mean annual rainfall**

321 Regression equations were computed for seven variables of each species. Among the 35 regression
322 equations, 21 were significant with geographical coordinates (Table 3, part A), but only 11 were
323 significant with mean annual rainfall (Table 3, part B). The effect of longitude was significant in 14
324 equations, and the effects of latitude and elevation were significant in only six equations. Regression
325 equations explained little variation: among the significant equations, the mean coefficient of
326 determination was 0.145 for latitude, 0.160 for longitude, 0.103 for elevation and 0.107 for mean
327 annual rainfall.

328 Some effects of geographical coordinates and mean annual rainfall on fuelwood properties differed
329 among species (Table 3, parts A and B). Carb increased from west to east in *C. glutinosum* and *C.*

330 *micranthum*, but from east to west in *C. nigricans* and *G. senegalensis*. Vol was negatively correlated
 331 with Carb, so Vol tended to vary in the opposite direction: higher Vol at lower elevation in *C.*
 332 *glutinosum*; in the west in *C. micranthum*; in the south, east and at higher elevation in *C. nigricans*;
 333 and at higher elevation in *G. senegalensis*. The effects of mean annual rainfall on Vol and Carb were
 334 significant in three of the species: Carb was higher (and Vol lower) in drier locations for *C. glutinosum*
 335 and *C. micranthum*, but in more humid locations for *G. senegalensis*. MC showed the most consistent
 336 relationship among the species: MC of *C. micranthum*, *C. nigricans*, *G. senegalensis* and *P.*
 337 *reticulatum* was higher in the north and/or east. The effect of mean annual rainfall on MC was
 338 significant in three of these species: MC was higher in drier locations for *C. micranthum*, *G.*
 339 *senegalensis* and *P. reticulatum*. GCV increased from higher to lower elevation in *C. glutinosum*, from
 340 west to east in *C. nigricans*, and from south to north in *P. reticulatum*. The effect of mean annual
 341 rainfall on GCV was not significant in any of the species. $GCVm^3$ increased from south to north and
 342 from higher to lower elevation in *C. micranthum*, from west to east in *C. nigricans*, and from south to
 343 north in *P. reticulatum*. The effect of mean annual rainfall on $GCVm^3$ was significant only in *C.*
 344 *micranthum*: higher $GCVm^3$ in drier locations. FVI increased from west to east in *C. nigricans* but
 345 from east to west in *P. reticulatum*. The effect of mean annual rainfall on FVI was not significant in *C.*
 346 *nigricans* and *P. reticulatum*, but it was significant in *C. micranthum*: higher FVI in more humid
 347 locations.

348

349 **Correlations of fuelwood properties with tree growth and wood basic density**

350 Some correlations between tree growth and fuelwood properties differed among species (Table 4:
 351 only statistically significant correlations are shown). Faster-growing trees (i.e. trees with greater values
 352 for height, stem diameter and/or mean ring width) had lower Vol and higher Carb in *C. micranthum*
 353 and *P. reticulatum*, but higher Vol in *C. glutinosum*; lower Ash in *C. glutinosum* and *C. nigricans*, but

354 higher Ash in *P. reticulatum*; lower MC in *C. micranthum* and *G. senegalensis*; lower GCVm³ in *C.*
355 *micranthum*, but higher GCV and GCVm³ in *G. senegalensis*; lower FVI in *P. reticulatum*, but higher
356 FVI in *C. glutinosum* and *G. senegalensis*. Correlations were generally stronger with height and stem
357 diameter than with mean ring width.

358 Most correlations of basic density with the other fuelwood properties of the species were not
359 significant (Table 4). There was a weak positive correlation between basic density and GCV in *C.*
360 *glutinosum* and *G. senegalensis*. In addition, denser wood tended to have lower MC in *G.*
361 *senegalensis*, but higher MC in *C. micranthum*. Basic density was not significantly correlated with
362 Carb in any species.

363 Correlations between Carb and GCV were significant in only two species (not tabled). Pearson $r =$
364 0.229 and 0.264, respectively in *G. senegalensis* and *P. reticulatum* ($P < 0.05$, $N = 80$ and 79 ,
365 respectively).

366 Because basic density and Carb were not strongly correlated with GCV, we used multiple
367 regression analysis (forward selection) to determine which fuelwood properties (Carb, Vol, Ash, MC,
368 basic density) had the strongest effects on GCV across species. Ash and Carb had the strongest effects
369 on GCV: negative for Ash and positive for Carb ($P < 0.001$, $R^2 = 0.192$ and 0.141 , respectively, $N =$
370 344). The other fuelwood properties were not significant ($P > 0.05$) with Ash and Carb in the model.

371

372 Discussion

373

374 Variation in fuelwood properties among species, land use, soil and terrain types

375 Values for gross calorific value of the species in this study were similar to those reported for *B.*
376 *aegyptiaca*, *C. glutinosum*, *G. senegalensis*, *P. reticulatum* and *Z. mauritiana* in Mali (Sotelo Montes
377 et al. 2012), *B. aegyptiaca* and *Prosopis africana* in Niger (Sotelo Montes et al. 2011) and 12 tree

species in the humid and sub-humid tropical forests of Nigeria (Erakhrumen 2009). They were 1–9 % lower, however, than the values reported for 24 tree and shrub species in tropical dry forests in India (Nirmal Kumar et al. 2011): this may be due to the lower wood density of the species in this study, compared with the species studied in India (mean basic density = 696 and 846 kg m⁻³, respectively).

Coefficients of variation for fuelwood properties of the species in this study were similar to those reported for five species in Mali (Sotelo Montes et al. 2012). The large coefficient of variation for ash content suggests that it is more affected by local environmental conditions than the other fuelwood properties. Ash contains calcium and potassium (Ragland et al. 1991), which are accumulated in the wood and mobilized when needed for various metabolic functions (Fromm 2010). One would expect higher calcium and potassium contents in plant tissues growing on soils with greater available calcium and potassium (Sarmiento et al. 1985). There is considerable spatial variability in soil calcium and potassium in Niger (Wezel et al. 2000), so one would expect considerable variability in ash content among trees.

The fuel value index was highest for *G. senegalensis* and lowest for *P. reticulatum* in this study, as also observed in Mali (Sotelo Montes et al. 2012). Farmers manage natural regeneration of both species for fuelwood and for soil/water conservation and soil fertility improvement in parkland agroforests (Faye et al. 2011). Although *P. reticulatum* has low quality fuelwood properties, its growth form (semi-evergreen with obliquely oriented adventitious shoots) creates a microenvironment that is favorable for growth of the plant itself and for seed germination of other species that are useful for animal browse and soil cover during the dry season (Wezel et al. 2000; Kizito et al. 2006).

We hypothesized that wood density would be positively correlated with gross calorific value, so we expected a positive relationship between mean basic density and mean gross calorific value of the species, but results were not consistent with this expectation. Similar results were observed in Mali (Sotelo Montes et al. 2012). This probably reflects the fact that gross calorific value is also affected by

402 volatile matter, fixed carbon, ash and moisture contents (Kataki and Konwer 2002; McKendry 2002;
403 Shanavas and Mohan Kumar 2003), and these properties varied among species in this study and in
404 Mali. In this study, multiple regression analysis indicated that ash and fixed carbon contents had
405 stronger effects (negative and positive, respectively) than basic density, volatile matter and moisture
406 contents on gross calorific value across species.

407 Wood with higher content of tannins and other volatile extractives tends to have higher calorific
408 value (Kataki and Konwer 2002). Mean condensed tannin content determined from disks from the
409 stem of trees in this study was 3.88, 3.62, 3.26, 2.06 and 0.41 %, respectively for *C. micranthum*, *G.*
410 *senegalensis*, *C. glutinosum*, *P. reticulatum* and *C. nigricans* (Santos 2014). There was a rough
411 relationship between mean condensed tannin content and mean gross calorific value: the species with
412 the lowest condensed tannin content (*C. nigricans*) had the lowest gross calorific value, and the species
413 with the highest or second highest condensed tannin content (*G. senegalensis* and *C. micranthum*) had
414 the highest or second highest gross calorific value).

415 Land use, soil and terrain types generally did not have significant effects on fuelwood properties of
416 the species in this study. In those cases where the effect was significant, the differences between means
417 of land use, soil and terrain types were much lower than the difference among species' means. Similar
418 results were reported for studies of fuelwood properties, wood color and wood stiffness in natural
419 populations in Mali (Sotelo et al. 2012, 2013, 2016). These results may be due to the qualitative rather
420 than quantitative nature of the site variables used in this study and in Mali. In addition, sample sizes
421 were very small for some species in some land use, soil and terrain types, reflecting differences in the
422 species' distributions. Future research should quantify environmental differences within the land use,
423 soil and terrain types (e.g., number of trees per hectare, soil texture, rockiness, soil fertility, depth to
424 the water table, percent slope, land use history) and, if possible, sample similar numbers of trees in
425 each land use, soil and terrain type.

426 The only significant effect of a site variable across species was the effect of soil type on fuel value
427 index: the fuel value index was greater on rocky than on sandy soils. The same result was observed in
428 Mali (Sotelo Montes et al. 2012). In contrast, soil type did not have a significant effect on growth
429 variables across species in Mali (Sotelo Montes et al. 2016) and in Niger (Weber et al. unpublished
430 data). These results suggest that sites with rocky soils, rather than sandy soils, should be targeted for
431 fuelwood production in both countries.

432

433 **Variation in fuelwood properties related to geographical coordinates and mean annual rainfall**

434 Geographical coordinates had more significant effects than mean annual rainfall on fuelwood
435 properties of the species in this study. Several fuelwood properties of the species varied significantly
436 with geographical coordinates, but not with mean annual rainfall. The gradient in mean annual rainfall
437 was stronger with latitude than with longitude, but longitude had more significant effects than latitude
438 on fuelwood properties. Similar results were observed in the study of fuelwood properties in Mali
439 (Sotelo Montes et al. 2014). Results suggest that there are other environmental variables, in addition to
440 mean annual rainfall, that directly or indirectly affect fuelwood properties and are correlated with
441 latitude, longitude and elevation (e.g., available soil water, soil fertility, temperature).

442 Some effects of geographical coordinates and mean annual rainfall on fuelwood properties differed
443 among species. This is expected based on studies of variation in wood properties in natural populations
444 (Sotelo Montes et al. 2013, 2014, 2016). As others have noted, any environmental factor that affects
445 tree growth may also affect wood properties and correlations between growth and wood properties,
446 and different species and trees within species respond differently to environmental factors (Zobel and
447 van Buijtenen 1989).

448 We hypothesized that fixed carbon and gross calorific value would be greater in more humid
449 locations, but results were not consistent with the hypothesis. The two fuelwood properties were

450 greater in more humid locations in some species, but in drier locations in other species. Similar results
451 were observed in Mali (Sotelo Montes et al. 2014).

452 Some studies have reported a negative correlation between wood density and moisture content (Al-
453 Sagheer and Prasad 2010; Longuetaud et al. 2016), while others have reported no significant
454 correlation between these wood properties (Wang et al. 1984). In this study, the correlation between
455 basic density and moisture content of air-dried sawdust was negative in *G. senegalensis*, positive in *C.*
456 *micranthum* and not significant in the other species. Basic density of *C. micranthum* decreased with
457 mean annual rainfall, but basic density of the other species did not vary significantly with mean annual
458 rainfall (Weber et al. unpublished data).

459 Moisture content of air-dried sawdust decreased with an increase in mean annual rainfall in three
460 species (*C. micranthum*, *G. senegalensis*, *P. reticulatum*). In *C. micranthum*, but not in the other
461 species, this geographical trend reflected the positive correlation between basic density and moisture
462 content and the negative effect of mean annual rainfall on basic density. The largest difference in
463 moisture content due to mean annual rainfall was 2% in *C. micranthum*: moisture content estimated
464 from linear regression was 8.8 % and 6.8 %, respectively at the locations with the lowest and highest
465 mean annual rainfall. Results suggest that these three species have evolved an adaptive mechanism (or
466 mechanisms) to maintain higher wood moisture content in drier locations. As others have noted,
467 woody tissue can act as a water reservoir for trees in semi-arid zones where water deficits are common
468 (Sternberg and Shoshany 2001). In Mali, moisture content was greater in drier locations for *G.*
469 *senegalensis* but in more humid locations for *C. glutinosum*, and basic density of these species did not
470 vary significantly with mean annual rainfall (Sotelo Montes et al. 2014).

471

472 **Correlations of fuelwood properties with tree growth and wood basic density**

473 We hypothesized positive correlations between wood density, fixed carbon and gross calorific
474 value, but results were not consistent with the hypothesis. Correlations of gross calorific value with
475 basic density and fixed carbon were weak but significant in only two species, while correlations
476 between basic density and fixed carbon were not significant in any species. Other studies have reported
477 positive, negative and non-significant correlations between gross calorific value and basic density in
478 tropical hardwood species (Doat 1997; Kataki and Konwer 2002; Shanavas and Mohan Kumar 2003;
479 Sotelo Montes et al. 2003; Weber and Sotelo Montes 2005; Sotelo Montes et al. 2011). The low or
480 non-significant correlations between gross calorific value and fixed carbon in the species in this study
481 may be due to the fact that wood with higher fixed carbon tended to have higher ash content. Fixed
482 carbon was not directly measured in this study. Other studies have reported that basic density and
483 carbon concentration (measured with carbon determinator) are not significantly correlated in some
484 species (Navarro et al. 2013), including four of the species in this study (Weber et al. unpublished
485 data).

486 We hypothesized that fixed carbon and gross calorific value would be positively correlated with
487 growth variables, but results were not consistent with this hypothesis. Correlations with growth
488 variables were weak but significant for fixed carbon in only two species, and for gross calorific value
489 in only one species. Similar results were observed in Mali (Sotelo Montes et al. 2014). In contrast to
490 fixed carbon, there were positive correlations between growth variables and carbon concentration
491 (measured with carbon determinator) in four of the species in this study (Weber et al. unpublished
492 data). Weak positive correlations between growth variables and gross calorific value have been
493 reported for some other tropical hardwood species (Goel and Behl 1995; Sotelo Montes et al. 2003;
494 Weber and Sotelo Montes 2005; Sotelo Montes et al. 2011).

495 For fuelwood production, we would like to identify species and sites in which trees grow relatively
496 fast and have desirable fuelwood properties. In this study, for example, faster-growing trees had wood

with higher gross calorific value and lower moisture content in *G. senegalensis*, lower ash content in *C. glutinosum* and *C. nigricans*, and higher fixed carbon and lower moisture content in *C. micranthum*. In contrast, faster growing trees of *P. reticulatum* had wood with higher ash content. Mean height across species in this study increased with mean annual rainfall, while mean stem diameter and ring width across species were greater in parkland agroforests than in woodlands (Weber et al., unpublished data). We recommend, therefore, promoting fuelwood production in parkland agroforests and in sites with higher mean annual rainfall in Niger, using species like *G. senegalensis*, which had a high fuel value index and positive correlations between growth and desirable fuelwood properties.

505

506 Conclusions

- 507 1. The fuel value index was highest in *G. senegalensis* and lowest in *P. reticulatum*.
- 508 2. The fuel value index across species was greater on rocky than on sandy soils.
- 509 3. Wood moisture content in *C. micranthum*, *G. senegalensis* and *P. reticulatum* decreased with
510 increasing mean annual rainfall.
- 511 4. Correlations of fuelwood properties with wood basic density and growth differed among species.
- 512 5. Parkland agroforests and sites with rocky soils and higher mean annual rainfall are recommended
513 for fuelwood production.

514

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519

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Table 1. Differences in fuelwood properties among species in Niger

Variables ^a	P ^b	<i>C. glutinosum</i>	<i>C. micranthum</i>	<i>C. nigricans</i>	<i>G. senegalensis</i>	<i>P. reticulatum</i>
Mean ^c						
Vol	***	80.33 c	80.03 bc	80.80 d	79.86 b	77.84 a
Carb	***	18.47 b	18.90 c	17.80 a	19.52 d	20.28 e
Ash	***	1.20 bc	1.07 b	1.40 c	0.62 a	1.88 d
MC	***	9.15 d	7.90 a	8.55 bc	8.72 c	8.33 b
GCV	***	18.79 b	18.91 b	18.54 a	19.51 c	18.88 b
GCVm ³	***	13,057 b	14,325 d	14,000 d	13,463 c	10,964 a
FVI	***	1,259 b	1,773 c	1,245 b	2,777 d	743 a
Coefficient of variation (%)						
Vol	---	1.3	1.3	1.4	1.1	1.4
Carb	---	5.1	5.1	4.5	4.2	4.3
Ash	---	33.0	30.8	39.7	46.6	28.0
MC	---	7.4	10.9	6.4	6.0	7.7
GCV	---	2.2	2.5	2.7	1.5	1.6
GCVm ³	---	6.9	6.0	5.5	6.4	5.0
FVI	---	38.5	35.0	42.8	36.4	38.3

^a Variables: Vol, Carb, Ash and MC = volatile matter, fixed carbon, ash and moisture content, respectively of air-dried sawdust samples (%); GCV and GCVm³ = gross calorific value per kg and m³, respectively of oven-dried sawdust samples (MJ kg⁻¹ and MJ m⁻³, respectively); FVI = fuel value index [(net calorific value x basic density)/(MC x Ash)]; values adjusted for tree age

^b P = probability of F for testing effect of species: *** P < 0.001; numerator/denominator degrees of freedom = 4/307

^c Tabled means are least squares means: 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 Honestly Significant Difference test; sample size = 75 for *C. glutinosum*, 70 for *C. micranthum*, 40 for *C. nigricans*, 80 for *G. senegalensis*, 79 for *P. reticulatum*

Table 2. Differences in fuelwood properties of species between land use, soil and terrain types in Niger^a

Species	Variables ^b	P ^c	Mean ^d		
			Land use type		
			Parkland	Woodland	
<i>C. glutinosum</i>	MC	*	9.52 b	9.01 a	
<i>G. senegalensis</i>	GCVm ³	*	13,359 a	13,899 b	
			Soil type		
			Sandy	Rocky	
All species	FVI	*	1,448 a	1,671 b	
<i>G. senegalensis</i>	FVI	*	2,625 a	3,373 b	
			Terrain type		
			Temporarily flooded	Flat	Hill slope
<i>C. micranthum</i>	Ash	*	1.00 ab	0.96 a	1.29 b
<i>C. micranthum</i>	FVI	*	1,839 ab	1,929 b	1,353 a

^a Results shown only for variables with significant difference between land use, soil or terrain types

^b Variables: Ash and MC = ash and moisture content, respectively of air-dried sawdust samples (%); GCVm³ = gross calorific value per m³ (MJ m⁻³) of oven-dried sawdust samples; FVI = fuel value index [(net calorific value x basic density)/(MC x Ash)]; values adjusted for tree age

^c P = probability of F for testing effects of land use, soil and terrain types: * P < 0.05; numerator degrees of freedom = 1 for land use and soil types and 2 for terrain type, denominator degrees of freedom = 307

^d Tabled means are least squares means: 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 Honestly Significant Difference test; sample size = 344 for all species, 75 for *C. glutinosum*, 70 for *C. micranthum*, 80 for *G. senegalensis*

Table 3. Linear regression equations of fuelwood properties of species with (A) geographical coordinates and (B) mean annual rainfall in Niger ^a

A. Regressions with geographical coordinates

Species	Variables ^b	Intercept ^c	Beta ^c			R ² and P ^c		
			Lat	Lon	Ele	Lat	Lon	Ele
<i>C. glutinosum</i>	Vol	81.80			−0.004			0.177***
	Carb	17.35		0.220			0.220***	
	GCV	19.11			−0.001			0.063*
<i>C. micranthum</i>	Vol	81.34		−0.278			0.222***	
	Carb	17.62		0.276			0.257***	
	MC	−1.34	0.644	0.130		0.398***	0.051*	
	GCVm ³	4855	779		−3.269	0.148***		0.057*
<i>C. nigricans</i>	Vol	83.50	−0.848	0.925	0.024	0.083*	0.183***	0.118**
	Carb	22.08		−0.578	−0.013		0.165***	0.132*
	MC	7.35		0.338			0.196**	
	GCV	17.74		0.267			0.138*	
	GCVm ³	12449		495.347			0.201**	
	FVI	533		280.535			0.110*	
<i>G. senegalensis</i>	Vol	79.15			0.003			0.073*
	Carb	20.03		−0.119			0.083**	
	MC	8.16		0.126			0.227***	
<i>P. reticulatum</i>	Ash	1.50		0.073			0.076	
	MC	4.04	0.323			0.092**		
	GCV	17.17	0.127			0.063*		
	GCVm ³	7381	265.444			0.086**		
	FVI	960		−48.180			0.114**	

B. Regressions with mean annual rainfall

Species	Variables ^b	Intercept ^c	Beta ^c	r ² and P ^c
<i>C. glutinosum</i>	Vol	78.80	0.004	0.091**
	Carb	20.00	−0.004	0.116**
<i>C. micranthum</i>	Vol	78.08	0.005	0.142**
	Carb	20.74	−0.004	0.146**

	MC	10.42	−0.006	0.326***
	GCVm ³	16156	−4.390	0.161***
	FVI	999	1.958	0.060*
<i>G. senegalensis</i>	Vol	81.14	−0.003	0.071*
	Carb	18.20	0.003	0.094**
	MC	9.56	−0.002	0.091**
<i>P. reticulatum</i>	MC	9.23	−0.002	0.069*

^a Only the statistically significant regressions are shown

^b Variables = dependent variables: Vol, Carb, Ash and MC = volatile matter, fixed carbon, ash and moisture content, respectively of air-dried sawdust samples (%); GCV and GCVm³ = gross calorific value per kg and m³, respectively of oven-dried sawdust samples (MJ kg^{−1} and MJ m^{−3}, respectively); FVI = fuel value index [(net calorific value x basic density)/(MC x Ash)]; values adjusted for tree age

^c Intercept = equation intercept; Beta = regression coefficient for independent variables – linear latitude (Lat, south to north, decimal °N), longitude (Lon, west to east, decimal °E), elevation (Ele, m) and mean annual rainfall (mm); R² for geographical coordinates and r² for mean annual rainfall = coefficient of determination; P = probability of F for testing the effect of the independent variable *** P < 0.001, ** P < 0.01, * P < 0.05; sample size = 75 for *C. glutinosum*, 70 for *C. micranthum*, 40 for *C. nigricans*, 80 for *G. senegalensis*, 79 for *P. reticulatum*

Table 4. Pearson correlation coefficients of fuelwood properties with tree growth and wood density of species in Niger ^a

Species	Variables ^{b,c}	Height	Diameter	Ring width	Density
<i>C. glutinosum</i>	Vol	0.241*	NS	NS	NS
	Ash	-0.366**	-0.327**	-0.283*	NS
	GCV	NS	NS	NS	0.228*
	FVI	0.329**	0.247*	NS	---
<i>C. micranthum</i>	Vol	NS	-0.284*	-0.240*	NS
	Carb	NS	0.302*	0.258*	NS
	MC	-0.304*	NS	NS	0.391***
	GCVm ³	-0.317**	NS	NS	---
<i>C. nigricans</i>	Ash	-0.415**	NS	NS	NS
<i>G. senegalensis</i>	MC	-0.288**	NS	NS	-0.309**
	GCV	0.273*	NS	0.221*	0.239*
	GCVm ³	0.319**	0.341**	0.353**	---
	FVI	0.320**	0.320**	0.267*	---
<i>P. reticulatum</i>	Vol	NS	-0.349**	-0.271*	NS
	Carb	NS	0.280*	NS	NS
	Ash	0.282*	0.266*	0.222*	NS
	FVI	NS	-0.241*	NS	---

^a Only the statistically significant correlations are shown; correlations between wood density and derived variables (GCVm³ and FVI) are not shown because density was used to calculate the derived variables

^b Variables: Height = tree height, Diameter = stem diameter under bark, Ring width = mean width of annual rings, Density = wood basic density; Vol, Carb, Ash and MC = volatile matter, fixed carbon, ash and moisture content, respectively of air-dried sawdust samples; GCV and GCVm³ = gross calorific value per kg and m³, respectively of oven-dried sawdust samples; FVI = fuel value index [(net calorific value x basic density)/(MC x Ash)]; values adjusted for tree age

^c Significance of Pearson r *** P < 0.001, ** P < 0.01, * P < 0.05, NS P > 0.05; sample size = 75 for *C. glutinosum*, 70 for *C. micranthum*, 40 for *C. nigricans*, 80 for *G. senegalensis*; 79 for *P. reticulatum*

Appendix 1. Sample size, mean elevation and mean annual rainfall by species, land use, soil and terrain types (part A), and minimum and maximum values for latitude, longitude, elevation and mean annual rainfall by species (part B) in Niger

A. Sample size, mean elevation and mean annual rainfall

Sample group	Variable ^a	<i>C. glutinosum</i>	<i>C. micranthum</i>	<i>C. nigricans</i>	<i>G. senegalensis</i>	<i>P. reticulatum</i>
<u>All trees</u>	Num.	75	70	40	80	79
	Elev.	310	292	239	306	303
	Rain	401	410	464	399	403
<u>Parkland agroforests</u>	Num.	39	20	6	50	50
	Elev.	365	351	241	327	335
	Rain	347	345	449	365	372
<u>Sandy soil</u>	Num.	34	14	6	45	42
	Elev.	351	337	241	318	316
	Rain	349	349	449	368	377
Temporarily flooded	Num.	--- ^b	2	--- ^b	--- ^b	--- ^b
	Elev.	---	219	---	---	---
	Rain	---	420	---	---	---
Flat	Num.	28	11	6	40	39
	Elev.	348	352	241	319	315
	Rain	350	338	449	372	373
Hill slope	Num.	6	1	--- ^b	5	3
	Elev.	365	410	---	311	323
	Rain	344	326	---	338	421
<u>Rocky soil</u>	Num.	5	6	--- ^b	5	8
	Elev.	455	381	---	407	433
	Rain	340	334	---	336	348
Temporarily flooded	Num.	--- ^b	1	--- ^b	--- ^b	--- ^b
	Elev.	---	380	---	---	---
	Rain	---	354	---	---	---
Flat	Num.	4	4	--- ^b	2	5
	Elev.	448	365	---	348	420
	Rain	341	329	---	316	347
Hill slope	Num.	1	1	--- ^b	3	3
	Elev.	483	447	---	446	454
	Rain	339	335	---	350	350
<u>Woodlands</u>	Num.	36	50	34	30	29
	Elev.	261	269	239	270	253
	Rain	457	437	467	456	454
<u>Sandy soil</u>	Num.	17	27	12	19	16
	Elev.	240	273	233	275	241
	Rain	447	433	482	454	466
Temporarily flooded	Num.	2	4	--- ^b	5	5
	Elev.	255	396	---	263	252
	Rain	365	379	---	443	489
Flat	Num.	14	22	12	13	10
	Elev.	238	246	233	284	236
	Rain	465	446	482	453	462
Hill slope	Num.	1	1	--- ^b	1	1
	Elev.	239	395	---	213	233

	Rain	353	373	---	524	401
Rocky soil	Num.	19	23	22	11	13
	Elev.	279	264	242	263	267
	Rain	466	441	459	458	439
Temporarily flooded	Num.	2	--- ^b	--- ^b	--- ^b	--- ^b
	Elev.	230	---	---	---	---
	Rain	477	---	---	---	---
Flat	Num.	13	16	19	8	11
	Elev.	255	263	244	240	254
	Rain	495	440	453	452	451
Hill slope	Num.	4	7	3	3	2
	Elev.	382	265	226	323	337
	Rain	366	443	496	476	377

B. Minimum and maximum values for latitude, longitude, elevation and mean annual rainfall

Variable ^a		<i>C. glutinosum</i>	<i>C. micranthum</i>	<i>C. nigricans</i> ^c	<i>G. senegalensis</i>	<i>P. reticulatum</i>
Lat.	Min.	11.98	11.98	11.98	11.97	11.91
	Max.	14.60	14.60	13.67	14.61	14.58
Long.	Min.	1.99	2.06	2.10	2.08	2.03
	Max.	7.94	7.86	4.23	7.94	7.94
Elev.	Min.	156	173	193	182	183
	Max.	613	521	299	585	576
Rain	Min.	278	278	349	284	288
	Max.	602	602	602	602	642

^a Variable: Num. = number of sampled trees, Lat. = latitude (°N), Long. = longitude (°E), Elev. = elevation (m), Rain = mean annual rainfall (mm)

^b --- No trees were sampled in this combination of land use, soil and terrain types

^c *C. nigricans* sampled only in two western regions (Fig. 1: regions #1 and #2)

Fig. 1. Geographic location of five tree/shrub species sampled in four regions in Niger, and mean annual rainfall isohyets across the sample regions.

209x148mm (300 x 300 DPI)