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Allometric Equations for Biomass Estimation of Woody Species and Organic Soil Carbon Stocks of Agroforestry Systems in West African: State Of Current Knowledge

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ABSTRACT

Since the Kyoto Protocol, agroforestry is considered as a mitigation and adaptation tool to climate change. Agro forestry systems are nowadays the subject of many investigations all over the world. This is because of their potential for carbon sequestration and storage. The parklands are some ancient cultural systems with a wide distribution in West Africa. The contribution of these systems to climate change mitigation has to do with the organic carbon storage in soils and sequestration of atmospheric carbon. This study aims at presenting an overview of the current knowledge on soils organic carbon and allometric equations for estimating aboveground biomass in agro forestry land use systems in West Africa. Significant amounts of carbon, ranging from 0.29 to 32 $MgC.ha^{-1}.year^{-1}$, were sequestered according to specific argroforestry systems. Yet, allometric equations for many species are lacking as carbon stock in several soil types needs to be estimated. Indeed, further studies need to be undertaken therein. We therefore recommend to pursuing investigations in evaluation of soils organic carbon and in development of allometric equations in West African region based on performance criteria.

Keywords: soil carbon, allometric equations, biomass estimation, woody species, agroforestry, West Africa.

INTRODUCTION

During land preparation for farming, West African farmers cleared natural vegetation like steppes and savannas leaving useful timber and other useful tree species (Ounteni, 1993; Yaomégo et al., 2005; Roch, 2008). They subsequently enriched the agroforestry systems by introducing new species or retaining part of the natural regeneration. Depending on the composition of the original trees stand, ecological conditions, knowledge and needs of people and their socio-economic environment, different types of wooded parks were well built (Ounteni 1993; Smektala et al., 2005). Thus occurred the parklands resulted from the coexistence of tree species with crops. The agroforestry parkland meets specific needs of rural populations in covering the needs that are not satisfied by the productions of Agriculture and Livestock (Ounteni, 1993; Breman et al., 1995; George et al., 2005; Larwanou et al., 2006; Roch, 2008; Faye et al., 2008). The park is an ethical concept, closely related to the general state of a rural society, by taking into account the regional history of settlement and productive, socio-cultural, ecological and economic consideration, (Smektala et al., 2005). In addition to these important functions by the people and the environment, parklands, like any agroforestry system also constitute an important source of emission and carbon sequestration (IPCC, 2007). The agroforestry parks are a source of carbon emission by degradation of woody cover, continuous mineralization of soil organic matter and poor agricultural practices (Oldeman et al., 1991). Managing these areas while avoiding further degradation, would be a major challenge to contribute to the reduction of emission of greenhouse gases in the atmosphere. However parklands can also be an important means of mitigating climate change through carbon sequestration in all its compartments, namely standing trees biomass, dead wood and soil (Pearson et al., 2005; Albrecht and Kandji, 2003; Takimoto et al., 2008).

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Thus, this particular ecosystem, like any other agroforestry system is considered as a way for mitigation to the effects of climate change through the Kyoto Protocol. In parklands little dead wood are, due to intense harvesting activities by people for various needs including lumber, and wood heating (Mahamane et al., 2005; Ouédraogo et al., 2006, Larwanou et al., 2006). Also, litter is almost low because of agriculture and livestock practices that are not conducive to its accumulation. Therefore, in order to assess the carbon stock of parkland in arid and semi-arid areas, three components are considered by many authors including aboveground biomass, root biomass and soil (Peltier et al., 2007; Henry et al., 2009; Henry et al., 2010; Sawadogo et al., 2010; Takimoto et al., 2008; Saidou et al., 2012).

Quantifying the carbon stock of a forest ecosystem begins with estimating the biomass of its different species. Forest biomass can be an indicator of biological and economic productivity including the presence of wood (Brown et al., 1989 and Chave et al., 2005). Direct and indirect methods are used to estimate the biomass of wood. The indirect method is related to the estimate of the biomass of trees without cutting them. This method is not without bias. The direct method involves cutting trees and monitoring of measurements in the field and in the laboratory to develop allometric equations for predicting biomass and carbon quantity by tree species. Because of its precision, this method is the most shedding in most publications and Manuals (Brown et al., 1989; Ponce-Hernandez et al., 2004; Pearson et al., 2005; Picard et al., 2012).

The soil organic carbon in parkland results as the interaction between the inputs and outputs of the system. It represents less than 1% of the mass of soil in arid and semi-arid areas (Trumper et al., 2008). The organic carbon content of soils is generally regarded as the main indicator of soil quality, both for their agricultural and environmental functions (Bernoux et al., 2013). Organic carbon plays a fundamental role in the overall behavior of soils, particularly agro-ecosystems by improving its physical qualities, stimulation of biological activity, storage and supply of water and plants nutrients and regulation of pollutants. The soil organic carbon contributes to climate change mitigation by slowing the increase of CO_2 in the atmosphere (IPCC, 2007; Ponce-Hernandez et al., 2004; Bernoux et al., 2013.). The carbon content of the soil can be increased by improving land use system, high carbon storage capacity and good management of crop products (Sampson et al., 2000). Several studies have been conducted around the world to assess the biomass of different tree species and organic carbon stocks of different soils (e.g. Henry et al., 2010; Chave et al., 2005; Brown et al., 1989; Mbow et al., 2013; Sileshi, 2014; Pardé et al., 1988; Peltier et al., 2007; Henry et al., 2009; Sawadogo et al., 2010; Bernoux et al., 2002; Vogel, 1994; Bajes, 1996; and Slepetiene et al., 2008, Kuyah et al, 2012, etc.). This review aims at putting together the available knowledge on the quantification of carbon in the soil-vegetation system of agroforestry parklands in arid and semi-arid areas in West Africa. It specifically aims at evaluating recent studies of soil organic carbon and allometric equations for estimating biomass of different parkland tree species of West African region.

DEFINITIONS OF SOME CONCEPTS

Agroforestry

This is an interdisciplinary land use approach combining three components namely woody plants, animals and crops on the same unit area. Of all the commonly used definitions, it follows that agroforestry is a combination of these components in ecological and/or socio-economic interactions where woody perennial are left in a space-time arrangement in the fields. These interactions can be positive (which is desirable) or negative and never remain stable over time (Raintree, 1989; Baumer, 1997; Takimoto et al., 2008). According to the International Centre for Research in Agroforestry (ICRAF), "Agroforestry is a collective term for systems and land use technologies where woody perennials (trees, shrubs, under shrubs, and assimilation, palms and bamboos) are deliberately cultivated on land otherwise used for the crop and/or livestock in a spatial or temporal arrangement, and where there are ecological interactions and/or economic differences between wood and other system components. Depending on the combination and arrangement in place, a range of agro forestry technologies and practices exist (Young, 1995; Baumer, 1997). As such, it may be noted that parklands are part of the West African landscape which are the subject of this study.

Parklands

The parklands are characterized by voluntary maintenance of trees on farmlands and fallow. The term refers to a park landscape shaped by agricultural activities (Roch, 2008, Sawadogo et al., 2010). To define the park, the concept of the dispersion of trees in the field is important, as well as several key elements that must be retained like: food (*Adansonia digitata*), the role of the dominant species in restoration of soil fertility production of wood, animal fodder and firewood (*Faidherbia albida*) or economic gains due to the presence of the species outweighs the reduction in crop yield (*Vitellaria paradoxa*) (Mahamane, 1997; Smektala et al., 2005; Roch, 2008).

METHODOLOGY

The information is collected through a literature review of recently published articles and other documents available on the subject for West Africa. The aspects covered are related to methods of collecting and analyzing data on soil carbon stock and the development of allometric equations for estimating biomass of parklands woody species. A summary of the results was made available in order to take stock of current knowledge, available and accessible on these issues in West Africa.

Methods for Estimating Soil Organic Carbon Stock

The soil organic carbon is determined by two methods: the wet and the dry burning combustion. These methods are all based on the determination of the amount of organic carbon oxidation by soil organic matter. Carbon is measured by the weight of the sample lost by titration of the excess oxidant by addition or the amount of CO_2 formed. For wet combustion, the amount of carbon is determined either directly by LECO methods and USDA or indirectly by the LOI method. The soil sample is subjected to high temperatures and the carbon is determined gravimetrically or absorption, thermal conductivity and by measuring weight loss of soil representing the mass of organic matter burned to CO_2. These methods have a recovery of about 100%. These methods are applied mostly on aerated soils with low clay content (Vogel, 1994 Bajes, 1996 and Slepetiene et al., 2008). In the dry combustion, the direct method and the indirect method are also used. The indirect method uses the chemical oxidation agents such as potassium dichromate ($K_2Cr_2O_7$) in acidic medium (H_2SO_4) (Walkley-Black 1934), permanganate ($KMnO_4$) (method Kumies), etc. to determine the amount of soil organic carbon. The direct method is one developed by Allison, (1965) from the oxidation of soil organic matter by dichromate in an acidic medium (sulfuric acid and phosphoric acid) and the carbon is determined gravimetrically. However, all these methods for determining carbon by dry combustion have a variable recovery of total carbon, between 70% and 100% (Vogel, 1994; Allison, 1965; Batjes, 1996 and Conyers and al., 2011). Walkley-Black method (1934) is widely used and may be best known for estimating soil organic carbon (Batjes, 1996; Vogel, 1994). These methods have been used in many publications in West Africa including Saidou et al., (2012), Traore et al., (2004), Volkov et al., (1999), Takimoto et al., (2008), Henry et al., (2009), Kumar et al., (2012), etc. The method Walkley-Black (1934) has some limitations, and the most important once are: the significant influence results for the temperature during the oxidation of the sample leading to incomplete oxidation of organic matter; the possibility of mistaking the color change of the indicator used to make judgment; the possibility of overestimating the carbon oxidation by soils' other inorganic compounds such as F2+ and Mn2+ and inoxydation by the chemical residues of non-decomposable plants such as coal (Vogel, 1994, Landon, 1991). The Walkley-Black (1934) method gives organic carbon variable recovery of soils ranging in average 75%. To estimate the total amount of carbon by this method, a standard conversion factor of 1.33 is determined by multiplying the amount of carbon fixed (Allison, 1965). On other hand, the accuracy of a particular method of estimating soil organic carbon remains bound to soil sampling methods, sampling season, history and types of land use (Batjes, 2003; Ciais et al., 2011).

In order to estimate soil organic carbon, soil samples were collected in the field and analyzed in the laboratory. Samples are taken very often in a given depth of thickness (E), depth beyond which little change occurs in the change of land use (Batjes, 1996), and a succession of horizons (Si) to monitor the dynamics and different variations of organic carbon (Ramarson, 2009, Henry et al., 2009, Marco et al., 2010). According to IPCC (2003), the soil samples can be taken following 0-30 cm and 0-100 cm depth. In the field, fresh soil sample is weighed and a part is taken and dried in an oven to determine the dry weight and consequently the bulk density (Da) (Vogel, 1994). Laboratory analysis can determine the physical and chemical soil properties including the amount of carbon (C) and coarse elements (Ramarson, 2009; Bellassen et al., 2010). The total carbon stock is estimated using the following formula: $Sct = \Sigma\ Sci = \Sigma\ Da \times 10 \times (100 - \%\ EG) \times C \times E$ (IPCC, 2003 and Bernoux et al., 2002).

Where, Sct: Stock of total carbon (Kg/m^2), Sci : carbon stock of horizon i, Da : bulk density (g/dm^3), EG : coarse elements, C : soil carbon (mg/g), E : thickness of soil horizon (cm)

General Approach for Estimating Tree Aboveground Biomass

The estimate of biomass of forest vegetation is made following an appropriate approach: characterization of woody vegetation, development of allometric equations for estimating biomass and the amount of carbon (Ponce-Hernandez et al. 2004; Pearson et al., 2005; Picard et al., 2012). The characterization of woody vegetation is made through forest inventory. This can take place on the ground (*e.g.* Saâdou 1990; Mahamane, 2005; Larwanou, 2005) or with the help of satellite images (Thenkabail *et al.*, 2004; Zhang *et al.*, 2014). The data are processed with appropriate software and the hierarchical woody vegetation (CTFT 1989; Ponce-Hernandez et al., 2004; Pearson et al., 2005; Picard et al., 2012). From the inventory, biomass is determined and used to develop allometric equations. Regressions models are established, expressing biomass or carbon with one or more dendrometric parameters including diameter, height and wood density of the species (Pardé et al., 1988; CTFT 1989; Ponce-Hernandez et al., 2004; Pearson et al., 2005; Peltier et al., 2007; Chave et al., 2005; Henry et al., 2009; Henry et al., 2010; Picard et al, 2012).

Sampling and Field Measurements

Sampling is an important step for developing allometric equations for estimating biomass. Significant bias leading to overestimation or contrary to the underestimation of biomass can result from a biased sample (Picard et al., 2012; Silesh, 2014). Thus the reliability and performance of equations that will result depends on adequate sampling (Jara et al., 2015). Sampling must take account of the distribution of individuals in proportion to their values dendrometric including diameter at breast height (DBH) (Picard et al, 2012; Chave et al, 2014).

Once sampling is established, trees are cut at ground level and separated measures trunks, branches and leaves are made (Preason et al., 2005; Jara et al., 2015). Samples of the biomass of each compartment are collected, dried and weighed to determine the dry biomass (Weiskittel et al., 2015).

Development of Allometric Equations

The allometric equation is a statistical formula between dendrometric parameters of a tree namely the diameter at breast height, total height or woody cover and dry biomass. The development of equations is not accidental. It must be rested and be justified first by the type of regression (Silesh, 2014; Jara et al., 2015). Regression is varied; it may especially be linear or non-linear. Depending on the type of regression used, data may undergo transformations or not including the logarithmic transformation (Mascaro et al., 2011; Packad, 2014 Mascaro et al., 2014). Finally, to assess the performance of equations statistical tests including normality test, homoscedacity and independence of residues are necessary (Graham, 2003; Zuur et al., 2010; Silesh, 2014). The validation of a model is to compare their predictions with independent observations from those used for fitting the model (Rykiel, 1996). The validation of Allometric equation does not rest on the mere fact of R^2 correlation coefficient values. For Allometric model given, the coefficient of correlation R^2 can be high along its residual. What constitutes an important source of bias for Allometric equations. In some times R^2 measures gives erroneous and misleading values. R^2 can be raised and the limited validity of the equation (Sileshi, 2014). It is necessary to involve other explanatory parameters found allometric relationship. Thus the calculation of the equation related errors are especially necessary (Silesh, 2014; Chave et al, 2014; Jara et al., 2015).

%Error and Residual Standard of Error (RSE)

The % error associated with the estimate of biomass is the difference between the observed biomass (y_{ob}) and the estimated biomass (y_{es}) divided by the observed biomass. The residual error is a percentage indicator:

$$\%RE=\frac{y_{ob}-y_{es}}{y_{ob}}\times 100 \qquad \text{(Chave } et\ al., \text{ 2005)} \qquad (10)$$

Depending on the value taken by the% error, the biomass can be overestimated or underestimated. The best relationship can be found using the standard residual error (RSE) (Dumont *et al.*, 2013; McCune and Grace, 2002):

$$RSE=\frac{\frac{\sigma}{\sqrt{n}}}{\bar{y}} \quad (in\ \text{Mbow}\ et\ al.,\ 2013) \qquad (11)$$

With y, the average of the observed biomass of the sample, σ the standard deviation, n is the number of sample. Ecological study with less than 20% RSE means that the relationship between the explanatory variable and the dependent variable is reliable (McCune and Grace, 2002). That biomass is reliably connected to dendrometric parameters considered. An Allometric equations to estimate woody biomass may be acceptable with RSE <30% (Sileshi, 2014). However, some authors use statistical parameters including the root mean square of errors (RMSE) to validate the models (eg Fayolle et al., 2013; Makungwa et al., 2013; Mugasha et al., 2013; Ma and Lei., 2015).

SOIL ORGANIC CARBON STOCK AND ALLOMETRIC EQUATIONS OF SOME WOODY SPECIES

Soil Organic Carbon Stock (S. O. C.)

In soil, carbon is found in two states namely organic carbon and inorganic carbon. The latter is contained in the rocks and gradually released due to chemical reactions in order to enter partially into the cycle of plant photosynthesis. Around the world, the inorganic carbon is estimated at approximately 755 Peta-grams at 1 m depth (1 pg = 10^{15}grammes) and organic carbon in 1550Pg (Batjes, 1996). In most cases, the soil organic carbon if estimated beyond 1 m soil depth; it becomes fairly weak and does not contribute to emissions of gases (IPCC, 1992). Worldwide, soil organic carbon is estimated at 814 and 1850 PgC respectively at 0-30 and 0-100 cm deep.

In arid and semi-arid areas, the estimated soil organic carbon stock varies with the type of land use. It is of the order of 0.1, 0.05 and 0.1 MgC (Bajes, 2003) per ha per year, respectively on cropland, grazing land and restored lands or degraded soils. These values are relatively low compared to those of other agro-ecological zones in the world (Table 1).

Table1. *Soil organic carbon sequestration potential in arid and semi-arid zones according to land management practices compared with other agro-ecological zones (Bajes, 2003)*

Land management practices	Agro-ecological zones (Mg C $ha^{-1}yr^{-1}$)			
	Arid	Sub tropical	Tropical	Temperate
Farmland	0–0.10	0.1–0.3	0.3–0.6	0.2–0.5
Pastureland	0–0.05	0.05–0.1	0.1–0.3	0.1–0.2
Restored land / degraded soils	0–0.1	0.2–0.4	0.4–0.8	0.3–0.6

According to the data sources, the global organic carbon is 8.6% and 9% of soil organic carbon respectively in 0-30 and 0-100 cm deep in Africa (Henry et al., 2009 and Henry, 2010) . These estimates are low compared to those of Williams et al., (2007), which can be 13%. By using multiple data sources, Henry et al., (2009) illustrate the soil organic carbon of different regions of Africa. Table 2 summarizes these data.

Table2. *Organic carbon stocks in soils in different geographical regions of Africa based on depths (Henry et al., 2009).*

n: number of soil samples collected

				Average stock per country (TgC)		total C stock (Tg or millions of tons) C	
Ecoregions	**Country**	**Surface**	**N**	**0-30cm**	**0-100cm**	**0-30cm**	**0-100cm**
East Africa	21	6 050 248	14 867	1089.57±1495.53	2139.20±3211.1	22 881	46 230
Central Africa	9	6 206 571	1 933	2959.11 ±3122.58	6144.22±6614.4	26 632	55 298
North Africa	10	8 566 401	8 744	1660.6±1989.11	2965.1±3694.27	16 606	29 652
South Africa	6	2 727 424	12 851	993.2±1131.48	1873.4±2061.27	4966	9 367
West Africa	17	5 886 378	2 437	876.35±894.97	1520.47±1537.5	14 897	25 850

At 30 cm depth, soil organic carbon content by country average is 1089.57±1495.53Tg for East Africa, 2959.11 ± 3122.58Tg for Centre Africa, 1660.6 ± 1989.11Tg for North Africa, 993.2 ± 1131.48Tg for South Africa and 876.35 ± 894.97Tg for West Africa. On the other hand, at 100 cm depth, the averages are 2139.20 ± 3211.14Tg, 6144.22 ± 6614.45Tg, 2965.1 ± 3694.27Tg, 1873.4± 2061.27Tg and 1520.47 ± 1537.50Tg respectively for East, Central, Northern, South and West Africa. The low vegetation cover in some areas compared to others and unbalanced samples of plant biomass may explain this phenomenon (Sanchez, 1997 and Schlesinger et al., 2000). These results provide information on the first organic carbon stocks in soils different eco-regions of Africa and in the land use practices including cropland, grazing land and restored degraded land or soil. These studies tell little about soils and vegetation of West Africa features including ferruginous tropical soils and steppe formations.

Agroforestry and Potential of Carbon Sequestration in the Sahel of West Africa

Some studies have shown the potential of carbon sequestration in agroforestry systems and its benefits to people (Nair et al., 2003; Takimoto et al., 2008; Nair et al., 2009). The amount of carbon sequestered in aboveground biomass in agroforestry systems, according to these studies ranged from 0.29 to 15.1 $Mgha^{-1}yr^{-1}$. These results show high potential of these systems to sequestere carbon. However, this potential depend on a number of factors including site characteristics, types of land use, species involved, stand age and management practices (Nair et al., 2009). Nevertheless a little more recent studies show an average capacity of carbon sequestration for 325.35 kg C / ha for *Pterocarpus lucens* in the Biosphere Reserve in Ferlo at Senegal (Ngom et al., 2014). Depending on the age of the plantation in Burkina Faso (4 years to 6 years), the shrub *Jatropha curcas* sequesters in the litter, 307.899 to 707.162 kg C / year (Bayen et al., 2015). Agroforestry, for the maintenance of trees in the cropping system is an important way for the sequestration of CO2 in sub-Saharan of Africa. The ability of agroforestry systems to sequester CO2 depends on the management of the species selected, soil characteristics, annual rainfall and agricultural practices among others (Mbow *et al.*, 2014). In West Africa, results from some studied on soil organic carbon in some cases of agroforestry systems are presented in Table 3.

Table3. *Amount of soil carbon sequestered in some agroforestry systems in West Africa.*

Agroforestry systems	Country	Depth	Ages (yrs)	C ($MgCha^{-1}\,yr^{-1}$)	Authors
Fodder banks (*Gliricidia septum, Pterocarpus lucens* and *P. erinaceus*)	Mali	0-100	7,5	0.29	Takimoto *et al.* (2008)
Hedges (*Acacia nilotica, Acacia senegal, Bauhinia rufescens, Ziziphus mauritiana* and *Lawsonia inermis*)	Mali	0-100	8	0.59	Takimoto *et al.* (2008)
Parklands (*Faidherbia albida* and *Vitellaria paradoxa*)	Mali	0-100	35	1.09	Takimoto *et al.* (2008)
Culture alley (*Leucaena*)	Nigeria	0-10	5	13.6	Lal, (2005)
Agroforestry park (*Vitellaria paradoxa* and *Parkia biglobosa*)	Benin	0-60		5.85	Saidou *et al.* (2012)
Agroforestry park (*Vitellaria paradoxa*)	Benin	0-50	Ages (yrs)	32	Volkoff *et al.* (1999)

Knowledge of organic soil carbon stocks of the different parklands of West Africa is very limited. The few available studies are on parks constituting of species of *Vitellaria paradoxa*, *Parkia biglobosa* and *Faidherbia albida*. Soil carbon stock in the parks of other species with high socio-economic and ecological values for people and the environment are unknown. Yet these species perform important roles in a balanced diet, foraging and especially in the agro-sylvo-pastoral production in semi-arid zone, particularly in Sahel (Mahamane, 1997 ; Smektala *et al.*, 2005 ; Breman *et al.*, 1995 ; Tougiani *et al.*, 2011 ; Larwanou *et al.*, 2006 ; Laouali *et al.*, 2014). These systems need to be studied in terms of their ability to store organic carbon in soil in order to improve their management systems for the well-being of the people.

Allometric Equations of Woody Species

In rainforest, several generic allometric equations for estimating biomass have been developed. Table 4 presents some of these equations.

Table4. *Generic allometric equations for estimating aboveground biomass of tropical rainforests*

Forest type	Equations	Dbh limits, n and R^2	Authors
Rain forests	$Y=\exp(-2.134 + 2.530 \times \ln(DBH))$	$5 \leq DBH \leq 148$cm, n=170, R^2=0.97	Brown et al., 1997
Rain forests	$Y = \exp(-2.977 + ln(\rho D^2H)) \equiv 0.0509 \times \rho D^2H$	$5 \leq DBH \leq 150$ cm, n = 2 410, R^2 = 0.989	Chave et al., 2005
deciduous forests	$ln Y = -1.232 + 2.178 \times ln(DBH)$	$6 \leq DBH \leq 200$, n = 122; R^2= 0.992	Basuki et al., 2009
African	$Y = 3.47 \times 10-3 \times DBH^{(2.0)} \times H \times WD$	$7 \leq DBH \leq 150$; n=42	Henry

tropical forest			et al., 2010
Rain forests	AGB est = 0.0673 x $(\rho D^2 H)^{0,976}$	10≤DBH≤158, =4004	Chave et al., 2014

Y: aboveground biomass of trees; DBH: diameter at breast height; H: height; ρ: wood density

Brown et al., (1997) used 170 trees with DBH of below 148 cm in evergreen forests. Chave et al., (2005) have developed generic allometric equations from 2410 trees with a DBH range of 5 to 150 cm in the same forest types as Brown et al., (1997). In deciduous forests, Basuki et al., (2009) had developed equations from 122 trees with a maximum diameter of 200 cm. From these equations, the above-ground biomass is expressed in terms of diameter at breast height giving an exponential pace to curve and a high correlation (Brown et al., 1997; Chave et al., 2005; Basuki et al. 2009). However Henry et al., (2010) developed allometric models on tropical forests in Africa especially in Ghana among others by integrating the total tree height, DBH and wood density (WD) from 42 trees with maximum DBH of 150 cm. In order to improve biomass estimation it is important that the height (H), DBH and WD are associated with each other (Henry et al., 2010). In West Africa, specific biomass estimation models have been developed for some genera and species. Table5 summarizes these models.

The Allometric equations presented in Table5 were obtained from scientific articles published in referenced journals and other scientific articles by Henry et al., (2011). Indeed databases from international libraries including those of ICRAF (World Agroforestry Center), FAO (United Nations Food and Agriculture), CIRAD (Centre for International Cooperation in Agronomic Research for Development), and IRD (Institute of Research for Development) were used. These allometric equations express aboveground biomass based on DBH, circumference (at 1.30m), diameter at the base and total tree height. Based on the correlation coefficient (R^2), most of these equations do not provide information on their validity or reliability. For some equations (Larwanou et al., 2010), we used the database to further deepen the analysis on the residual. However, these models have the merit of allowing the estimation of the total aboveground biomass of several woody species in the West African region to assess tree fodder and especially the agro- sylvo- pastoral productivity (Cissé, 1980; the Houerou, 1980; Larwanou et al., 2010).

Table5. *Allometric equations for estimating aboveground biomass of woody species in West Africa.*

Species	n	Equations	Pluviometry (mm)	R^2	RSE	Dendrometric parameters	Country	Authors
Pterocarpus erinaceus	320	Y(Vf) = 3.491 D $^{2.198}$	806	0.810	0.316	D in cm : 25.49±7.8	Burkina Faso (Cassou)	Rabiou et al., 2015
Pterocarpus erinaceus	105	Vf = 3.024 D 2.259	740	0.873	0.353	D in cm : 43.15±11.19	Niger (Gaya)	Rabiou et al., 2015
Jatropha curcas	390	AGB = 1.01 – 0.60 9*D + 0.08 9 *D^2	800 -900	0.95		Dbh <20 in cm	Burkina Faso	Bayen et al., 2015
Bombax costatum	56	√ PSc (kg) = – 0.051 + 0.025 x Dhp (cm)	750-850	0.97	0.43	Dbh >50 in cm	Burkina Faso	Ouédraogo et al., 2014
Pterocarpus lucens	40	Log10 y (g MS) = 0.6156 + 1.862 Log 10 C	474	0.75		C en cm : 10-150	Sénégal	Ngom et al., 2014
Acacia senegal	44	y = 0.032Dbh^3 - 1.016Dbh^2 + 10.87Dbh + 7.429	300	0.963		Dbh in cm: 1-12	Sénégal	Thiam et al., 2014
Acacia sp	20	Y=5.066Dbh -0.696Dbh^2 +0.05Dbh^3	600 - 1 000	0.732	0.109	Dbh in cm: 5.5–32.0	Sénégal	Mbow et al., 2013
Combretum sp	45	Y=-3.524Dbh +0.946Dbh^2 - 0.010Dbh^3		0.923	0.127	Dbh in cm: 5.1–27.1		Mbow et al., 2013
Terminalia macroptera	9	Y= 9.255Dbh -1.563Dbh^2 + 0.089Dbh^3		0.993	0.160	Dbh in cm: 5.7–41.5		Mbow et al., 2013
Acacia ehrenbergiana	15	Log(y) = 0.38.Log(D1) + 0.49.Log(D2) - 1.47.Log(C) + 0.65	134	0.96		C : in cm17-38	Niger	Chaibou et al., 2012
Maerua crassifolia	15	y= 2.73 + 4.65.D1 - 1.12.D2 - 1.25.H	134	0.98		H in cm 98-179	Niger	Chaibou et al., 2012
Afzelia africana	26	ln(y)=-2.3129+1.7953*ln(Dbh) + 0.6833ln((H)	1 100	0.9784		Dbh in cm:2.3-94.9	Benin	Guendehou et al. 2012
Anogeissus leiocarpa	20	ln(y)=-2.4996 + 1.5133ln(Dbh) +1.1256 ln(H)	1 100	0.9576		Dbh in cm:2.5-88.5	Benin	Guendehou et al. 2012
Ceiba	35	ln(y)= -2.4266 +1.7292ln(Dbh)	1 100	0.932		Dbh in cm:8.1-	Benin	Guendehou

pentandra		+0.6230ln(H)				190		et al. 2012
Dialium guineense	20	ln(y)= -2.4198 + 1.5585ln(Dbh)+ 1.2315ln(H)	1 100	0.9562		Dbh in cm:4.2-56	Benin	Guendehou et al. 2012
Diospyros mespiliformis	22	ln(y)= -2.6709 + 1.5089ln(Dbh) + 1.3247ln(H)	1 100	0.9639		Dbh in cm:1.8-53	Benin	Guendehou et al. 2012
Tectona grandis	39	ln(y)=-2.9489+ 2.2201ln(Dbh)+ 0.6945ln(H)	1 100	0.9805		Dbh in cm:3.5-65.5	Benin	Guendehou et al. 2012
Faidherbia albida	9	y = 7.985Dbh + 32.277	500	0.33	0.1647	Dbh in cm: 25 -39	Kollo (Niger)	
					0.2111	Dbh in cm: 40 - 59		
					0.2447	Dbh in cm: >60		Larwanou et al., 2010
Propsopis africana	9	y = 16.48Dbh + 47.577		0.88	0.2214	Dbh in cm: 30-40		
					0.1313	Dbh in cm: 41 -59		
					0.1255	Dbh in cm: >60		Larwanou et al., 2010
Piliostigma reticulatum	9	y = 5.485Dbh + 15.717		0.87	0.1989	Dbh in cm: 12 -19		
					0.1134	Dbh in cm:		
					0.1959	Dbh in cm: >31		Larwanou et al., 2010
Bauhinia rufecens	9	y = 7.61Dbh + 7.4867		0.86	0.2438	Dbh in cm: 10 -15		
					0.2880	Dbh in cm: 16 -20		
					0.1681	Dbh in cm: >20		Larwanou et al., 2010
Ziziphus mauritiana	9	y = 5.46Dbh + 6.6167		0.99	0.096	Dbh in cm: 09 -12		
					0.2427	Dbh in cm: 13 - 20		
					0.2182	Dbh in cm: >21		Larwanou et al., 2010
Acacia dudgeoni	558	Y=0.938+0.119Db+0.099Dbh +0.001H-0.004Db×Dbh	845 at Tiogo and 886 at Laba	0.569	0.435	Dbh in cm: 8.98±0.123	Tiogo et Laba (Burkina Fasso)	Sawadogo et al., 2010
Acacia macrostachya	523	Y= 3.935-0.0.199Db-0.088Dbh-0.007H+0.017Db×Dbh+0.0008 Db×H+0.006Dbh×H-0.00006Db×Dbh×H		0.428	0.516	Dbh in cm:7.206±0.110		Sawadogo et al., 2010
Anogeissus leiocarpa	120	Y= 0.889+0.107Dbh+0.304Dbh+0.004H-0.006Db×Dbh-0.00002Dbh×H+0.000004Db×Dbh×H		0.905	0.516	Dbh in cm: 19.752±1.173		Sawadogo et al., 2010
Combretum ghasalense	433	Y= 0.961+0.086Db+0.168Dbh+0.0009H-0.004Db×Dbh		0.708	0.471	Dbh in cm: 8.975±0.196		Sawadogo et al., 2010
Combretum glutinosum	103	Y= 0.661+0.121Db+0.190Dbh-0.005Db×Dbh		0.852	0.349	Dbh in cm: 9.594±0.392		Sawadogo et al., 2010
Combretum micranthum	89	Y= 0.827+0.184Db+0.0337Dbh-0.001Db×Dbh+0.0004Dbh×H		0.671	0.473	Dbh in cm: 7.490±0.379		Sawadogo et al., 2010
Combretum nigricans	98	Y =0.213+0.0132Db+0204Dbh+ 0.0007H-0.005DbxDbh		0.900	0.318	Dbh in cm: 17.509±0.694		Sawadogo et al., 2010
Crossopterix febrifuga	253	Y= 0.002Dh×Dbh+0.00007Db×H-0.0002Dbh×0.0001Dbh×H		0.800	0.360	Dbh in cm: 15.293±0.355		Sawadogo et al., 2010
Detariummicrocarpum	1177	Y= 0.758+0.028Db+0.237Dbh+0.0009H-		0.731	0.352	Dbh in cm: 12.731±0.105		Sawadogo et al., 2010

		0.003Dbh+0.0001Db×H-0.0002Dbh×H						
Entada Africana	957	Y= 0.232+0.101Db+0.141Dbh+0.002H-0.004Db×Dbh		0.763	0.423	Dbh in cm: 9.920±0.123		Sawadogo et al., 2010
Piliostigma thonnigii	443	Y= 0.358+0.100Db+0.169Dbh+0.001H-0.004Db×Dbh		0.693	0.461	Dbh in cm: 9.303±0.167		Sawadogo et al., 2010
Combretum fragrans		y= –0.0066+0.0023×X+0.4752×(X^2)	1067	0.93		C in m (0.15. 0.7)	Sikasso (Mali)	Bagnoud, N. et Kouyaté, A. M. (1996) (in Henry et al., (2011)
Combretum ghazalense		y= (0.23/(1+(95×exp(–29×X))))×10^(–6)	954			D1.3 in cm (1. 200)	Siani (Mali)	Manlay, R.J., Kairé, M., et al. (2002) (in Henry et al., (2011)
Daniellia oliveri	60	y= –0.0057–0.0386×2+0.5539×(X^2)	1067	0.95		C in m (0.41. 0.94)	(Sikasso) Mali	Bagnoud, N. and Kouyaté, A. M. (1996) (in Henry et al., (2011)
Isoberlinia doka	100	y= –0.05182+0.24489×X+0.56703×((X^3))	1067			C in m (0.22. 1.5)	Sikasso (Mali)	Nouvellet, Y. (2002) (in Henry et al., (2011)
Isoberlinia doka	60	y= 0.0444–0.3464×X+1.0141×(X^2)		0.96		C in cm (15. 100)	Sikasso (Mali)	Bagnoud, N. and Kouyaté, A. M. (1996) (in Henry et al., (2011)
Terminaliasp	116	y= –0.01564+0.13174×X+0.57929×((X^3))	1067			C in m (0.22. 1.4)	Sikasso (Mali)	Nouvellet, Y. (2002) (in Henry et al., (2011)
Terminaliasp	60	y= 0.0067–0.1114×X+0.6995×(X^2)	1067	0.92		C in cm (15. 79)	Sikasso (Mali)	Bagnoud, N. and Kouyaté, A. M. (1996) (in Henry et al., (2011)
Combretum ghazalense	663	y= 0.23/(1+95×exp(–29×X))				D1.3 in cm (1. 200)	Mali	Nouvellet, Y. (2002) (in Henry et al., (2011)
Combretum glutinosum	24	y= –0.00707×X+0.07584×(X^2)+0.57874×(X^3)		0.99		C in m (0.22. 1.1)	Bamako (Mali)	Malimbi, R. E., Luoga, E., et al. (2000) (in Henry et al., (2011)
Cordyla pinnata	24	y= –0.02038×X+0.13130×(X^2)+0.51060×(X^3)	1152	0.97		C in m (0.22. 1.5)	Bamako (Mali)	Malimbi, R. E., Luoga, E., et al. (2000) (in Henry et al., (2011)
Ziziphus mauritania	100	y(g)= 1.38×(X^(1.91))×10^(–3)		0.99		C in cm (3. 628)	Mali	Bellefontaine, R., Gaston, A., et al. (1997) (in Henry et al., (2011)
Ziziphus mauritania	46	y(g)= 1.38×(X^1.91)×10^(–3)		0.85		C in cm (5. 61)	Mali	Cissé, M. I. (1980) (in Henry et al., (2011)
Ziziphus mauritania	46	y(g)= 0.58×(X^1.1)×10^(–3)		0.85		CA in dm2 (78. 67214)*	Mali	Cissé, M. I. (1980)
Ziziphus mauritania	46	y(g)= 3×(10^(–6))×X^(2.83)×10^(–3)				H in cm (292. 5369)	Mali	Cissé, M. I. (1980)
Combretum nigricans	100	y(g)= 4.3184×(X^2.0077)×10^(–3)	815	0.99		Cb in cm (4. 708)	Gouani (Mali)	Bazile, D. (1998) (in Henry et al.,

								(2011)
Combretum nigricans	100	y(g)= 1.2289×(X^2.5806)×10^(–3)	896	1		Cb in cm (4. 708)	N'goukan (Mali)	Bazile, D. (1998) (in Henry et al., (2011)
Commiphora africana	9	log10y= –2.69+(2.6×log10(X))	224	0.99		Cb in cm (4. 708)	FétéOlé (Senegal)	Poupon, H. (1979) (in Henry et al., (2011)
Commiphora africana	10	log10y= –4.96+(3.56×log10(X))	224	0.99		Cb in cm (4. 708)	FétéOlé (Senegal	Poupon, H. (1979) (in Henry et al., (2011)
Commiphor aafricana	9	log10y= –2.6+(2.37×log10(X))	224	0.99		Cb in cm (4. 708)	FétéOlé (Senegal	Poupon, H. (1979) (in Henry et al., (2011)
Commiphora africana	9	log10y= –3.43+(2.53×log10(X))	224	0.97		Cb in cm (4. 708)	FétéOlé (Senegal	Poupon, H. (1979) (in Henry et al., (2011)
Commiphora africana	15	y(g)= 1.51×(X^1.78)×10^(–3) C		0.9		C in cm (5. 61)	Mali	Poupon, H. (1979) (in Henry et al., (2011)
Commiphora africana	50	y(g)= 0.155×(10^(–6))×X^(3.21)×10^(–3)		0.85		H in cm (292. 5369)	Mali	Cissé, M. I. (1980)
Detarium microcarpum	50	y(g)= 2.0919×(X^2.3118)×10^(–3)	815	0.85		Cb in cm (4. 708)	Gouani (Mali)	Cissé, M. I. (1980)
Gardenia ternifolia	16	y(g)= 4.5738×(X^2.0836)×10^(–3)	896			Cb in cm (4. 708)	N'goukan (Mali)	Poupon, H. (1979) (in Henry et al., (2011)
Grewia bicolor	10	log10y= –3.27+(2.45×log10(X))	224	1		Cb in cm (4. 708)	Fété Olé (Senegal)	Poupon, H. (1979) (in Henry et al., (2011)
Grewia bicolor	10	log10y= –1.67+(1.77×log10(X))	224	0.99		Cb in cm (4. 708)	FétéOlé (Senegal)	Poupon, H. (1979) (in Henry et al., (2011)
Grewia bicolor		log10y= –1.81+(2.12×log10(X))	224	0.96		Cb in cm (4. 708)	FétéOlé (Senegal)	Ngom, D., Diatta, S., et al. (2009) (in Henry et al., (2011)
Grewia bicolor		- y(g)= 6.39×(X^1.53)×10^(–3)	234	0.96		C in cm (3. 628)	FétéOlé (Senegal)	Ngom, D., Diatta, S., et al. (2009) (in Henry et al., (2011)
Guiera senegalensis		log10y(g)= (0.55+(1.89×log(X)))×10^(–3)	429	0.6		D1.3 in cm (1. 200)	Tongomayel (Burkina Faso)	Bellefontaine, R., Gaston, A., et al. (1997) (in Henry et al., (2011)
Guiera senegalensis	5	y(g)= 3.09×(X^(1.89))×10^(–3)		0.84		C in cm (3. 628)	Mali	Poupon, H. (1979) (in Henry et al., (2011)
Guiera senegalensis	5	log10y= –2.18+(2.15×log10(X))	224	0.96		Cb in cm (4. 708)	FétéOlé (Senegal)	Poupon, H. (1979) (in Henry et al., (2011)
Guiera senegalensis	21	log10y= –2.45+(1.93×log10(X))	224			Cb in cm (4. 708)	FétéOlé (Senegal)	Poupon, H. (1979) (in Henry et al., (2011)

Guiera senegalensis		log10y= –2.54+(1.96×log10(X))	224	0.98		Cb in cm (4. 708)	FétéOlé (Senegal)	Poupon, H. (1979) (in Henry et al., (2011)
Guiera senegalensis		y= 1.0806×exp(−2.241+1.8577×ln(X))	555	0.95		D1.3 in cm (1. 200)	Guesselbodi (Niger)	Alegria, J., Heermans, J. G., et al. (1986) (in Henry et al., (2011)
Pterocarpus lucens		logy(g)= (–0.4+(2.86×log(X)))×10^(–3)	429	0.95		D1.3 in cm (1. 200)	Tongomayel (Burkina Faso)	Sanon, H. O., Kaboré-Zoungrana, C., et al. (2007) (in Henry et al., (2011)
Pterocarpus lucens		y(g)= 0.95×(X^(2.07))×10^(–3)		0.9		C in cm (3. 628)	Mali	Bellefontaine, R., Gaston, A., et al. (1997) (in Henry et al., (2011)
Pterocarpus lucens	40	y(g)= 65×(10^(–6))×X^(2.83)×10^(–3)				H in cm (292. 5369)	Mali	Cissé, M. I. (1980)
Pterocarpus lucens	40	y(g)= 0.6×(X^1.22)×10^(–3)		0.80		CA in dm2 (78. 67214)	Mali	Cissé, M. I. (1980)
Pterocarpus lucens	40	y(g)= 93×X^(2.07)×10^(–3)		0.79		C in cm (5. 61)	Mali	Cissé, M. I. (1980)

Dbh: diameter at breast height, n: sample C: circumference, H: height, Db: base diameter.

CONCLUSION AND RECOMMENDATIONS

Soil is an important sink for both organic and inorganic carbon. In West Africa, studies have highlighted organic carbon stocks sequestered by soils of some agroforestry systems especially parklands. The results showed a significant increase in organic carbon sequestration capacity with agroforestry practices. Despite these attempts in determining soil carbon in West Africa parklands, much effort remains to be done in order to investigate and improve the management of these parklands system for the socio-economic and cultural benefits of the population. Specific studies on carbon sequestration of different agroforestry technologies and systems are needed to identify the most promising technics in the Sahel and supports the resilience and adaptation of populations to climate change. Allometric models for estimating the aboveground biomass of tree species of West Africa parklands are available. Nowadays, scientific research tends towards minimizing biases in the methodology for developing these models including sampling, measurements, choice of suitable models and criteria for validation of the equations. Thus, it is necessary to conduct more research on the development of allometric models for tree species biomass especially those with high socioeconomic, cultural and ecological values.

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