Sustainable Cities and Society 50 (2019) 101653

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

West African Sahelian cities as source of carbon stocks: Evidence from Niger

Soulé Moussa[a,*], Boateng Kyereh[b], Abasse Tougiani[c], Shem Kuyah[d], Mahamane Saadou[e]

[a] West African Science Centre on Climate Change and Adapted Land Use (WASCAL), Department of Civil Engineering, College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[b] Department of Silviculture and Forest Management, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science & Technology, Kumasi, Ghana
[c] Département de Gestion des Ressources Naturelles, Institut National de la Recherche Agronomique du Niger (INRAN) Niamey, Niger
[d] Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200, Nairobi, Kenya
[e] Département de Biologie, Faculté des Sciences et Techniques, Université Dan Dicko Dankoulodo Maradi, BP: 465, Maradi, Niger

ARTICLE INFO

Keywords:
Urban forest
Eco-urbanization
Carbon neutrality
Sustainable cities

ABSTRACT

The need for sustainable cities under a changing climate calls for intensive research on the role of urban forests in climate change mitigation. This study estimated the carbon stocks and carbon emission factors in Niamey and Maradi. Stratified random sampling approach was used for the urban forests inventory. Biomass was estimated using the generalized model. Stock-difference method was used for the carbon emission factor. Focusing on woody plants with a diameter at breast height > 5 cm, 2,027 stems (78 species) were measured in Niamey and 2,456 stems (90 species) were measured in Maradi. The mean carbon stock was 31.63 (15.63, 47.64) in Niamey and 58.30 (13.10, 103.50) t/ha in Maradi. The mean carbon stock was significantly different in each city ($p < 0.05$) across land use types. The results show that the conversion of peri-urban forests into the urban forest in any of the land use types is associated with carbon gain. This study illustrated the potential benefits of accounting for urban forest carbon stocks within Sahel cities under rapid urbanization. This study recommends that the urban forest carbon stocks should be included in climate change mitigation in Niger.

1. Introduction

Cities are expanding quickly in size. At present about 55% of the world's population lives in cities and this figure is projected to reach 68% by 2050 with 90% of the increase occurring in Asia and Africa (United Nations, 2018). Urban areas are extremely important for the global carbon balance as 75% of carbon emissions comes from cities (UN, 2017). This is one of the contributing factors to climate change, which is a complex global environmental problem due to its impacts on ecological (Walther et al., 2002) and socio-economic systems (Jin et al., 2018). In most parts of the word, the expansion of cities involves conversion of forests and agricultural lands to urban land use. This impacts negatively on vegetation (Seto, Guneralp, & Hutyra, 2012) leading to a huge reduction in biomass (Arroyo-Rodríguez et al., 2017) and therefore exerting influence on biogeochemical cycles (Wang et al., 2017) and climate at regional and global scale (Seto & Shepherd, 2009). Urban expansion pressure on forested areas is particularly high in the tropics where for instance, 5% of the annual carbon emissions are due to urban expansion (Seto et al., 2012). Urbanization however does not lead to total vegetation loss as city dwellers would normally establish and manage green spaces some of which may qualify as urban forests with a good level of tree cover. Such urban forests become important sources of carbon stocks in cities. The initial attempts to estimate urban forest carbon stocks included studies by (Dorney, Guntenspergen, Keough, & Stearns, 1984) who used allometric models to quantify urban forest carbon stocks in a suburb of Milwaukee. Since then studies of urban forest carbon stocks have become increasingly common across the world (Mitchell et al., 2018). The limitation however, is that the majority of the studies have been done is North America, Europe and Asia notably Korea and China (Brown, 1997; Chen, 2015; Nowak, Green, Hoehn, & Lapoint, 2013; Weissert, Salmond, & Schwendenmann, 2014; Wilkes, Disney, Vicari, Calders, & Burt, 2018) resulting in limited information on urban forest carbon stocks across different climatic zones (Weissert et al., 2014). From some of these studies it has emerged that despite the fact that, urbanization drives carbon loss, in certain cases cities become important centres for biodiversity conservation and carbon storage, which are useful indicators for ecosystem service provision (Nadrowski, Wirth, & Scherer-Lorenzen, 2010). This suggests that cities may have complex relations with vegetation and therefore carbon sequestration and storage. Some studies already point out the importance of urban forests in carbon storage despite their small sizes (Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011; Mitchell

---

[*] Corresponding author.
E-mail address: moussa_soulesama@yahoo.fr (S. Moussa).

https://doi.org/10.1016/j.scs.2019.101653
Received 14 October 2018; Received in revised form 25 March 2019; Accepted 10 June 2019

et al., 2018; Nowak et al., 2013). Building on such findings, it will be crucial to identify the patterns and trends that define urban forests distribution and therefore carbon storage. For example, which urban land use stores what amount of forest carbon will be an important data input for climate change policies especially in dry environments such as the Sahel where carbon stocks are generally low in even natural vegetation. Again, the need to provide shade in the dry and hot climate that prevails in the Sahel has created a culture of tree planting whose impact may be significant in terms of carbon storage. It is thus important to understand the pattern of urban forest carbon distribution in the context of the heterogeneity of urban landscapes. Nevertheless, our understanding of urban carbon reservoir dynamics and specifically urban forest carbon stocks dynamics remains scarce (Tang, Chen, & Zhao, 2016).

Also, there is prolific literature on the carbon emission from urban expansion by urban people yet there is little work on carbon emission resulting from the conversion of peri-urban forests into urban space including its forests. Niamey and Maradi are two leading and rapidly urbanized cities in Niger but with different socio-economic attractions and cultures that may influence the way urban forests are perceived, valued and managed by people. These factors are determinant of urban forest structure (Hope et al., 2003; Sanders, 1984) which are also the factors of urban forest services such as carbon stock (Nowak, Hoehn, Bodine, Greenfield, & Neil-dunne, 2016). They therefore present an opportunity to address the knowledge gap that exists about the distribution of carbon stocks within cities and between cities, and the land use and land cover types from which cities are created. Therefore, this paper aimed to assess the role of urban forests in the climate change debate by estimating the carbon stocks of urban forests and carbon emission factors from the conversion of peri-urban forests into urban forests in Niamey and Maradi, two important sahelian cities in West Africa. A good knowledge of urban forests carbon stock is essential for sustainable carbon management, which goes with climate action and sustainable cities. In this regards, urban forests constitute one of the most effective strategies to attenuate the consequences of climate change and promote more resilient environment in urban areas.

2. Materials and methods

2.1. Study area

The study was carried out in Niamey and Maradi which are two cities in the Sahel climatic zone of Niger with rainfall ranging from 150 mm to 530 mm (CNEDD, 2016). The Niamey region is located in the western part of Niger between latitudes 13° 35′ and 13° 24′ South and longitudes 2° 15′ East (Fig. 1). Its altitude extends from 160 m to 250 m above sea level and its administrative boundaries extend over 552.27 km^2 of which approximately 297.46 km^2 is urbanized (Institut National de la Statistique du Niger (INS), 2016). Niamey is the political capital and largest city of Niger. Niamey had a population of a population of 1,026,848 people (Institut National de la Statistique du Niger (INS), 2016). The vegetation of Niamey city belongs to the South Western Sahelian compartment (B_1) where vegetation types consist of *Combretum* thicket on the plateau lateritic soils and steppe found on sandy terraces, in dry valleys and on the dunes (Saadou, 1990). Natural vegetation in Niger consists also of gallery forests on the Niger River and some urban wetlands. At the periphery of the city, the vegetation consists of agroforestry parklands and tiger bush. Inside the city, the vegetation consists of the green belt of Niamey and other green spaces such as roadside plantations and many urban woodlots.

Maradi city is located between latitudes 13° 32′ N and 13° 26′ N and longitudes 7° 40′ E and 7° 13′ E (Fig. 1), with an average altitude of around 400 m above mean sea level. Maradi is the economic capital of Niger and covers an area of 86 km^2 with a population of 326,804 inhabitants (Institut National de la Statistique du Niger (INS), 2016). The natural vegetation belongs to the Southern Central Sahelian (B_2) with some vegetation types such as savannah on the southern sandy terraces, steppes on dunes and dry valleys and *Combretum* thicket on lateritic plateaus (Saadou, 1990).

2.2. Urban forest sampling and mensuration

We used stratified random sampling approach for the inventory of in the various land use and land cover (LULC) types in the two cities. FAO (2016) defined urban forest a collection of woody plants in urban areas and peri-urban areas. Based on this definition, we defined seven LULC, which are:

i Commercial areas that consisted of market centres, shops, restaurants and garages;
ii Roads covering the main streets, the derelicts corners and boulevards;
iii Residential areas covering houses, mosques and churches;
iv Schools covering private and public training and learning institutions such as primary schools, secondary schools, universities, polytechnics, training colleges;
v Administrative areas such as government offices and private offices;
vi Forested areas consisting of urban agriculture plots, inner city green belts, inner city agroforestry systems, and wetlands, irrigated farmlands and botanical gardens. The six above LULC formed the urban forests or inner city of the two cities.
vii Peri-urban forests: peri-urban farmlands, peri-urban pastoral lands. This stratum started from the end of the city (where there were no buildings) to a distance of 4 km away into the non-built area.

The LULC types were randomly selected from five districts in Niamey and three in Maradi. A random list for sampling was selected from the list of schools, administrative posts, urban green spaces, roads, markets and residential compounds obtained from Regional services of education, environment, urban equipment and habitat and quarters of the districts in Niamey and Maradi, respectively. We used plot inventory approach to collect the urban woody species data in a plot of 50 m × 50 m, consistent with guidelines for inventories in the Sahel (Thiombiano, Glele KaKai, Bayen, & Mahamane, 2016). The plot size varied in some cases and was less than 0.25 ha if a randomly selected point could not allow a plot of a 2500 m^2 to be laid without getting into another LULC type. For each woody plant on a sample plot, the species names were recorded. The diameter at breast height (DBH) was measured 1.30 m from the ground using a diameter tape. Woody species with forks below 1.3 m forks were considered multi-stemmed; their individual stems were measured separately while those with forks above 1.30 m were considered a single stem. Total woody species height was measured with graduated ranging poles. Urban forests within embassies, barracks, and presidential residence are not included in this study due to restrictions. The specimen and photographs were collected for unknown woody species in the field for later identification at “Laboratoire de Biologie Garba Mounkaila”, University of Niamey and at Department of Biology of the University of Maradi.

2.3. Data analysis

The overall diameter for the multi stems diameters were determined as the square root of the sum of squares of individual stems (Thiombiano et al., 2016). Urban woody species data were grouped into three DBH classes [5–22.74], [22.75–40] and above 40 cm to provide the number of plants in each diameter class LULC in two cities. The mean diameter and height were calculated across LULC types in the two cities.

The estimation of biomass using species-specific equations was not feasible because of scarcity of species-specific equations in the literature (Henry et al., 2013) mostly in urban areas where woody species diversity is high (Konijnendijk, Sadio, Randrup, & Schipperijn, 2004).

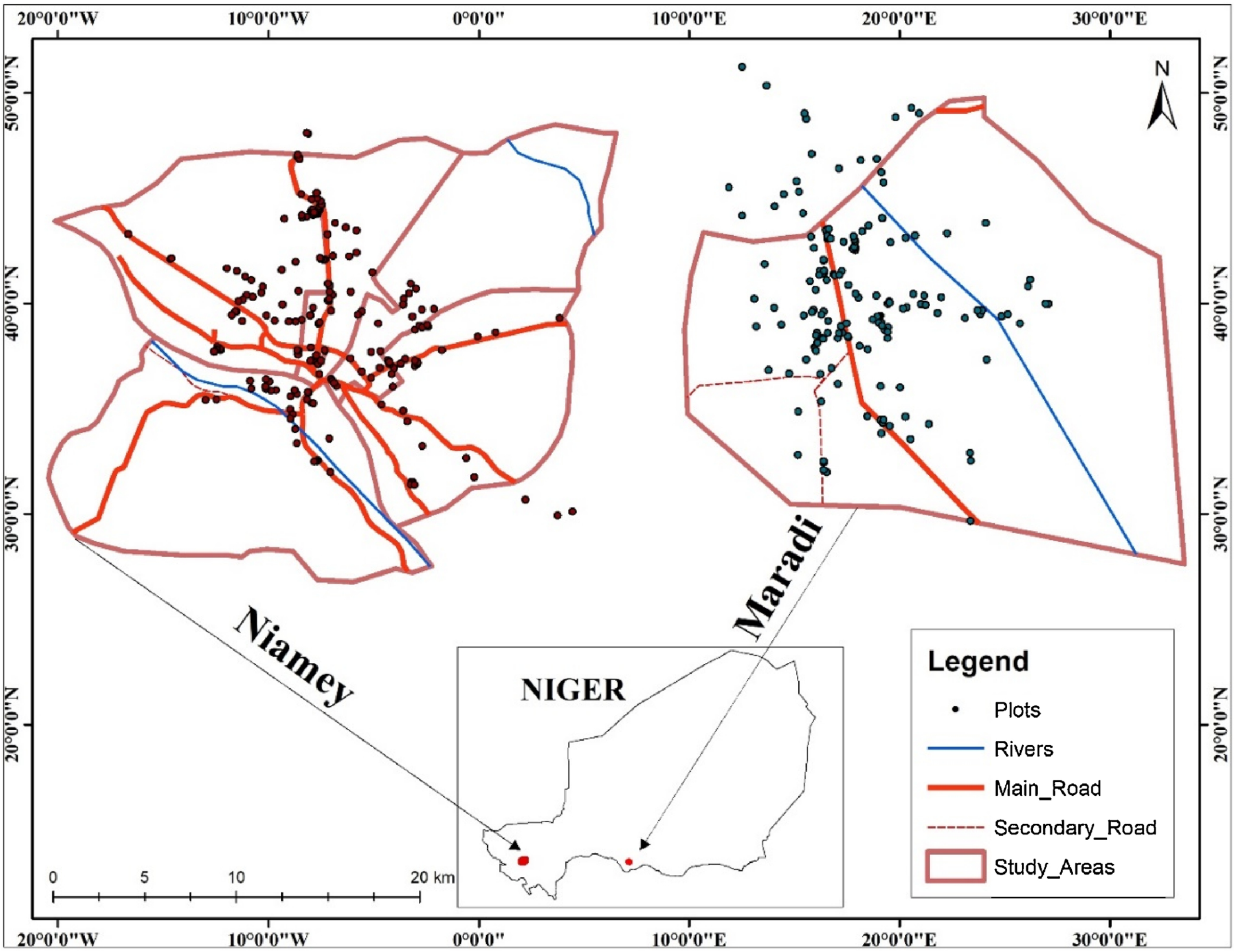

Fig. 1. Study areas.

Therefore, through a critical review of the literature allometric models potentially suitable for estimating aboveground biomass (AGB) in Niamey and Maradi were identified. The model was the allometric equations developed by Chave et al. (2014). The model is given as AGB (kg) = $0.0673(\rho D^2 H)^{0.976}$. Where AGB = aboveground biomass in kg, ρ = wood density (gcm^{-3}), D = diameter in cm at breast height (1.3 m), H = total neem trees height (m) is used by authors when destructive methods are not applicable like the case of urban forests (Henry et al., 2013). The wood density was obtained from the Global wood density database (Zanne et al., 2009). For species without available wood density figures, Wood density of the genus or family was used. The model developed by Chave et al. (2014) has a diameter range of 5–212 cm.

Species-specific allometric models for below-ground biomass are relatively scarce in the literature (Cairns, Helmer, & Baumgardner, 1997; Koala, Sawadogo, Savadogo, & Aynekulu, 2017). Thus, below-ground biomass (BGB) was quantified as a proportion of AGB using the equation BGB (kg) = AGB*(0.24) developed by Cairns et al. (1997) for tropical vegetation. The total urban forests biomass was obtained by summing up the AGB and BGB, which was multiplied by 0.47 (IPCC, 2006a) to obtain carbon content. Stock-difference method was used for the carbon emission factor. The carbon emission factor was calculated as EF = peri-urban forest carbon stocks − urban forest carbon stock (IPCC, 2006b), where EF is the carbon emission factor in tonnes of carbon per hectares (t/C/ha). The AGB and BGB of peri-urban forests were estimated using Chave model (2014) and Cairns model (1997).

Prior to the statistical analysis, the Ryan-Joiner test and Levene' test were used to check the normality and homogeneity of the data. The test of significance was determined at $p < 0.05$. One-way ANOVA test was used to test the differences in the mean H, DBH, carbon stocks, and carbon emission factors in each city across the LULC. A two-sample *t*-test was used to test the difference between the two urban forests mean carbon stock. Descriptive statistics was used also to determine the contributions of species to the AGB. Excel was used for the statistical analysis.

3. Results

3.1. Aboveground biomass across land use and land cover types in the two cities

The study sampled 4,483 stems with DBH ≥ 5 cm that belong to 108 species in both cities. About 2027 stems (78 species) were measured from 202 sample plots covering 30.7 ha in Niamey and 2,456 stems (90 species) were measured from 155 plots with a total area of 20.25 ha in Maradi. Table 1 presents the mean DBH, H, AGB, and number of stems recorded in Niamey and Maradi across the LULC types. The mean DBH, H, and AGB varied significantly across the LULC in Niamey and Maradi (p = 0.00) (Table 1). Among the LULC types, the commercial areas and roads had trees with the highest mean diameter in Niamey (Table 1), while in Maradi this occurred along the roads and in peri-urban forests. However, the trees of lowest diameter were observed in residential urban forests in Niamey and in forested areas in Maradi. For tree height, the highest mean values were observed in commercial areas and roads

Table 1
No. of plots, the total number of stems, Mean standard error (SE) of DBH (cm), Height (m) and Mean confidence interval of AGB (t/ha) and the total land area by the LULC types surveyed in Niamey and Maradi are presented.

Cities	LULC types	Number of plots	Area (ha)	Number of stems (DBH ≥ 5 cm)	Mean (SE) DBH (cm)	Mean (SE) Height (m)	Mean (95% CI) AGB (t/ha)
Niamey	Administrative areas	21	3.98	305	31.9 ± 1.13	9.12 ± 0.23	56.18 (45.35, 67.02)
Maradi		24	3.6	563	31.45 ± 0.68	7.90 ± 0.15	47.39 (31.31, 63.47)
Niamey	Commercial areas	9	1.87	93	37.02 ± 1.99	10.38 ± 0.35	109.9 (54.3, 165.4)
Maradi		11	0.97	176	28.25 ± 1.13	9.20 ± 0.36	116.8 (6.7, 226.8)
Niamey	Residential areas	51	3.75	233	27.92 ± 1.32	8.36 ± 0.23	31.25 (19.79, 42.71)
Maradi		23	1.72	349	23.97 ± 0.66	6.85 ± 0.15	235 (3, 467)
Niamey	Forested areas	33	7.37	443	31.86 ± 0.88	7.3 ± 0.16	32.31 (21.81, 42.81)
Maradi		17	3.93	340	23.82 ± 0.70	6.25 ± 0.16	26.74 (11.24, 42.23)
Niamey	Schools	26	6.74	482	29.54 ± 0.49	8.62 ± 0.14	54.1 (20.2, 87.9)
Maradi		26	5.34	617	29.27 ± 0.51	7.90 ± 0.09	70.73 (42.7, 98.8)
Niamey	Roads	45	2.74	293	37.49 ± 1.35	9.78 ± 0.21	75.03 (52.8, 97.3)
Maradi		42	1.7	325	32.59 ± 0.84	8.45 ± 0.15	182.8 (93.5, 272)
Niamey	Peri-urban forests	17	4.25	178	31.86 ± 1.81	6.26 ± 0.26	28.34 (13.74, 42.94)
Maradi		12	3	86	31.50 ± 2.01	7.66 ± 0.33	15.13 (8.93, 21.33)
Niamey	Overall	202	30.7	2027	32. 5 1 ± 1.35	7.97 ± 0.26	55.3 (28.10, 82.5)
Maradi		155	20.25	2456	28.69 ± 1.36	7.74 ± 0.36	99.2 (22.3, 176.2)
Niamey	P-values	–	–	–	0.00	0.00	0.00
Maradi		–	–	–	0.00	0.00	0.01

in Niamey and in commercial areas in Maradi. For the AGB, the highest mean values were observed in commercial areas in Niamey and residential urban forests in Maradi. While the lowest mean values were observed in peri-urban forests in both cities. There were significant differences in the mean DBH, H, and AGB between the two cities (F-stats = 12.57, df = 2, p = 0.00). The average DBH across the two cities was 32.51 ± 1.35 cm in Niamey and 28.69 ± 1.36 cm in Maradi (Table 1). The average tree height of the two cities were 7.97 ± 0.26 m in Niamey and 7.74 ± 0.36 m in Maradi. The corresponding values of the mean AGB and its confidence interval at 95% were 55.3 (28.10, 82.5) t/ha for Niamey and 99.2 (22.3, 176.2) t/ha for Maradi (Table 1). The three most dominant species in terms of AGB were *Azadirachta indica* (47%), *Faidherbia albida* (16%), and *Khaya senegalensis* (12%) in Niamey. While the three most dominant species in terms of AGB were *Azadirachta indica* (61%), *Terminalia mantaly* (7%), and *Faidherbia albida* (6%) in Maradi. The exotic species in the urban forests represented 60% of the total AGB in Niamey and 78% in Maradi.

The large diameter classes (DBH > 40 cm) was the leading class in terms of the diameter classes contributions to the AGB in the two cities while the small trees [5–22.74] cm class represented 0 and 1% of AGB in Niamey and Maradi respectively (Fig. 2). Tree size-class distribution profiles showed the greatest number of stems in the diameter classes above 40 cm having an overall percentage of 88% in Niamey. However, the [22.75–40] cm was dominant DBH classes in terms of the number of the stems in Niamey with 12% contributions to the AGB. A similar trend was observed in Maradi where the DBH classes greater than 40 cm are leading classes in terms of AGB contribution (59%) although the diameter class [22.75–40] represented the highest number of stems in Maradi.

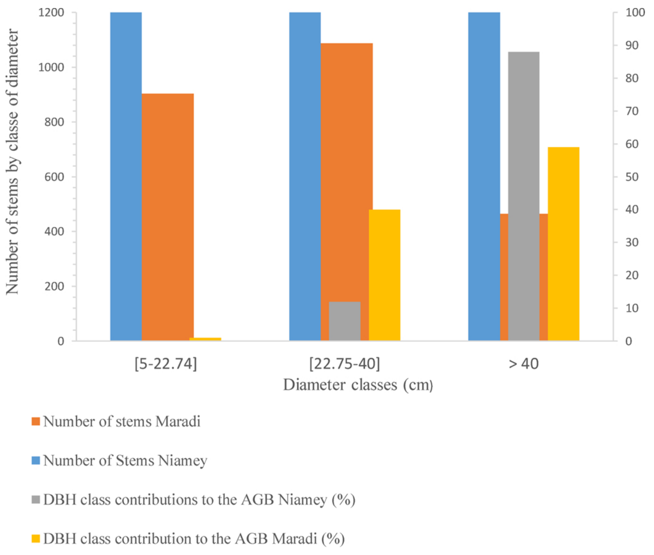

Fig. 2. Number of stems per DBH classes and the contribution of each classes to the AGB.

3.2. Carbon Stocks of the urban forests in the two cities

Table 2 presents the mean carbon stocks of the urban forest in the two cities. The mean carbon stock varied significantly (F-stats = 17.57, df = 1, p = 0.00) among LULC types in Niamey. Urban forests store 34.13 (15.75, 52.52) more carbon than peri-urban forests 16.65 (8.07, 25.23) t/ha around Niamey (F-stats = 21.72, df = 1, p = 0.00). The overall carbon stock in Niamey was 31.63 (15.63, 47.64) t/ha. A similar trend was observed in Maradi, the average carbon stock varied significantly (F-stats = 8.61, df = 1, p = 0.01) across the LULC. Urban forests (66.5 (16.2, 116.90) t/ha in Maradi store also more carbon than peri-urban forests (8.90 (5.25, 12.53) t/ha (F-stats = 9.55, df = 1, p = 0.00). The overall carbon stock in Maradi was 58.30 (13.10, 103.50) t/ha. There were no differences in the mean carbon stock between the two cities across the LULC (T-Value = −1.36, p = 0.22, df = 7).

Table 2
Mean carbon stock at confidence interval (CI) across the LULC in two cities.

Cities	LULC	Mean Carbon stock (t/ha)
Niamey	Administrative areas	27.84 (13.07, 42.61)
Maradi		27.84 (18.39, 37.29)
Niamey	Commercial areas	64.60 (42.0, 87.1)
Maradi		68.60 (4.0, 133.2)
Niamey	Forested areas	18.98 (7.20, 30.76)
Maradi		15.71 (6.61, 24.81)
Niamey	Residential areas	18.36 (8.79, 27.93)
Maradi		138.10 (1.9, 274.2)
Niamey	Roads	43.24 (33.58, 52.91)
Maradi		107. 40 (55.0, 159.8)
Niamey	Schools	31.77 (18.24, 45.31)
Maradi		41.56 (25.09, 58.02)
Niamey	Peri-urban forests	16.65 (8.07, 25.23)
Maradi		8.90 (5.25, 12.53)
Niamey	P-values	0.00
Maradi		0.01

Table 3
Carbon emission factors from the conversion of peri-urban forests to urban forests.

LULC types	Cities	Carbon emission factors (EFs) (t/ha)
Residential areas	Niamey	−1.71
	Maradi	−129.21
Schools	Niamey	−15.12
	Maradi	−32.67
Commercial areas	Niamey	−47.95
	Maradi	−59.71
Roads	Niamey	−26.59
	Maradi	−98.51
Administrative areas	Niamey	−11.19
	Maradi	−18.95

Table 4
List of trees and shrubs species documented in Niamey and Maradi. The values indicate the species average aboveground biomass (AGB) (t/ha).

Species	Maradi	Niamey
Acacia holosericea A. Cunn. ex G. Don	0.00012	0.0007
Acacia senegal (L.) Willd.	0.0079	0.0426
Adansonia digitata L.	0.2894	0.1609
Adenium obesum (Forssk.) Roem.	0.0074	
Albizia chevalieri Harms	0.0048	
Albizia lebbeck (L.) Benth.	0.5832	0.0697
Anacardium occidentale L.		0.0072
Annona muricata L.	0.0008	
Annona senegalensis Pers.	0.0032	0.0002
Annona squamosa L.	0.0313	0.0000
Anogeissus leiocarpus (DC.) Guill. & Perr.	0.0000	0.0032
Azadirachta indica A. Juss.	28.7274	19.0648
Balanites aegyptiaca (L.) Del.	1.3327	2.4758
Bambusa vulgaris Schrad. Ex J.C.Wendl.		0.0333
Bauhinia monandra Kurz	0.0003	
Bauhinia rufescens Lam.	0.1044	0.0043
Blighia sapida Koenig	0.0264	0.0178
Borassus aethiopum Mart.	0.1071	0.0959
Boscia angustifolia A. Rich.		0.0084
Boscia salicifolia Oliv.	0.0552	
Boswellia dalzielii Hutch.	0.0014	
Boswellia papyrifera (Del.) A. Rich.	0.0096	
Bougainvillea spectabilis Willd	0.0033	
Calliandra brevipes Benth.	0.0003	
Calotropis procera (Ait.) Ait. f.	0.0071	0.0129
Caesalpinia pulcherrima (L.) Sw.	0.0003	0.0002
Cassia sieberiana DC.		0.0037
Casuariana equisefolia Forst.		0.0107
Ceiba pentandra (L.) Gaertn.	0.5383	0.2279
Citrus grandis (L.) Osbeck	0.0384	0.0008
Citrus limon (L.) Burm. f.	0.1124	0.0067
Citrus reticulata Blanco	0.0092	
Citrus sinensis (L.) Osbeck	0.0162	
Cola cordifolia (Cav.) R. Br.		0.0020
Combretum glutinosum Perr. ex *DC.*	0.0063	0.2957
Combretum nigricans Lepr. ex Guill. et Perr.		0.0264
Commiphora africana (A. Rich.) Engl.	0.0041	
Dalbergia sissoo Roxb.	0.0454	0.1591
Daniellia oliveri (Rolfe) Hutch. & Dalz	0.0015	
Delonix regia (Boj.) Raf.	0.2848	0.0599
Dialium guineense Willd.		0.0650
Diospyros mespiliformis Hochst. ex A. Rich.	0.0765	0.0226
Duranta repens Linn.		0.0003
Eucalyptus camaldulensis Dehnh.	0.7946	0.8041
Euphorbia balsamifera Ait.	0.0086	0.0033
Euphorbia kamerunica Pax	0.0182	
Faidherbia albida (Del.) Chev.	2.6053	6.4268
Ficus benjamina L.		0.0635
Ficus elastica Roxb. ex Hornem.	0.0015	
Ficus platyphylla Del.	0.0533	0.0800
Ficus sycomorus ssp. gnaphalocarpa (Miq.) C.C. Berg	0.1997	0.0175
Ficus thonningii Blume	0.0500	0.0224
Gardenia erubescens Stapf & Hutch.	0.0002	
Gliricidia sepium (Jacq.) Walp.	0.0049	0.0120
Gmelina arborea Roxb.	0.3401	0.1724
Grewia bicolor Juss.	0.0000	0.0042
Guiera senegalensis J.F. Gmel.	0.0046	
Hura crepitans L.	0.0036	
Hyphaene thebaica (L.) Mart.	0.0831	0.1226
Jatropha curcas L.	0.0006	0.0001
Jatropha gossypiifolia L.	0.0001	
Khaya senegalensis (Desr.) A. Juss	2.0786	4.9302
Kigelia africana (Lam.) Benth.	0.1398	0.0702
Lannea microcarpa Engl. & K. Krause	0.0418	0.0321
Lawsonia inermis L.	0.0112	0.0007
Leucaena leucocephala (Lam.) de Wit	0.0684	0.0510
Maerua angolensis DC.		0.0081
Maerua crassifolia Forssk.	0.0405	0.0028
Mangifera indica L.	0.7400	0.9367
Melia azedarach L.		0.0117
Mitragyna inermis (Willd.) Kuntze	0.0078	
Moringa oleifera Lam.	0.0071	0.0032
Moringa stenopetala Baker f.	0.0424	0.0246

(*continued on next page*)

At LULC level, commercial areas had the highest mean carbon stock of 64.60 t/ha in Niamey (Table 2). The lowest average carbon stocks were observed in forested area, peri-urban forests and residential areas in Niamey (Table 2). A reverse trend was observed in Maradi, where residential areas (138.10 t/C/ha) and roads (107.40 t/C/ha) had the highest mean carbon stock (Table 2). The lowest mean carbon stocks were observed in forested areas and peri-urban forests in Maradi (Table 2).

3.3. Carbon emission factors from the conversion of agroforestry parklands

Table 3 presents the carbon emission factors from the conversion of peri-urban forests to urban forests in Niamey and Maradi. There were no significant differences in the mean values of carbon emission factor from the conversion of the peri-urban forests across the LULC types in Niamey (F-stats = 4.83, df = 1, p = 0.06). While there was significant difference the in mean carbon emission factor in Maradi (F-stats = 9.55, df = 1, p = 0.00). The mean carbon emission factor and standard error in Maradi (67.81 ± 20.5 t/ha) was higher than the mean carbon emission factor in Niamey (20.51 ± 7.93) (F-stats = 9.99, df = 1, p = 0.01). The conversion of peri-urban forests to the residential urban forests in Maradi leads to the highest carbon gain (129.21 t/ha) while the conversion to commercial urban forests leads to the highest carbon gain (47.95 t/ha) in Niamey. The conversion of peri-urban forests to the residential urban forests in Niamey shows small values of carbon emission factors (Table 3). While the lowest was observed from the conversion of peri-urban forests to the administrative urban forests in Maradi (Table 3).

4. Discussion

The results show variation in density of carbon stocks across LULC types in the two cities. This is an observation which is shared by Hutyra, Byungman, and Marina (2011), Nero and Callo-concha (2018) and Raciti, Hutyra, Rao, and Finzi (2012) who reported that urban forest carbon stocks were associated with LULC types in Seattle, Boston and Kumasi respectively. These variations in carbon stocks across LULC types may be explained by the need to balance the presence of trees and forests for specific purposes in the various LULC types with the desire to reserve enough space for urban infrastructure and human activities (McKinney, 2002). It may also reflect the age of the various urban forests whereby LULC types typical of older parts of the city such as commercial areas may hold more carbon stocks than those associated with newly developed areas. Also for safety reasons certain LULC e.g. administrative areas may not be compatible with the retention of large trees which store more carbon and will therefore naturally differ in carbon stocks from areas where large trees are allowed to grow. The Table 4 presents the total woody species AGB recorded in the urban forests in Niamey and Maradi.

Between the two cities, no significant differences were found in carbon stocks held in urban forests. This was notwithstanding the fact

Table 4 (*continued*)

Species	Maradi	Niamey
Neocarya macrophylla (Sabine) Prance	0.0060	
Newbouldia laevis (P. Beauv.) Seem.	0.0137	
Parkia biglobosa (Jacq.) R. Br. ex G. Don	0.0277	0.0295
Parkinsonia aculeata L.	0.0015	0.0009
Phoenix dactylifera L.	0.0560	
Phoenix reclinata Jacq.	0.0513	
Piliostigma reticulatum (DC.) Hochst.	0.1260	0.0284
Pithecellobium dulce (Roxb.) Benth.	0.0701	0.0037
Plumeria rubra L.	0.0131	0.0088
Polyalthia longifolia. Sonn	0.0199	0.0003
*Prosopis africana (*Guill. & Perr.) Taub.	0.7081	
Prosopis juliflora (Sw.) DC.	0.7420	0.3231
Psidium guajava L.	0.0156	0.0012
Punica granatum L.	0.0049	0.0011
Sclerocarya birrea (A. Rich.) Hochst.	0.2365	0.1153
Senna siamea (Lam.) Irwin & Barneby	0.5093	0.3633
Senna singueana (Del.) Lock	0.0356	
Sterculia setigera Del.	0.0002	
Syzygium guineense (Willd.) DC.	0.0285	0.0498
Syzygium malaccense (L.) Merr. & L.M.Perry		0.0035
Tamarindus indica L.	0.0966	0.0403
Tectona grandis L. f.		0.0012
Terminalia catappa L.	0.0910	0.0106
Terminalia mantaly H. Perrier	3.2394	1.9058
Thevetia neriifolia Juss.	0.0029	0.0000
Vachellia nilotica subsp. Nilotica	0.5138	0.1373
Vachellia seyal (Delile) P.J.H.Hurter	0.0048	0.1520
Vachellia sieberiana (DC.) Kyal. & Boatwr.		0.0003
Vachellia tortilis(Forssk.) Galasso & Banfi	0.2095	0.4736
Vitellaria paradoxa Gaertn. f.	0.0066	0.0058
Vitex doniana Sweet	0.0203	0.0849
Vitex simplicifolia Oliv.	0.0407	0.0004
Ziziphus mauritiana Lam.	0.1354	0.0517
Ziziphus mucronata Willd		0.0636
Ziziphus spina-christi (L.) Desf.	0.4683	

that Maradi had 21% more stems/ha in its urban forests than Niamey. A plausible explanation to account for the lack of difference in carbon stocks may lie in the differences in the tree sizes between the two cities with Niamey being associated with larger trees than Maradi. Being the capital city Niamey may have a longer history of urban forests and therefore older and larger trees than Maradi.

The results show that Niamey and Maradi cities contain considerable amounts of aboveground biomass in their urban forests which confirmed the findings of (Myeong, Nowak, & Duggin, 2006) who concluded that cities are important areas of aboveground biomass. These results are also indication of the fact that cities in the Sahel region may be important areas of tree biomass, and for that matter carbon stocks. The values in this study are higher than those recorded in the Sudano-Sahelian Woodlands in Burkina Faso (Karlson et al., 2015) despite the higher annual rainfall received in the Sudano-Sahelian zone. Many factors could account for this but the differences in the attention and protection given to urban forests in the two countries may probably best explain why carbon stocks are higher in the present study. This study found an average carbon stock of 31.63 t/C/ha in Niamey and 58.30 t/C/ha in Maradi. Nowak and Crane (2002) found out that the national average urban forest carbon storage density is to be 25.1 t/C/ha in the urban forests of 10 cities in USA. Chen (2015) found also an average carbon stock of 21.34 t/ha for 35 major Chinese cities. The mean carbon stock found in Niamey and Maradi appear greater than those reported by these authors. May be methodological differences may explain the apparent high levels of carbon stocks in the present study. Nonetheless, it may be reasoned that the hot dry climate of the Sahel zone may have created a culture of tree planting for shade making sahelian cities unique in their urban forest management. Trees of diameter greater than 40 cm held the highest percentage of AGB in the urban forests in both cities. The study confirmed studies which show that tree classes with large diameters lead in AGB in temperate forests (Karlson et al., 2015), miombo woodlands (Kuyah, Sileshi, Njoloma, Mng, & Neufeldt, 2014) and urban forests in Kumasi (Nero & Callo-concha, 2018). These results demonstrate the importance of tree size in carbon conservation in both natural and man-made forests. In protected areas in Kenya, old large trees were found to store a huge amounts of biomass and their presence made a whole lot of difference in carbon stocks (Willcock et al., 2016). This implies that in planting and nurturing trees for carbon sequestration and storage, an important selection criterion could be the species maximum attainable size. It must, however, be borne in mind that due to the potential hazard posed by large trees to urban infrastructure, property and people (Roy, Byrne, & Pickering, 2012) their use in urban forests may be restricted.

Looking at how carbon storage is partitioned between exotic and indigenous species in this study revealed that, exotic species contribute about 65% of the total carbon stocks in the two cities. The results show the important role exotic species play in carbon storage in the cities. This may be a reflection of the popularity of exotics in urban forests due to their aesthetic appeal and ease of establishment (McKinney, 2002). The results also demonstrate the role of urbanization in species selection for planting and its implications for native species conservation. Probably a conscious effort to target native species for urban forest development could provide a dual benefit of carbon and native species conservation that is at present lacking in the two cities. In Agartala, Majumdar and Selvan (2018) reported that native species dominated the carbon stocks of urban and peri-urban forests. This contradicts these results and show that with conscious effort native species can be made to play a more significant role in urban forest carbon storage. The results also show that conversion of peri-urban forests into urban forest in any of the LULC types is associated with carbon gain. This implies that although urbanization has negative impacts on forest biomass as commonly known (Ren et al., 2012; Seto et al., 2012) in the case of sahelian cities, city expansion may lead to less biomass and carbon losses if a little more effort can be made in urban forest development.

5. Conclusions

The study examined the importance and variations of above ground biomass in urban forests and its associated carbon stocks across land use and land cover types in two important sahelian cities in West Africa. Among LULC types, carbon stocks in urban forests vary significantly with forested areas playing a lesser role in carbon storage. The two cities did not differ in their mean carbon stocks despite a higher number of tree stems in Maradi. Large trees (> 40 cm DBH) were found to be more important for carbon stocks than others. Conversion of peri-urban forests into urban forests in any of the LULC types was associated with carbon gain suggesting urban forests may have a significant role to play in climate change mitigation projects for sustainable urban development.

Acknowledgments

My sincere appreciation goes to the German Federal Ministry of Education and Research (BMBF) and West African Science Centre on Climate Change and Adapted Land Use (WASCAL, www.wascal.org) for providing the scholarship and financial support for this research.

References

Arroyo-Rodríguez, V., Melo, F. P. L., Martínez-Ramos, M., Bongers, F., Chazdon, R. L., Meave, J. A., et al. (2017). Multiple successional pathways in human-modified tropical landscapes: New insights from forest succession, forest fragmentation and landscape ecology research. *Biological Reviews, 92*, 326–340. https://doi.org/10.1111/brv.12231.

Brown, S. (1997). *Estimating biomass and biomass change of tropical forests: A primer (FAO Forestry Paper-134). FAO For. Pap.* https://doi.org/10.1016/j.tvjl.2012.04.018.

Cairns, M. A., Helmer, E. H., & Baumgardner, G. A. (1997). Root biomass allocation in the world's upland forests. *Oecologia, 111*, 1–11. https://doi.org/10.1007/s004420050201.

Chave, J., Mechain, M. R., Burquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B., et al. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global, 20*, 3177–3190. https://doi.org/10.1111/gcb.12629.

Chen, W. Y. (2015). The role of urban green infrastructure in offsetting carbon emissions in 35 major Chinese cities: A nationwide estimate. *Cities, 44*, 112–120. https://doi.org/10.1016/j.cities.2015.01.005.

CNEDD (2016). NiameyTroisieme Communication Nationale a la Conference des Parties de la Convention Cadre des Nations Unies sur les Changements Climatiques2016. *Troisieme Communication Nationale a la Conference des Parties de la Convention Cadre des Nations Unies sur les Changements Climatiques,* 1–157. https://unfccc.int/sites/default/files/resource/nernc3_0.pdf.

Davies, Z. G., Edmondson, J. L., Heinemeyer, A., Leake, J. R., & Gaston, K. J. (2011). Mapping an urban ecosystem service: Quantifying above-ground carbon storage at a city-wide scale. *The Journal of Applied Ecology, 48*, 1125–1134. https://doi.org/10.1111/j.1365-2664.2011.02021.x.

Dorney, J. R., Guntenspergen, G. R., Keough, J. R., & Stearns, F. (1984). Composition and structure of an urban woody plant community. *Journal of Urban Ecology, 8*, 69–90. https://doi.org/10.1016/0304-4009(84)90007-X.

FAO (2016). Guidelines on urban and peri-urban forestry. In F. Salbitano, S. Borelli, M. Conigliaro, & Y. Chen (Eds.). *FAO Forestry Paper No. 178*Rome: Food and Agriculture Organization of the United Nationswww.fao.org/3/a-i6210e.pdf.

Henry, M., Bombelli, A., Trotta, C., Alessandrini, A., Birigazzi, L., Sola, G., et al. (2013). GlobAllomeTree: International platform for tree allometric equations to support volume, biomass and carbon assessment. *iForest, 6*, 326–330. https://doi.org/10.3832/ifor0901-006.

Hope, D., Gries, C., Zhu, W., Fagan, W. F., Redman, C. L., Grimm, N. B., et al. (2003). Socioeconomics drive urban plant diversity. In: *Proceedings of the National Academy of Sciences of the United States of America, 100*, 8788–8792. https://doi.org/10.1073/pnas.1537557100.

Hutyra, L. R., Byungman, Y., & Marina, A. (2011). Terrestrial carbon stocks across a gradient of urbanization: A study of the Seattle, WA region. *Global Change Biology, 17*, 783–797. https://doi.org/10.1111/j.1365-2486.2010.02238.x.

Institut National de la Statistique du Niger (INS) (2016). *Le Niger en Chiffres 2016.* 1–84. http://www.stat-niger.org/statistique/file/Affiches_Depliants/NigerEnChiffres2016.pdf.

IPCC (2006a). *Volume 4: Agriculture, forestry and other land use. 2006 IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES, Hayama, Japan.* Hayama, Japan: IGES.

IPCC (2006b). *ANNEX 2: Summary of equations: IPCC guidelines for national greenhouse gas inventories.* 1–34. www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

Jin, L., Whitehead, P. G., Appeaning Addo, K., Amisigo, B., Macadam, I., Janes, T., et al. (2018). Modeling future flows of the Volta River system: Impacts of climate change and socio-economic changes. *The Science of the Total Environment, 637–638*, 1069–1080. https://doi.org/10.1016/j.scitotenv.2018.04.350.

Karlson, M., Ostwald, M., Reese, H., Sanou, J., Tankoano, B., & Mattsson, E. (2015). Mapping tree canopy cover and aboveground biomass in Sudano-Sahelian woodlands using Landsat 8 and random forest. *Remote Sensing, 7*, 10017–10041. https://doi.org/10.3390/rs70810017.

Koala, J., Sawadogo, L., Savadogo, P., & Aynekulu, E. (2017). Allometric equations for below-ground biomass of four key woody species in West African savanna-woodlands. *Silva Fennica, 51*, 1–15. https://doi.org/10.14214/sf.1631.

Konijnendijk, C. C., Sadio, S., Randrup, T. B., & Schipperijn, J. (2004). Urban and peri-urban forestry in a development context – Strategy and implementation. *Journal of Arboriculture, 30*, 269.

Kuyah, S., Sileshi, G. W., Njoloma, J., Mng, S., & Neufeldt, H. (2014). Estimating aboveground tree biomass in three different miombo woodlands and associated land use systems in Malawi. *Biomass & Bioenergy, 66*, 214–222. https://doi.org/10.1016/j.biombioe.2014.02.005.

Majumdar, T., & Selvan, T. (2018). Carbon storage in trees of urban and peri-urban forests of Agartala, Tripura. *Journal of Advanced Research in Applied Sciences, 5*, 715–731. http://iaetsdjaras.org/gallery/38-february-528.pdf.

McKinney, M. L. (2002). Urbanization, biodiversity, and conservation. *Bioscience, 52*, 883–890. https://doi.org/10.1641/0006-3568(2002)052[0883:UBAC]2.0.CO;2.

Mitchell, M. G. E., Johansen, K., Maron, M., McAlpine, C. A., Wu, D., & Rhodes, J. R. (2018). Identification of fine scale and landscape scale drivers of urban aboveground carbon stocks using high-resolution modeling and mapping. *The Science of the Total Environment, 622–623*, 57–70. https://doi.org/10.1016/j.scitotenv.2017.11.255.

Myeong, S., Nowak, D. J., & Duggin, M. J. (2006). A temporal analysis of urban forest carbon storage using remote sensing. *Remote Sensing of Environment, 101*, 277–282. https://doi.org/10.1016/j.rse.2005.12.001.

Nadrowski, K., Wirth, C., & Scherer-Lorenzen, M. (2010). Is forest diversity driving ecosystem function and service? *Current Opinion in Environmental Sustainability, 2*, 75–79. https://doi.org/10.1016/j.cosust.2010.02.003.

Nero, B. F., & Callo-concha, D. (2018). Structure, diversity, and carbon stocks of the tree community of Kumasi, Ghana. *Forests, 9*, 1–17. https://doi.org/10.3390/f9090519.

Nowak, D. J., & Crane, D. E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution, 116*, 381–389. https://doi.org/10.1016/S0269-7491(01)00214-7.

Nowak, D. J., Green, E. J., Hoehn, R. E., & Lapoint, E. (2013). Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution, 178*, 229–236. https://doi.org/10.1016/j.envpol.2013.03.019.

Nowak, D. J., Hoehn, R. E., Bodine, A. R., Greenfield, E. J., & Neil-dunne, J. O. (2016). Urban forest structure, ecosystem services and change in Syracuse, NY. *Urban Ecosystems, 19*, 1455–1477. https://doi.org/10.1007/s11252-013-0326-z.

Raciti, S. M., Hutyra, L., Rao, P., & Finzi, A. C. (2012). Soil and vegetation carbon in urban ecosystems: The importance of urban definition and scale. *Ecological Applications, 22*, 1015–1035. https://doi.org/10.1890/11-1250.1.

Ren, Y., Yan, J., Wei, X., Wang, Y., Yang, Y., Hua, L., et al. (2012). Effects of rapid urban sprawl on urban forest carbon stocks: Integrating remotely sensed, GIS and forest inventory data. *Journal of Environmental Management, 113*, 447–455. https://doi.org/10.1016/j.jenvman.2012.09.011.

Roy, S., Byrne, J., & Pickering, C. (2012). A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban Forestry & Urban Greening, 11*, 351–363. https://doi.org/10.1016/j.ufug.2012.06.006.

Saadou, M. (1990). *La végétation des milieux drainés nigériens à l'est du fleuve Niger. Thèse de doctorat.* Niger: Université Niamey 393 p.

Sanders, R. A. (1984). Some determinants of urban forest structure. *Journal of Urban Ecology, 8* 13.27.

Seto, K. C., & Shepherd, J. (2009). Global urban land-use trends and climate impacts. *Current Opinion in Environmental Sustainability, 1*, 89–95. https://doi.org/10.1016/j.cosust.2009.07.012.

Seto, K. C., Guneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. In: *Proceedings of the National Academy of Sciences of the United States of America, 109*, 16083–16088. https://doi.org/10.1073/pnas.1211658109.

Tang, Y., Chen, A., & Zhao, S. (2016). Carbon storage and sequestration of urban street trees in Beijing, China. *Frontiers in Ecology and Evolution,* 1–11. https://doi.org/10.3389/fevo.2016.00053.

Thiombiano, A. R., Glele KaKai, P., Bayen, J. I. B. A., & Mahamane, A. (2016). *Méthodes de collecte et d'analyse des données de terrain pour l'évaluation et le suivi de la végétation en Afrique Methods for sampling and analysis of field data to evaluate and monitor vegetation in Africa, Annales des sciences agronomiques.* FSA/UAC.

UN (2017). *Goal 11-sustaimnable cities and communities.* [WWW Document]. URL https://www.unenvironment.org/explore-topics/sustainable-development-goals/why-dosustainable-development-goals-matter/goal-11 (Accessed 13 June 2018).

United Nations (2018). *Revision of world urbanization prospects.* [WWW Document]. URL https://www.un.org/development/desa/en/news/population/2018-revision-of-worldurbanization-prospects.html (Accessed 13 June 2018).

Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., et al. (2002). Ecological responses to recent climate change. *Nature, 416*, 389–395. https://doi.org/10.1038/416389a.

Wang, H., Marshall, C. W., Cheng, M., Xu, H., Li, H., Yang, X., et al. (2017). Changes in land use driven by urbanization impact nitrogen cycling and the microbial community composition in soils. *Scientific Reports, 7*, 1–12. https://doi.org/10.1038/srep44049.

Weissert, L. F., Salmond, J. A., & Schwendenmann, L. (2014). A review of the current progress in quantifying the potential of urban forests to mitigate urban CO_2 emissions. *Urban Climate, 8*, 100–125. https://doi.org/10.1016/j.uclim.2014.01.002.

Wilkes, P., Disney, M., Vicari, M. B., Calders, K., & Burt, A. (2018). Estimating urban above ground biomass with multi-scale LiDAR. *Carbon Balance and Management, 13*, 1–20. https://doi.org/10.1186/s13021-018-0098-0.

Willcock, S., Phillips, O. L., Platts, P. J., Swetnam, R. D., Balmford, A., Burgess, N. D., et al. (2016). Land cover change and carbon emissions over 100 years in an African biodiversity hotspot. *Global Change Biology, 22*, 2787–2800. https://doi.org/10.1111/gcb.13218.

Zanne, A. E., Lopez-Gonzalez, G., Coomes, D. A., Ilic, J., Jansen, S., Lewis, S. L., et al. (2009). *Global wood density database.* [WWW Document]. URL http://hdl.handle.net/10255/dryad.235 (Accessed 10 July 2018).