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Applying an indirect method for estimating and modelling the aboveground biomass and carbon for wood energy in the arid ecosystems of Aïr Tenéré of Niger

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Maintaining the economic, ecological and social services provided by the oases and the valley ecosystems of Aïr, in the northern part of Niger, is important for local communities. The purpose of this study is to evaluate the supply and regulation services provided by these ecosystems through wood energy and carbon sequestration. Semi-structured surveys and dendrometric parameter measurements of woody species were carried out. In total, 9 villages were surveyed, and 558 trees of all woody species were inventoried in 65 plots. Most of the resources are distributed in lowlands and valleys along the toposequence. These topographical units are favourable for the accumulation of rainwater and also serve as resources for the wellbeing of the local population, especially their wood energy needs. Businesses have developed around the production and sale of charcoal. The carbon stock of the woody species was found significantly varied ($P \leq 0.05$) between the different topographical units. Four allometric models of carbon estimation were developed, of which the model with diameter at breast height (DBH), height and wood density as the predictor variables was the most efficient. This study can be used for the formulation of policies and strategies for the sustainable management of Aïr Massif's natural resources to benefit the welfare of local communities.

Key words: Ecosystem services, wood density, allometric models, Aïr massif, Niger.

INTRODUCTION

Niger is subdivided into 3 major ecological zones: The Sudanian, Sahelian and Saharian zones (Saadou, 1990), and the Aïr Massif belongs to the Saharian zone. The aïr massif includes the entire mountainous region and the hydrographic network that is created by and linked to the great Ténéré desert (Bruneau and Gillet, 1956), within which there is also a succession of upland and plain chains. This large structure stands on a Precambrian

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crystalline base. The ecosystems are located in valleys and inter-mountainous upland areas. Located between 600 and 1000 m; these geomorphologic units shelter relatively abundant vegetation because of the favourable water table generated by the flows coming from the mountains. These ecosystems are home to a wide range of Saharan plant species mixed with species from the Sudano-Sahelian and Mediterranean zones (Bruneau and Gillet, 1956; Sâadou, 1990; Anthelme et al., 2008). Surrounding these ecosystems are important socioeconomic activities, such as livestock and oases, for agriculture. Indeed, studies have illustrated the vital importance of these ecosystems for local communities through their annual agricultural production, which includes a high diversity of crops that supply the other communities around the southern band of the country (Anthelme et al., 2006). Other studies have highlighted the important contributions of these ecosystems in pastoral and fodder terms (Chaibou et al., 2011, 2012). Most recently, with the Aïr Ténéré natural resources co-management project (COGERAT, 2009) studies have been carried out to assess the ecosystem services provided by these ecosystems, as well as their current trends and strategies for their conservation and restoration. Similar studies were carried out on the wood energy sector and wood services (COGERAT, 2008). This study clearly approaches the sector in comparison with other areas of Niger. However, with trend towards the proliferation of invasive plants in some parts of the massif (COGERAT, 2006) and the increasing needs of the populations, the wood sector received attention from various stakeholders. Among the various studies conducted, almost none have performed forest carbon estimation. However, since the Kyoto Protocol (2005), followed by the Paris Convention (2015), forest carbon estimations have attracted considerable ecological and political interest. Aboveground biomass is a parameter that indicates the functional and structural attributes of a forest ecosystem (Chave et al., 2005). In the Sahel, the aboveground biomass of a forest is used to express its economic, agronomic, forage and biological productivity (Breman and Kessler, 1997). Estimations of aboveground biomass are also essential for the quantification of atmospheric carbon sequestered by forest vegetation through the photosynthetic cycle (Brown, 1997; Chave et al., 2005). Due to a lack of field data, especially on land use, land use changes and forestry sectors, default data have been regularly used according to the National Council for the Environment for Sustainable Development in 2014. There is little information on allometric models for estimating biomass concerns in the Sahelo-Sudanian zones of the country (Moussa, 2016; Weber et al., 2018; Moussa and Larwanou, 2018). In addition, none of the pantropic or generic models address the Saharan zone of Niger (Brown, 1997; Chave et al., 2005; Henry et al., 2011; Chave et al., 2014). Therefore, building allometric models specific to the Saharan zone of Niger is important for improving the evaluation accuracy of the biomass and sequestered carbon in the area. The overall objectives of this study are to provide reliable data and a relevant analysis that can contribute to the development of sustainable management strategies for the ecosystems of the Aïr massif. Specifically, this study's objectives are (i) to analyse the needs and the supply chain of wood energy of the massif; (ii) to assess the biomass and carbon sequestration potential of the ecosystems; and (iii) to develop reliable allometric models for estimating the biomass and carbon of the major woody species in the massif.

METHODOLOGICAL APPROACHES

Study zone

The Aïr massif is an area of high aridity characterized by very low and uncertain precipitation, high average temperatures and low atmospheric humidity (Anthelme et al., 2007). Data from the meteorological station of Agadez airport were used to characterise certain climatic parameters, particularly rainfall and temperature. The average annual rainfall is 183.02 ± 26.43 mm, the minimum annual mean temperature is 22.30 ± 0.24°C and the maximum is 37.50 ± 0.30°C. A month is considered wet if its average rainfall is less than or equal to 2 times its average temperature. Figure 1 shows that in Agadez, two months are considered wet: July and August.

The soils of the zone are regosols and lithosols that occur along the ara's rivers (Giazzi, 1996 cited by Anthelme et al., 2006). The soils are mostly sandy in the plains and shallows and rocky on the plateaus and mountains. The valleys are mostly agricultural soils of loamy, loamy-clayey or clay compositions. Water erosion caused by runoff is a major environmental challenge, as it deposits large amounts of sediment in untreated koris, plains and valleys.

Site sample

An interview was carried out with the administrative and customary authorities and the technical agents at the regional, departmental and communal levels for site selection. This interview made it possible to determine a reasonable number of villages where data collection activities would take place. Since the reliability of the results depends on the established sampling techniques (Gerville-Réache and Couallier, 2011), the choice of villages was based on criteria such as the availability of natural resources and populations and, especially, the development of activities such as forestry and domestic charcoal production. Table 1 presents the list of villages visited during this study.

Surveys

The surveys were carried out between July and August, 2018. This study adopted a focus group using a questionnaire developed for the assessment of domestic energy needs. For this purpose, a sample of 8 to 12 representative participants from each village was used. The participation criteria were gender (female and male), age (young, adult and old people), socio-professional activities (farmers, pastoralist, blacksmiths, craftsmen, loggers) and other resource persons in the village. The surveys focused on the potentialities of villages in terms of their natural resources, such as forest

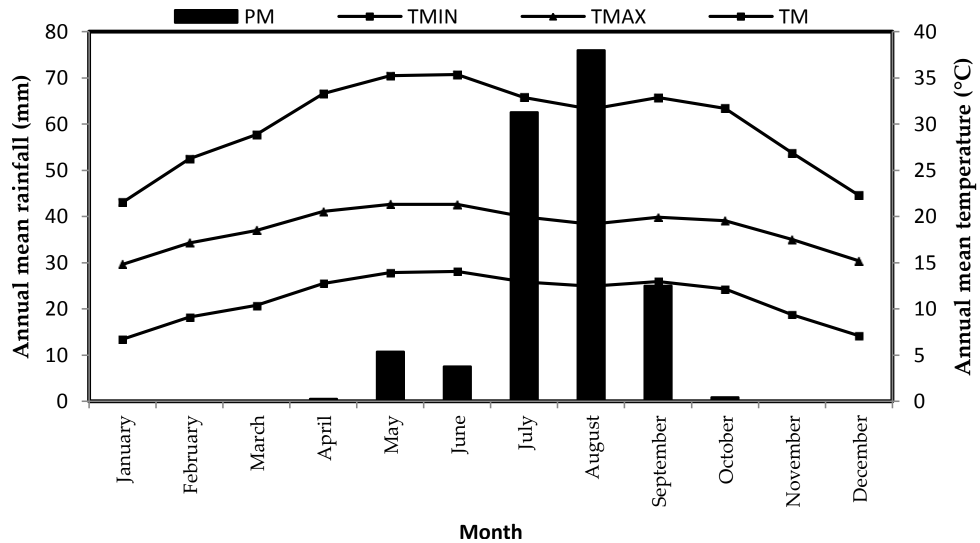

Figure 1. Ombrothermal diagram of the Agadez airport station. PM: Annual average rainfall; TMIN: Minimum annual average temperature; TMAX: Maximum annual average temperature; TM: Annual average temperature.

Table 1. Location of sites.

Site	District	Latitude	Longitude	Altitude (m)
Tassalam Salam	Dabaga	N 17°15'45.6''	E008°06'12.3''	622
Takaya	Dabaga	N17°18'26''	E008°10'24''	653
Dabaga	Dabaga			
Telwas	Tabelot	N17°39'11.8''	E008°53'47''	895
Nabaraw	Tabelot	N17°36'32.6''	E008°52'07.8''	894
Tabelot	Tabelot			
Nabalawe	Timia	N18°14'58.3''	E008°57'01.6'	975
Tefararawe	Timia	N18°00'38.9''	E008°29'45.7''	758
Timia	Timia	N18°06'50.8''	E008°46'50''	1091

resources; the different socio-economic activities related to the exploitation of these ecosystems through the practice of charcoal production; the woody species used; and the stand trends.

Woody species inventory

To evaluate forest biomass and carbon, an inventory was conducted in five different sites, namely, Tassalam Salam, Takaya, Nabaraw, Nabalawe and Tefaraou (Table 1). Satellite images from 2017 were used to guide the inventory towards the different physiographic units along the vegetation toposequence. The woody species are mainly distributed on the plateaus or uplands around water points, dry valleys, plains and agrosystems of the lowlands. In each physiographic unit, square plots of 30 m x 30 m were delineated with an equidistance of 100 m between plots to evaluate the heterogeneity of the environment (Larwanou and Saadou, 2011; Thiombiano et al., 2015). The homogeneous size of the plots also made it possible to compare different landscape units (Larwanou and Saadou, 2011). A total of 65 plots were installed as indicated in Table 2.

Within each plot, a systematic count of all woody species was carried out. For each adult tree, that is, a diameter greater or equal to 2 cm, the following measurements were made: The circumference at 1.30 m from the ground for trees and 0.20 m from the ground for shrubs, the total height, the height of the trunk and two perpendicular crown diameters (d1 and d2).

Table 2. Distribution of the inventory plots per landscape unit.

Physiographic unit	Plot
Lowland	19
Plain	22
Plateau	9
Valley	30
Total	**65**

Data analysis

Survey data were processed using IBM (International Business

Machines Corporation) SPSS 22 (Statistical Package for the Social Sciences) software to perform descriptive statistics (population citation frequency, averages, and standard deviation). Similarly, mapping of the production and supply chain of wood charcoal was carried out.

Determination of wood biomass

Determination of wood volume

Inventory data were processed and analysed using the Excel and Minitab 14 software. The following parameters were determined:
For multi-stem species, the mean root mean square diameter was calculated using the following formula (Thiombiano et al., 2015):

$$DBH = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(DBH)^2} \quad (1)$$

where DBH is the diameter at breast height and n is the number of stems.

Before determining the total volume of the tree and the volumes of the trunk, the crown was determined separately. The dendrometric parameters of each tree were used to calculate the volume of wood using the following formulas (Rondeux, 1999):

For the trunk, it was assimilated to the volume of the cylinder:

$$V_{trunk}\ (m^3) = \frac{\pi}{4} \times DBH^2 \times H_{trunk} \quad (2)$$

For the crown, the exact calculation of its external surface and its volume is, in principle, impossible (Assmann, 1970). Under these conditions, an approximation must be made by taking advantage of directly feasible measures, such as the height and diameter of the crown, to estimate the volume of the cone (Rondeux, 1999). Thus, the volume of the crown was calculated based on the following formula:

$$V_{crown} = \frac{1}{3} x \frac{\pi}{4} x Dm^2 x H_{crown} \quad (3)$$

This formula underestimates the real volume; however, if the crown was assimilated as a half-sphere, the real volume would be overestimated (Rondeux, 1999).

The total volume of the tree was calculated as follows:

$$V_{total} = V_{trunk} + V_{crown} \quad (4)$$

where, V is in m^3, DBH is in cm converted into m, H_{trunk} and H_{crown} are in m and Dm, respectively; the mean diameter, in m, was obtained using the average of two crossed diameters of the crown d1 and d2.

Determination of aboveground biomass

The total volume of each tree was used to calculate its dry aerial biomass (GBS in kg) and the biomass of the whole stand using the following formula:

$$AGB = \rho \times V_{total} \quad (5)$$

With ρ= density of wood by species.

Wood density was determined using an approach similar to that used by Peltier et al. (2007), Henry et al. (2010) and Moussa and Larwanou (2018). This approach involves taking samples of wood from each species and determining its volume by means of a graduated test tube (500 ml) in the laboratory. The following formula was used:

$$\rho = \frac{Drymassofwood\ sample}{Fresh\ volumeofwood} \quad (6)$$

where, ρ is in g/cm^3, mass is in g and volume is in cm^3.

Carbon determination

The total aboveground carbon per physiographic unit was calculated based on the following:

$$AGC = AGB \times 0.5 \quad (7)$$

With 0.5 as the default carbon factor as recommended by UNFCCC (2006); AGC is the above-ground carbon, and AGB is aboveground biomass.

Modelling the estimation of aboveground carbon

The modelling was performed using allometry. Tree allometry is defined by different measures and their relationships to the mass or volume (Lehtonen, 2005). Three types of aboveground biomass or carbon estimation models were tested based on one predictor (DBH or Total Height), two predictors (DBH and H) and three predictors (DBH, H and density). The methodological approach was based on the following sequence of steps: (i) a logarithmic transformation of the data to reduce error variances (Xiao et al., 2011; Mascaro et al., 2014); (ii) elimination of data with residuals that deviate from the global observation to further reduce error variances (Zuur et al., 2010); and (iii) testing of the following models:

i. $\ln AGC = \beta_0 + \beta_1 \ln(DBH) + \varepsilon_i \varepsilon_i \sim N(0, \sigma^2)$ (8)

II. $\ln AGC = \beta_0 + \beta_1 \ln(H) + \varepsilon_i \varepsilon_i \sim N(0, \sigma^2)$ (9)

III. $\ln AGC = \beta_0 + \beta_1 \ln(DBH) + \beta_2 \ln(H) + \varepsilon_i \varepsilon_i \sim N(0, \sigma^2)$ (10)

IV. $\ln AGC = \beta_0 + \beta_1 \ln(DBH) + \beta_2 \ln(H) + \beta_3 \ln(\rho) + \varepsilon_i \varepsilon_i \sim N(0, \sigma^2)$ (11)

where, ln is the logarithm; AGC is the aboveground carbon; β_0 ... β_3 are the coefficients of independent variables, such as DBH, H, Dc and ρ, ε_i is the error; N is the normal law with σ^2 as the deviation; and $\varepsilon_i \varepsilon_i$~ errors follow a normal distribution.

Error analysis

Error analysis was performed based on the overall significance of the equations (P-value < 0.05) and its coefficients (P < 0.05) as well as the coefficient of determination (R^2) (Sileshi, 2014). However, correlation coefficients were not enough to judge the performance of the model. For this purpose, an analysis of the percentage of root means square of error (RMSE) was made using the following formula (Yao et al., 2013):

$$RMSE = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n}(Co - Cp)^2} \times 100 \quad (12)$$

This approach is widely used to assess errors related to the prediction of a biomass estimation model (Fayolle et al., 2013; Moussa and Larwanou, 2018). To avoid errors related to the back transformation, the correction factor was calculated for each model using the following formula (Chave et al., 2005; Mascaro et al., 2014):

$$CF = \exp(\frac{MSE}{2}) \quad (13)$$

Where, MSE is the mean square of errors of the model.

For models with two or more predictors, the effect of the variable multi-collinearity was analysed using the value taken by the variance of inflation factor (VIF) (Graham, 2003).

Validation of the models

The performance of each model was first assessed by checking the homogeneity and normality of the standardized residuals (Zuur et al., 2010). Second, the model was accepted when the significance of the coefficients and the regression was justified and the errors were small (Sileshi, 2014; Moussa and Larwanou, 2018).

Finally, ANOVA associated with the GLM (Generalized Linear Model) and the Tukey method was applied at the 5% significance level to compare the sequestered carbon averages per physiographic unit and the wood density per woody species.

RESULTS

Household energy sources

Figure 2 shows the organization of the domestic energy supply chain of the survey area, which is mainly based on domestic gas (70%), and firewood and/or charcoal (30%). The gas supply is mostly provided by organized entities, including state services, NGOs and, to some extent, private individuals. In the mountains, gas is most often acquired from the neighbouring countries Algeria and Libya. The energy type consumed by households is mainly firewood as well as some crop residues, represented by date and doum palms leaves or citrus twigs. Wood is most often from forest formations in plateaus or dry valleys and, sometimes, in lowlands. The main actors involved in the supply of wood energy are woodcutters (100%) according to the villages. To supply the villages with firewood, animals such as donkeys and camels are used. Similarly, wood intended for urban centres as well as charcoal is transported by trucks, small transit vehicles or motorcycles. Wood charcoal production is currently booming in the Air massif. 33.33% of the villages surveyed expressed this activity. Increasingly, private producers have settled in villages around wooded areas by planting *P. juliflora* according to 100% of the village citations and are hiring labour at a low price. However, certain species, such as *Acacia raddiana* and *Acacia ehrenbergiana*, are also used. In one of the Tefarawe sites visited, a charcoal producer can produce 250 to 400 bags of charcoal before transporting them to the markets of the nearest big cities, such as the mining towns of Arlit or Agadez, or to local markets. On average, a bag is sold to wholesalers at 4000 FCFA or 7.14 US dollars. This wood energy is most often consumed for household cooking or for the preparation of tea, which is an important cultural item for the massif community.

Assessment and modelling of the biomass and carbon stock

Assessment of the carbon stock of aboveground biomass

Dendrometric parameters measured: The dendrometric parameters of the measured trees were the diameter at breast height (DBH), total height, and average crown diameter (Dm). The mean DBH was equal to 15.96 cm, with minimum and maximum values of 2.87 and 69.75 cm, respectively. For the total height, the average was 4.47 m, with minimum and maximum values of 0.8 and 16 m, respectively. The Dm average was 0 3.30 m, with a minimum value of 0 m and a maximum of 21.25 m, and the calculated average biomass per tree was 50.64 kg, with a minimum value of 0.02 kg and a maximum of 2131.22 kg (Table 3).

Wood density: The wood densities of the eight main species were determined. These are *B. aegyptiaca* (0.66 ± 0.03 g/cm^3), *M. crassifolia* (0.68 ± 0.01 g/cm^3), *A. raddiana* (0.74 ± 0.03 g/cm^3), *A. erhenbergiana* (0.72 ± 0.03 g/cm^3), *B. senegalensis* (0.84 ± 0.06 g/cm^3), *A. nilotica* (0.77 ± 0.02 g/cm^3), *P. juliflora* (0.65 ± 0.04 g/cm^3) and *S. persica* (0.60 ± 0.01 g/cm^3). ANOVA shows a globally significant difference between the wood densities of these eight species (F = 5.74/ P = 0.001).

Carbon stock: The amount of sequestered carbon for aboveground biomass accounts for the eight most important species in the area. The amount of sequestered carbon is significantly different (F = 3.06 / P = 0.036) among the physiographic units. The amount of carbon is highest in the lowlands (2880 ± 181 kg/ha), followed by plateaus (1694 ± 556 kg/ha), valleys (1328 ± 265 kg/ha) and lowlands (1294 ± 441 kg/ha) (Figure 3). A higher variability was observed in the plateau plots with a standard error of 556 kg/ha.

Modelling carbon sequestration

Models of carbon estimation

The selection and validation parameters of the developed models were the correlation coefficient (R^2), the error (RMSE), the multi-collinearity (VIF) and the probability (P-value). The statistical parameters of the selected and validated models are presented in Table 4. For each of the four models, the error percentage shows a relatively low range from 1.7 to 3.58%. For models with more than two predictors, VIF also has a low range from 1.2 to 2.8. A strong correlation between the model variables was

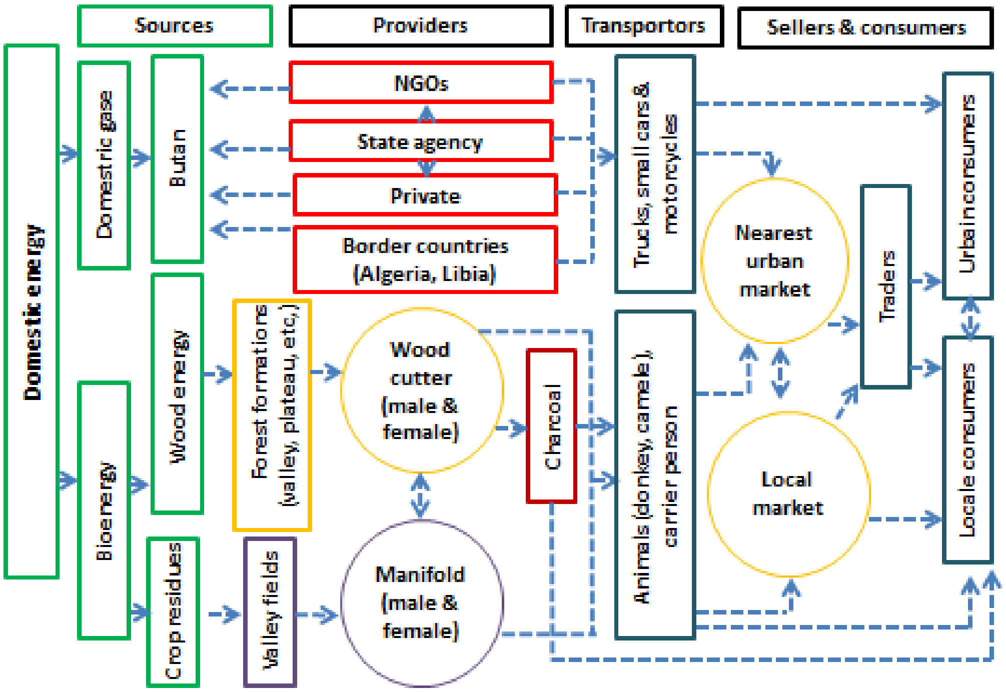

Figure 2. Mapping of the domestic energy supply pathway of the study area.

Table 3. Statistical parameters of individuals used in model development.

Species	N	DBH (cm)			Height (m)			Dm (m)			Biomass (kg)		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Acacia ehrenbergiana	132	3.18	12.7	69.75	1.1	3.54	16	0	3.58	7.50	0.02	14.8	276.28
Acacia nilotica	8	27.39	49.72	63.69	6.5	11.75	16	0	9.98	21.25	23.26	370.1	679.62
Acacia raddiana	168	2.87	22.4	63.69	0.8	5.4	14.5	0	6.68	16.00	0.02	98.26	2131.22
Balanites aegyptiaca	26	4.14	20.2	41.4	1.4	5.4	8	0	5.79	10.75	1.86	60.56	221.56
Boscia senegalensis	24	5.41	14.06	23.89	1.3	3.33	4.5	0	3.03	6.25	3.48	22.2	81.88
Maerua crassifolia	17	4.78	22.56	36.94	1.4	4.9	8	0	3.75	5.75	2.66	48.66	112.26
Prosopis juliflora	153	2.87	7.54	36.31	1.5	3.7	8.5	0	1.37	13.00	0.02	13.4	121.78
Salvadora persica	22	6.05	17.88	25.96	2.3	4.37	7	1.85	3.74	7.00	0.74	16.34	49.86
Ziziphus spina-chisti	8	9.24	34.43	57.01	3	7.69	10	1.50	4.47	6.25	4.88	186.92	368.56
Total	**558**	**2.87**	**15.96**	**69.75**	**0.8**	**4.47**	**16**	**0**	**3.30**	**21.25**	**0.02**	**50.64**	**2131.22**

N: number, Min: minimum, Max: maximum.

observed. This correlation varies from 0.75 to 0.95 depending on the model (Table 4); the correction factor is always close to 1 and is the highest in model I and lowest in IV.

Goodness of models

The performance rates of these four models were assessed and confirmed using normality testing and error variance homogeneity. Figure 4 shows a normal distribution of residuals along the diagonal. Homogeneity of standardized residuals is also observed in each of the four models (Figure 5).

DISCUSSION

Strengths and weaknesses of the methodological approach

Evaluation and mapping of the wood energy needs in the

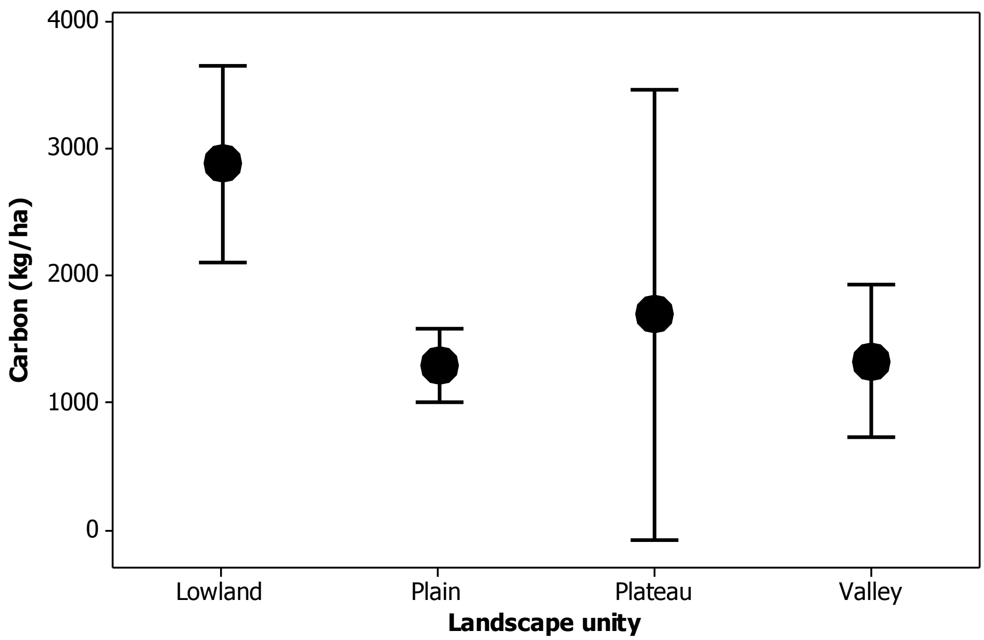

Figure 3. Sequestered carbon distribution per unit of vegetation occupancy.

Table 4. Statistical parameters and carbon estimation models of above-ground biomass for eight dominant woody species.

S/N	N	Model	R^2	RMSE (%)	VIF	CF	P-value
		One predictor					
I	504	ABC = 1.12 x exp (-3.35 + 2.10 x lnDBH)	0.91	2.18	-	1.12	0.0000
II	510	ABC = 1.37 x exp (-1.91 + 2.78 x lnH)	0.75	3.58	-	1.37	0.0000
		Two predictors					
III	510	ABC = 1.09 x exp (-3.44 +1.56 x lnDBH + 1.09xlnH)	0.93	1.86	2.3	1.09	0.0000
		Three predictors					
IV	498	ABC = 1.07 x exp (-4.23 + 1.63 x lnDBH + 1.05 x lnH - 1.89 x lnρ)	0.95	1.70	1.2 - 2.8	1.07	0.0000

R^2: Correlation coefficient; N: Number of tree samples; VIF: Variances inflation factor; RMSE: Root mean square error; CF: Correction factor.

study area were performed by using semi-structured focus group surveys. This method is widely used by researchers, especially in the social sciences, because of its cost effectiveness and its abilities to evaluate the global trends and obtain immediate answers to questions (Schmidt and Hollensen, 2006; Birch and Pétry, 2011). The purpose of the study is also one of the fundamental reasons for using this method (Baribeau, 2009; Birch and Pétry, 2011). However, there is little consensus among researchers as to the sample size that should be investigated and the approach to processing and analysing data collected in focus groups (Baribeau, 2009). Thus, the focus group provides qualitative data. As far as the context of this study is concerned, the study area is one of the most difficult places to access in Niger because the natural landscape has inaccessible roads. Moreover, the availability of the populations is very random in villages. Villagers are more concerned with field work or migrate, so maintaining a consistent population at any time was difficult during the study. This issue justified the use of our methodological approach. Additionally, in conducting similar studies in the same area, Anthelme et al. (2006) used the same methodological approach.

The study of biomass was based on the use of the indirect method that uses tree dendrometric parameters to determine the total volume and specific wood densities and thus deduce biomass. This method has the advantage of avoiding the destruction of trees in an arid environment and can also provide measurement data for many tree samples at a lower cost and over a short time to build high performance allometric models. Although no limit has been given for the construction of allometric models (Moussa et al., 2015), it is still important to have a

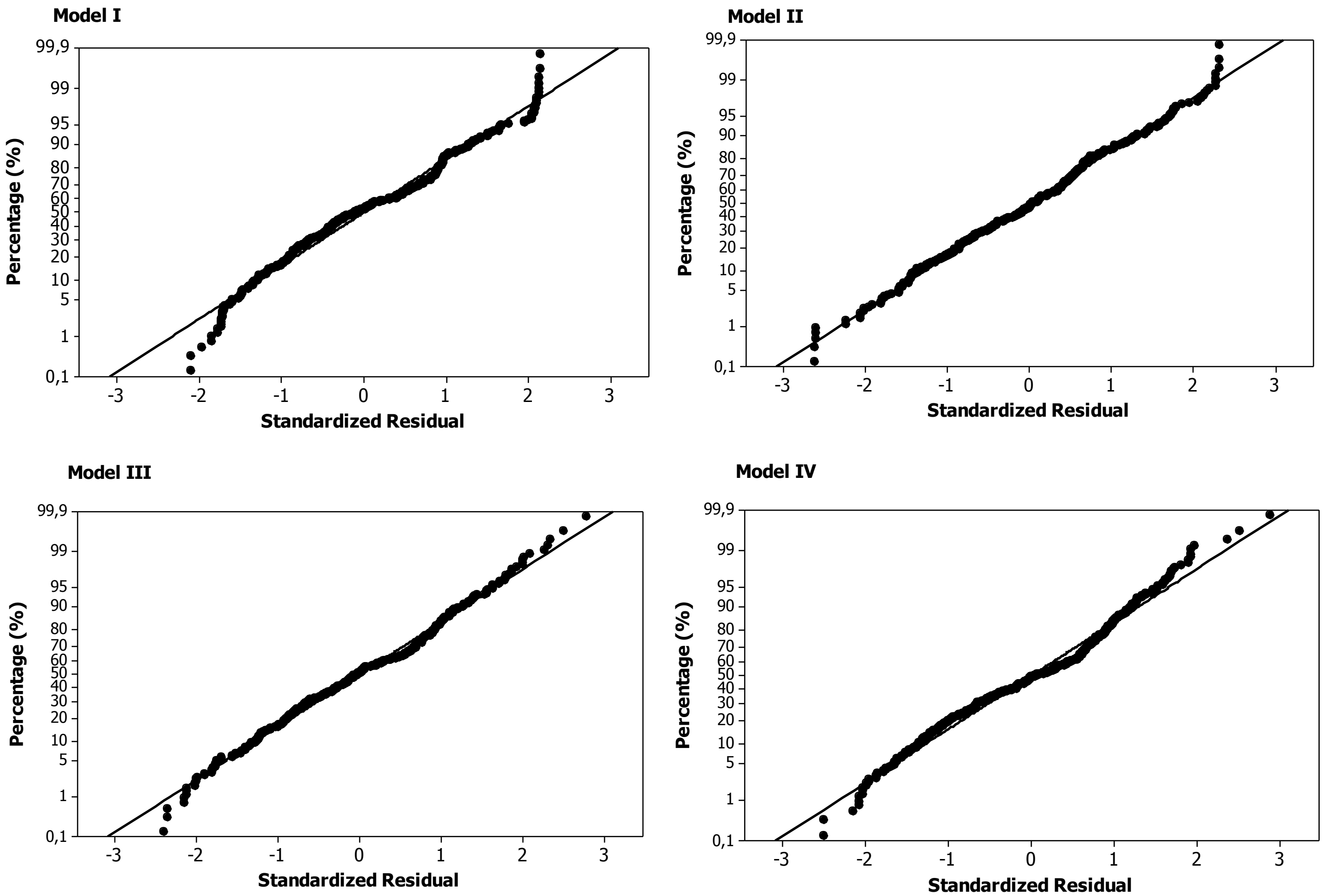

Figure 4. Normal distribution of standardized residues.

large sample size of trees with a range of dendrometric parameters to ensure the best representation of the stand (Brown, 1997; Chave et al., 2005; Chave et al., 2014). However, this method does not remain unbiased. If the volume of the crown is assimilated as a cone, the formula underestimates the actual situation, whereas if the crown is assimilated as a half-sphere, the real volume is overestimated (Rondeux, 1999). Therefore, the exact calculation of the surface and the volume of a tree's crown is, in principle, impossible (Assmann, 1970), which leads to the use of the directly feasible measures for estimating the crown height and diameter and by applying the previously mentioned geometric formulas similar to those used by Nouvellet et al. (2006).

Wood energy need

Although not well endowed with forest resources, the ecosystems of the massif offer important services in regard to wood energy for the local populations. These services mainly comprise firewood from species such as *P. juliflora* and *A. raddiana*. The first species was introduced as a part of the fight against desertification in Niger in the 1980s, and the second is a native species. The wood energy value chain is highly organized in the Aïr massif, with various actors ranging from collectors to consumers through transporters and traders. Because of the socially structured nature of the population, the actors are organized into well-defined social classes. Even though the resources are sparse in different physiographic units, they supply the major urban centres of Arlit, Agadez and Chirozerine. In Niger, firewood consumption at the national level per inhabitant in urban centres has been estimated at 1.15 m^3 / year. On this basis, the population of the region would need 651,414.05 m^3 of fire with a population of 566,447 inhabitants estimated in 2017 (COGERAT, 2008). However, the area has long been deficient in terms of the relationship between forest productivity and population consumption (COGERAT, 2009). For example, local communities are now using domestic gas to replace wood energy. However, the accessibility, availability and high price of gas limits its use in the area according to the

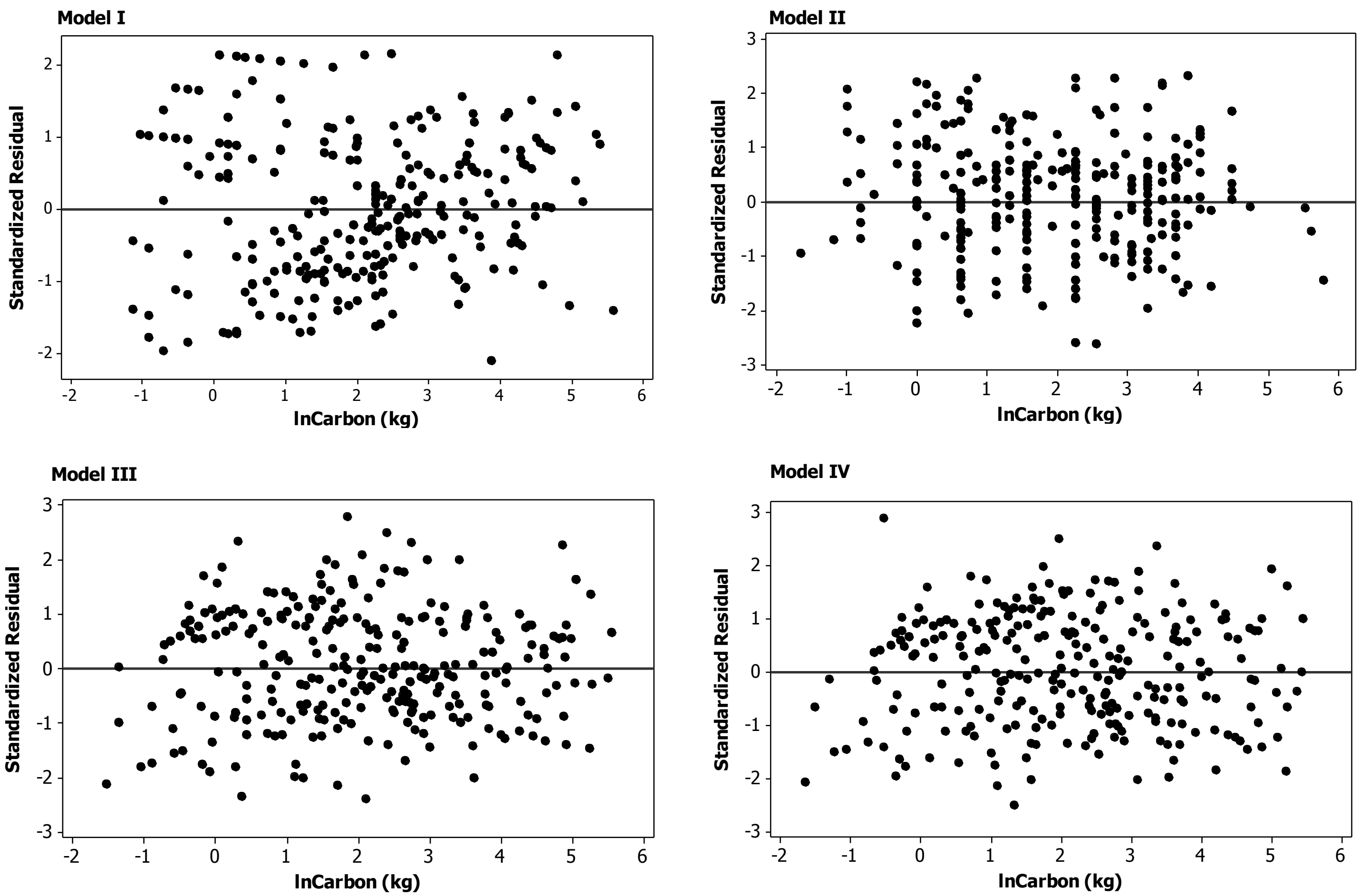

Figure 5. Homoscedasticity of the standardized residuals of the four models**.**

populations, and the use of woody biomass is still the primary energy source for poor citizens (Portner et al., 2009). Increasing trends in charcoal production due to the population are being felt not only because of economic profit but also the real needs of the market. This activity mostly occurs without control in many cases because woodcutters harvest protected species, which impacts the dynamics and, particular, the sustainability of the forest resources of the massif. Sustainability is the goal of any forest management operation. Above all, the quality of the ecosystem services provided at the ecological threshold must be reconciled (Blanco et al., 2018). The ecological threshold is defined as the moment when there is an abrupt change in the quality of an ecosystem, a property or a phenomenon, or in which small changes in an environmental factor produce important reactions in the ecosystem (Groffman et al., 2006). Safeguarding this threshold is extremely important for maintaining communities in the area by protecting the farmland around lowlands. Actions and especially interventions are needed in terms of recovering degraded lands followed by seeding or reforestation by maintaining natural regeneration. There has been substantial momentum in the Sahelo-Sudanian zone of Niger towards this aim with the active involvement of the populations (Larwamou et al., 2006), which has allowed a global return of vegetation cover (Hermann et al., 2005; Olsson et al., 2005; Brandt et al., 2018). Moreover, potentialities in terms of the valourization of crop residues exist in the areas where agriculture is highly developed by producing biogas or by setting up renewable energy production systems. This will reduce greenhouse gas emissions from forest ecosystem degradation in line with the spirits of the Kyoto Protocol and the Paris Agreement.

Carbon sequestration

The amount of biomass or sequestered carbon by woody stands is higher in the lowlands and valleys than on the plains and plateaus. This may be explained by the differential productive capacities of these landscape units where most of the vegetation is distributed. The rain water runs from the uplands through the valleys and plains to settle in the lowlands. Wherever moisture is present, vegetation occurs (Bruneau and Gillet, 1956; Sâadou, 1990). This functioning of the Sahelian ecosystems was explained by Maisharou et al. (2015) and Paxie and Larwanou (2017). Thus, the accumulation of woody biomass in these ecosystems is important because of its environmentally and socio-economically important roles in the protection of lowland agrosystems and the aboveground fodder it provides to animals, and particularly large ruminants (Chaibou et al., 2012). In the southern part of Niger, important data on the quantity of sequestered carbon in agroforestry parklands have shown that the quantity varies depending on the relative density of trees (Weber et al., 2018; Moussa and Larwanou, 2018).

Modelling

The allometric models developed in this study are the expression of carbon according to the dendrometric parameters of DBH, total height and wood density of the main inventoried species. Four models have been validated with a very precise performance. The models' errors were very low, between 1.70 and 3.58%. The assessment of the performance of the models based on this indicator does not cross any threshold in most cases (Sileshi, 2014). The assessment was made based on small errors. For VIF, this only applies to models with more than two predictors. There are also VIF values between 1.2 and 2.3. The VIF value reflects the instability or collinearity between model predictors (Zuur et al., 2010). The higher the VIF, the lower is the model efficiency. Studies have shown that inflation may occur with a VIF value greater than 5 (Sileshi, 2014), or 10 (Graham, 2003). Thus, models III and IV proved a low VIF, and hence were validated. At the current stage of biomass research in the Aïr massif, knowledge is very limited. The few equations available are those of Chaibou et al. (2012), which deal with the fodder biomass of *A. ehrenbergiana* and *M. crassifolia* with very little information on the criteria for their validation, in which an assessment was made on the correlation coefficient. The comparison of the models with those of Chaibou et al. (2012) will not be informative. When generic and pantropical models of biomass estimation (Brown, 1997; Chave et al., 2005; Henry et al., 2010; Chave et al., 2014) were taken, their use in the study area remains problematic. The same authors defined the geographical areas of their development, which are wet and dry forests and a part of the savannah. An allometric model can only be used in strict compliance with the conditions related to the geographical area and the range of dendrometric parameters that have governed its development (Rondeux, 1999). Moreover, these pantropical models are not superior to the models of this study in terms of errors. For example, Chave et al. (2005) show a variability of the error in Model II for wet and dry forests that reflects a biomass overestimation between 5.5 and 16.4%. To avoid the back transformation problem, the correction coefficient has been calculated. This coefficient is often close to 1 (Baskerville, 1972), as attested by the study's models. The most successful of the four models is IV because of its higher correlation coefficient, and its weaker RMSE and CF. The other models can be used as alternative models for the default of a given predictor.

Conclusion

This study highlighted the energy needs of the rural communities of the Aïr massif that are strongly dependent on natural resources, such as residues and woody species. The local communities depend on the light species of the landscape, specifically *A. raddiana* and *A. ehrenbergiana* and, especially, *P. juliflora*. In view of the difficulties of collecting wood, people are engaged in charcoal production, which is a practice that is increasingly becoming an income-generating activity. This activity is closely linked to the real wood energy needs of large urban centres, which are growing in proportion with the ever-increasing local demography. The charcoal economy also involves various actors and is a situation in which everyone benefits. This study also intended to evaluate the aboveground biomass and carbon stock of the woody species available in the massif. The carbon stock is more dependent on the toposequence of the massif, with rainwater runoff and valleys being more important than plateaus and plains. At the end of the study, it was possible to develop allometric models for estimating aboveground carbon, which is related to biomass. The models were developed based on an analysis of the correlation between the variables and prediction errors. Thus, model IV of the form $ABC = 1.07 \times \exp(-4.23 + 1.63 \times \ln DBH + 1.05 \times \ln H - 1.89 \times \ln \rho)$ was the most efficient. The results of this study can be used to formulate sustainable management policies in the massif, which is of paramount importance for its local communities.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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REFERENCES

Anthelme F, Waziri-Mato M, de Boissieu, D, Giazzi F (2006) Dégradation des ressources végétales au contact des activités humaines et perspectives de conservation dans le massif de l'Aïr (Sahara, Niger). Vertigo 7(2):1-12. DOI: 10.4000/vertigo.2224.

Anthelme F, Saadou M, Michalet R (2007). Positive associations involving *Panicum turgidum* Forssk. In the Aïr-Ténéré Réserve, Niger. Journal of Arid Environment 68:348-362.

Anthelme F, Abdoulkader A, Besnard G (2008). Distribution, shape and clonal growth of the rare endemic tree *Olea europaea* subsp. *laperrinei* (Oleaceae) in the Saharan mountains of Niger. Plant Ecology 198(1):73-87

Assmane E (1970). The principles of yield study. Oxford, Pergamon Press 506 p.

Baribeau C (2009). Analyse des données des entretiens de groupe. Recherches Qualitatives 28(1):133-148.

Baskerville GL (1972). Use of logarithmic regression in the estimation of plant biomass. Canadian Journal of Forest Research 2:49-53.

Birch L, Pétry F (2011). L'utilisation des groupes de discussion dans l'élaboration des politiques de santé. Recherches Qualitatives 29(3):103-132.

Blanco JA, Candel-Pérez D, Lo Y-H (2018). Determinants and Tools to Evaluate the Ecological Sustainability of Using Forest Biomass as an Alternative Energy Sources. http://dx.doi.org/10.5772/intechopen.76005.

Brandt M, Rasmussen K, Hiernaux P, Herrmann S, Tucker C J, Tong X, Tian F, Mertz O, Kergoat L, Mbow C, David JL, Melocik K A, Dendoncker M, Vincke C, Fensholt R (2018). Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands. Nature Geoscience 11:328-333.

Breman H, Kessler JJ (1997). The potential benefits of agroforestry in the Sahel and other semi-arid regions. European Journal of Agronomy 7:25-33.

Brown S (1997). Estimating Biomass and Biomass Change of Tropical Forests: a Primer. FAO Forestry Paper. FAO, Rome.

Bruneau de Miré Ph., Gillet H (1956). Contribution à l'étude de la Flore du Massive de l'Aïr (3e partie). Journal D'agriculture Traditionnelle et de Botanique Appliquée 3(12):857-886.

Chaibou M, Faye B, Vias G (2011). Composition botanique du régime des dromadaires et valeurs alimentaires des plantes ingérées sur un parcours aride du Niger. Bulletin of Animal Health and Production in Africa 59(2):259-273.

Chaibou M, Faye B, Ali M, Vias G (2012). Évaluation du potentiel fourrager aérien du bassin laitier d'Agadez au Niger en Afrique de l'Ouest. Bulletin de la Recherche Agronomique du Bénin (BRAB) 71:1-12.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Folster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riera B, Yamakura T (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87-99.

Chave J, Rejou-Mechain M, Burquez A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman MHRC, Martınez-Yrı ´zar A, Mugasha WA, Muller Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz Malavassi E, Pe ´lissier R, Ploton P, Ryan CM, Saldarriaga JG, Vieilledent G (2014). Improved pantropical allometric models to estimate the above ground biomass of tropical forests. Global Change Biology 20:3177-3190.

Projet de Cogestion des Ressources Naturelles de l'Aïr et du Ténéré (COGERAT) (2006). Stratégie de contrôle des espèces envahissantes. Rapport d'étude 63 p.

Projet de Cogestion des Ressources Naturelles de l'Aïr et du Ténéré (COGERAT) (2008). Étude de la filière bois énergie, bois de construction, technologies alternatives dans la RENAT et zones connexes. Rapport d'étude 102 p.

Projet de Cogestion des Ressources Naturelles de l'Aïr et du Ténéré (COGERAT) (2009). Évaluation économique de la valeur des biens et services fournis par les écosystèmes arides de l'Aïr Ténéré. Rapport d'étude 57 p.

Fayolle A, Doucet J-L, Gillet, J-F, Bourland N, Lejeune P (2013). Tree allometry in Central Africa: Testing the validity of pantropical multi-species allometric equations for estimating biomass and carbon stocks. Forest Ecology and Management 305:29-37.

Gerville-Réache L, Couallier V (2011). Échantillon représentatif (d'une population finie): définition statistique et propriétés. Échantillon représentatif, Sondage, Quotas, Probabilités d'inclusion. Version 1. <hal-00655566>

Graham MH (2003). Confronting multicollinearity in ecological multiple regression. Ecology 84:2809-2815.

Groffman PM, Baron JS, Blett T, Gold AJ, Goodman I, Gunderson LH (2006). Ecological thresholds: The key to successful environmental management or an important concept with no practical application? Ecosystems 9(1):1-13. DOI: 10.1007/s10021-003-0142z

Henry M, Besnard A, Asante WA, Eshun J, Adu-Bredu S, Valentini R, Bernoux M, Saint Andre L (2010). Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. Forest Ecology and Management 260:1375-1388.

Henry M, Picard N, Trotta C, Manlay R, Valentini R, Bernoux M, Saint-Andre ´ L (2011). Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fennica 45:477-569.

Hermann SM, Anyamba A, Tucker CJ (2005). Recent trends in vegetation dynamics I the African Sahel and their relationship to climate. In: Global Environmental Change 15:394-404.

Larwamou M, Saadou M, Hamadou S (2006). Les arbres dans les systèmes agraires en zone sahélienne du Niger: mode de gestion, atouts et contraintes. Tropicultura 24(1):14-18.

Larwanou M, Saâdou M (2011). The role of human interventions in tree dynamics and environmental rehabilitation in the Sahel zone of Niger. Journal of Arid Environment 75:194-200.

Lehtonen A (2005). Carbon stocks and flows in forest ecosystems based on forest inventory data No. Dissertationes Forestales 11, Finnish Forest Research Institute. Vantaa Research Center, Helsinki.

Maisharou A, Chirwa PW, Larwanou M, Babalola F, Ofoegbu C (2015). Sustainable land management practices in the Sahel: review of practices, techniques and technologies for land restoration and strategy for up-scaling. International Forestry Review 17:1-19.

Mascaro J, Litton CM, Hughes F, Uowolo A, Schnitzer SA (2014). Is logarithmic transformation necessary in allometry? Ten, onehundred, one-thousand-times yes. Biological Journal of the Linnean Society 111:230-233.

Moussa M, Larwanou M (2018). Allometric models for estimating aboveground biomass and carbon in *Faidherbia albida* and *Prosopis africana* under agroforestry parklands in drylands of Niger. Journal of Forestry Research 29(6):1703-1717.

Moussa M, Larwanou M, Saadou M (2015). Allometric equations for biomass estimation of woody species and organic soil carbon stocks of agroforestry systems in West African: state of current knowledge. International Journal of Research in Agriculture and Forestry 2(10):2394-590.

Moussa M (2016) Analyses de la situation de référence pour les mesures de conservation des écosystèmes des Oasis et Forêts des Vallées sèches. Rapport d'étude.

Nouvellet Y, Kassambara A, Besse F (2006). Le parc à karités au Mali : inventaire, volume, houppier et production fruitière. Bois et Forêt des Tropiques 287(1):5-20.

Olsson L, Ekhlund L, Ardö J (2005) A recent greening of the Sahel-trends, patterns and potential causes. Journal of Arid Environment 63(3):556-566.

Paxie C, Larwanou M (2017). Overview of restoration and management practices in the degraded landscapes of the Sahelian and dryland forests and woodlands of East and southern Africa. Southern Forests: a Journal of Forest Science 19(2):87-94.

Peltier R, Forkong CN, Mama F, Ntoupka M, Manlay R, Henry M, Morillon V (2007). Evaluation du stock de carbone et de la productivité en bois d'un parc à karités du Nord Cameroun. Bois Forêt des Tropiques 294(4):39-50.

Portner B, Salmi A, Kläy A, Enz FK, von Dach WS, Ehrensperger A

(2009). Bioénergie pour les pauvres pour les pauvres Risques et opportunités. InfoRessources, Focus 3/09.
Rondeux J (1999). La mesure des arbres et des peuplements forestiers, vol 2. Les Presses agronomiques de Gembloux, Gembloux.
Saadou M (1990). La végétation des milieux drainés nigériens à l'est du fleuve Niger. [Thèse]. Faculté des Sciences, Université de Niamey, Niger.
Schmidt MJ, Hollensen S (2006). Marketing Research: An international Approach. (1 ed.) Harlow, UK: Prentice-Hall.
Sileshi GW (2014). A critical review of forest biomass estimation models, common mistakes and corrective measures. Forest Ecology and Management 329:237-254.
Thiombiano A, Glélé KR, Bayen P, Boussim JI, Mahamane A (2015). Méthodes et dispositifs d'inventaires forestiers en Afrique de l'Ouest : état des lieux et propositions pour une harmonisation. Annales des Sciences Agronomiques 19:15-31.
United Nations Framework Convention on Climate Change (UNFCCC) (2006). Revised simplified baseline and monitoring methodologies for selected small-scale afforestation and reforestation project activities under the clean development mechanism (Version 02) 20 p. https://cdm.unfccc.int/EB/026/eb26_repan17.pdf.
Weber JC, Montes CS, Abasse T, Sanquetta CR, Silva DA, Mayer S, Muniz GBI, Garcia RA (2018). Variation in growth, wood density and carbon concentration in five tree and shrub species in Niger. New Forest 49(1):35-51.
Xiao X, White EP, Hooten MB, Durham SL (2011). On the use of logtransformation vs. nonlinear regression for analyzing biological power laws. Ecology 92:1887-1894.
Yao X, Fu B, Lu Y, Sun F, Wang S, Liu M (2013). Comparison of four spatial interpolation methods for estimating soil moisture in a complex terrain catchment. PLoS One 8(1):e54660.
Zuur AF, Ieno EN, Elphick CS (2010). A protocol for data exploration to avoid common statistical problems. Methods Ecology Evolution 1:3-14.