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Richness of Forest Stands and Atmospheric Carbon Dioxide Storage in Urban Institutional Lands of Bukavu, D.R. Congo

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Abstract

Improving the urban environmental quality relies mainly on the increasing of urban forests capacity to store carbon dioxide. This study assesses the floristic diversity of urban institutional lands in Bukavu and their potential to reduce atmospheric CO_2. An exhaustive inventory over three sites (Collège Alfajiri, Cathédrale Notre-Dame de la Paix and Institut Supérieur Pédagogique) of Bukavu led to the identification of 1,113 trees of which the diameter at breast height (1.30 m) ranged from 4.9 to 161 cm. Results reveal a floristic diversity made up of 4 families of conifers with 4 species and 14 of broadleaves with 21 species. Average densities were of 54 trees ha^{-1} and 5.21 m^2 ha^{-1} of basal area. Urban-based allometric equations used yielded up to 312.8 tons of carbon stored in trees aboveground biomass equivalent to 1,147.9 tons of CO_2 reduced from the atmosphere over the three sites. The rate of carbon storage reaches 15.1 tons ha^{-1}. Thus, trees of the three institutional sites in Bukavu play an important role in reducing atmospheric CO_2 and contribute, thereby, to mitigate global climate change effects. Given the current environmental challenge associated with high population growth rate in cities, the urban forest ecosystem in DRC requires to be extended and further investigation.

Key Words: aboveground biomass, allometric equations, broadleaves/conifers, carbon dioxide, urban forest

Introduction

Cities represent an environmental challenge due to the high levels of air pollutants but also to the overwhelming temperatures (Vergriette and Labrecque 2007), and multiple artificial surfaces which expose them exceedingly to the consequences of global climate change (Nowak and Crane 2002). Fortunately the forest vegetation particularly plays a key role in improving the quality of the urban environment (Yang et al. 2005; Nowak et al. 2008). In fact, trees shade surfaces and reflect sunlight to reduce temperatures; cool local air through evapotranspiration; supply citizens with oxygen, reduce air pollutants by capturing particulate matters, absorbing gaseous pollutants like sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3) (Peck et al. 1999; Yang et al. 2005; Bell and Wheeler 2006; Lessard and Boulfroy 2007).

In addition, urban trees offer a double benefit in reducing atmospheric CO_2. First, they directly store and sequester atmospheric carbon while they grow. Second, properly located around buildings, trees in urban areas also conserve energy by reducing the demand for heating and air conditioning, thereby reducing emissions associated with electricity power production (Nowak 1993; Nowak 1994a;

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McPherson 1998; Brack 2002). Thus, urban forest management programs for improving the quality of the urban environment are, in many ways, necessary.

However, in the Democratic Republic of Congo (DRC), data on urban trees or forest ecosystems remain rather scanty, yet they represent useful information to undertake management of the urban forest cover and could serve as a tool basis with which to plan actions for enhancing and maintaining the ligneous potential in overpopulated cities.

Therefore, there is a dearth of documented information on numerous benefits provided by the vegetation, especially the amount of carbon sequestered by trees in urban areas of DRC. Yet, it would help to assess the contribution of cities in mitigating climate change effects and, hence, serve to claim the offset in the international system of carbon credits. The improvement of carbon sinks as of many other tree functions faces, in cities of DRC, the constraint due to lack of baseline research in urban forestry field. Then, the general lack of data on trees in cities arouses the interest to undertake, nowadays, studies on the urban forest ecosystem of DRC including the appraisal of its ability to store atmospheric carbon dioxide.

Thus, this study aims to (1) assess the structure of trees including species composition identification, tree size and density in three of institutional sites in Bukavu and (2) to determine how the amount of carbon stored from the atmosphere does vary within these sites.

Materials and Methods

Study area

The study was conducted in Bukavu, an eastern city of the Democratic Republic of Congo being the capital of the South-Kivu province. Administratively, it covers 60 km^2 and is composed of four municipalities, which are Ibanda, Kadutu, Bagira and Kasha making up to 1 million inhabitants in 2014.

Located at about 1,600 m on the southwestern shore of the Lake Kivu, Bukavu lies between 2° 26' and 2° 33' south and 28° 49' and 28° 53' East (Anonymous 2012). The land is very uneven and increases gradually as one moves away from the Lake. The climate is humid temperate with the altitude. The rainfall ranges from 1,500 to 2,000 mm per year while the annual average temperature is around 19°C. The two seasons in Bukavu are unequally distributed over the year; the dry one is spread over 3 months from June to September, while the rainy season covers the remaining 9 months. The soil of Bukavu, of volcanic type, relatively fertile, clayey and permeable, belongs entirely to the group of reddish clay soils (Anonymous 2005; Anonymous 2012; Polepole 2007).

Study sites

For selecting institutional sites in which this study was carried out, the physical characteristics of the sites, their location and the accessibility for data collection were the most important criteria. Thus, three public institutional sites were selected in the city of Bukavu, and identified as S-ISP for *Institut Supérieur Pédagogique de Bukavu*, S-CA for *Collège Alfajiri* and S-ND for *Cathédrale Notre-Dame de la Paix*. Diverse in their location in the town landscape, in land use characteristics as well as in their property status as being a church, a secondary and a higher educational lands, these sites constitute a sizeable and reliable sample for such investigation.

Materials

Three types of materials used comprised of biological ones consisting of trees on which measurements were taken, and the various key tools used for data collection on the ground among which a Global Positioning System (Garmin™ GPS) and a diameter tape of 6.5 m. The third category consisted of tools for data processing notably, Microsoft Excel software and the allometric equations as well.

Tree inventory

All trees in the three institutional sites selected in Bukavu were inventoried and thereafter subjected to species identification, diameter measurements, site area calculation and tree coordinates determination. The area determination of each of the three study sites was conducted in activating the GPS option related to 'area calculation' and turning around the considered site. Then, the GPS served for locating each of the trees, using three variables which are latitude, longitude and elevation above sea level. The identification of some species was facilitated by thereon pasted labels with scientific names and botanical families of trees existing within the S-ISP. For all species, the expertise of botanists was secured for identification.

The diameter at breast height (DBH) at 1.30 m was measured on all trees inventoried. In addition, information on the morphological structure of each tree was noted.

Data analysis

Results from angiosperms and gymnosperms were separated during data processing. However, gymnosperms are often designed as conifers because all gymnosperms trees inventoried in Bukavu belong to the coniferous group. All the same, angiosperms are designed as broadleaves or hardwoods.

Tree size distribution

The structure of trees diameter is determined to characterize the size distribution of trees in order to assess the intensity of the planting activity in recent years and their potential for CO_2 sequestration. Thus, nine diameter classes of 10-cm interval were defined using Sturge's formula : Number of classes = 1 + 3.3 log n; with n being sample size.

Tree density calculation

To express the tree cover within chosen institutional sites, the density was calculated in terms of (a) number of trees per site area as well as of (b) basal stem area expressing the percentage covered by tree canopies over the ground area they occupy, as follows:

(a) *Density* (N/ha) = *Number of trees of all species/Site area* (ha)

(b) $Basal\ area\ (m^2/ha) = \sum_{i=1}^{n} \pi \frac{Di^2}{4}(m^2)/Site\ area(ha)$

where i is an integer varying from 1 to n stems

Di diameter at breast height (1.30 m) for i stem

Carbon stock estimates

Current allometric equations were used to calculate trees carbon storage. They are from 26 open-grown trees equations used in the Tree Carbon Calculator (CTCC) and described as typical of urban areas (CFUR 2008; Bruyat 2011; Aguaron and McPherson 2011). Proposed by the Center for Urban Forest Research (CUFR 2008), a United States research laboratory specialized in urban forestry, these equations compute aboveground volume of trees based on their DBH. However, specific equations for some of surveyed species in the landscape of Bukavu were not found. In such cases, allometric equations of trees belonging to the same genus were used; otherwise generic equations of conifers and broadleaves were applied. Table 1 lists different specific and generic equations used in this study. Thus, to determine the total carbon stored, the dry weight biomass was first calculated.

Dry weight biomass calculation

Generic allometric formulas for broadleaves and conifers (Table 1) served in calculating directly the fresh weight biomass of trees. However, individual equations of Table 1 computed the green volume of trees. In both cases, conversion factors were used to derive the dry weight biomass.

Thus, for specific equations, conversion factors in the

Table 1. Individual and generic allometric equations used*

DBH only			DW Density for Vol. to DW conversion
Species	DBH Range (cm)	Volume (m^3)	(kg/m^3)
Acacia longifolia	15.0-57.2	$0.0283168466(0.048490*(dbh/2.54)^{2.347250})$	630
Cupressus macrocarpa	15.7-146.6	$0.0283168466(0.035598*(dbh/2.54)^{2.495263})$	460
Eucalyptus globulus	15.5-130	$0.0283168466(0.055113*(dbh/2.54)^{2.436970})$	620
Jacaranda mimosifolia	17.3-59.7	$0.0283168466(0.036147*(dbh/2.54)^{2.486248})$	380
Pinus radiata	16.8-105.4	$0.0283168466(0.019874*(dbh/2.54)^{2.66079})$	440
General Broadleaf	6.4-136.7	0.280285*(dbh cm) ^ 2.310647	Multiply FW by 0.56
General Conifer	6.4-136.7	0.05654*(dbh cm) ^ 2.580671	Multiply FW by 0.48

*Source: Center for Urban Forest Research (2008); Bruyat (2011).

column 'DW density for volume to DW conversion' of Table 1 allow to move from volume to dry weight biomass as follows:

*Dry weight biomass (kg)=Volume (m^3)*DW density*
DW density is dry weight density expressed in kg/m^3

However, generic equations computing the fresh weight (FW) biomass were multiplied by the conversion factors of 0.48 and 0.56 to obtain dry weight biomass respectively for conifers and broadleaves.

Carbon stock and CO_2 calculation

Dry weight biomass of trees was converted into total carbon stock by multiplying its value by 0.5 according to Nowak et al. (2008) and Nowak and Crane (2002). To obtain the amount of atmospheric CO_2, values of carbon stock were multiplied by 3.67, the molecular weight of carbon dioxide, according to McPherson (1998). Then data of carbon dioxide stock were reported in metric tons by multiplying their values expressed in kilograms by 0.001.

Error estimate

Equations of Table 1 were designed for being used with a DBH at 4.5 ft (1.37 m). But, as diameters used in this study were measured at 1.30 m, volumes and biomass calculated tend to be overestimated. However, given that such overestimation accounted for less than 1% (Bruyat 2011),

Table 2. Distribution of trees in institutional sites by species and family

	Family	Species	Number of trees per institutional site			Total
			S-ND	S-ISP	S-CA	
Conifers	*Araucariaceae*	*Araucaria araucania*	0	1	0	1
	Cupressaceae	*Cupressus lusitanica*	74	5	41	120
	Pinaceae	*Pinus patula*	31	0	0	31
	Podocarpaceae	*Podocarpus usambarensis*	16	2	5	23
		Total conifers	121	8	46	175
Broadleaves	*Anacardiaceae*	*Mangifera indica*	0	2	0	2
	Agavaceae	*Dracaena steudneri*	0	0	1	1
	Annonaceae	*Annona reticulata*	0	1	1	2
	Apocynaceae	*Plumeria alba*	0	2	0	2
	Asteraceae	*Vernonia amygdalina*	0	0	3	3
	Bignoniaceae	*Jacaranda mimosifolia*	0	19	111	130
		Markhamia lutea	25	3	52	80
		Spathodea campanulata	5	3	17	25
	Combretaceae	*Terminalia chebula*	37	14	0	51
	Euphorbiaceae	*Euphorbia candelabrum*	0	3	0	3
		Euphorbia tirucalli	0	1	0	1
	Fabaceae	*Acacia spp*	0	45	35	80
		Albizia lebbeck	0	6	0	6
		Albizia gummifera	0	0	55	55
		Leucaena leucocephala	0	2	9	11
	Lauraceae	*Persea americana*	2	4	2	8
	Meliaceae	*Cedrela serrata*	28	43	13	84
		Melia azedarach	23	2	14	39
	Moraceae	*Ficus exasperata*	0	0	11	11
	Myrtaceae	*Eucalyptus globulus*	0	232	11	243
	Proteacea	*Grevillea robusta*	8	26	67	101
		Total broadleaves	128	408	402	938
	Total trees		249	416	448	1,113

the gap was found negligible.

Results

Species composition

Trees surveyed in institutional urban sites of Bukavu are of diverse nature and of species belonging to numerous different botanical families within the two classes, angiosperms and gymnosperms. A detailed breakdown of inventoried trees within the three study sites (Table 2) reveals a wide tree diversity characterized by 4 species representing 4 families of conifers and 21 species of 14 families of broadleaves (Table 2). In contrast to scarcity of *Araucaria araucania* which was only found in the ISP site and *Pinus patula* present only in S-ND, other species of gymnosperms (*Cupressus lusitanica* and *Podocarpus usambarensis*) are rather common to all the three sites.

Among identified angiosperms only five species, namely *Markhamia lutea*, *Spathodea campanulata*, *Persea americana*, *Melia azedarach* and *Grevillea robusta* are widespread in the three sites of Bukavu. Nevertheless, only four families i.e. *Bignoniaceae*, *Euphorbiaceae*, *Fabaceae* and *Meliaceae* were represented by more than one species.

Among sites, numbers of broadleaves and conifers trees varied greatly (Table 2). On the overall, stems of broadleaves are by far more numerous than those of conifers. Thus, the ratio broadleaves/conifers are 1.05; 8.74 and 51 respectively in S-ND, S-CA and S-ISP.

Tree distribution into diameter classes

Fig. 1 displays the number of trees per diameter class for both conifers and broadleaves. For conifers, diameter classes of 20-30 cm and 30-40 cm show the highest numbers and are followed by 10-20 cm and 40-50 cm classes. These four diameter classes comprise 85% of all trees surveyed. Specifically, more than 80% of conifers have a DBH between 10 and 50 cm (Fig. 1). Meanwhile, the 10-20 cm up to 40-50 cm diameter classes are the most dominant for broadleaves, making up nearly 84% of total inventoried trees. Thus, it is particularly observed that for each class size, broadleaves remain by far more prevalent than conifers. Irrespective of study sites, the number of trees shows a decreasing pace with increasing diameter girth as from the 10-20 cm class (Fig. 1).

Tree density in institutional lands

Total area calculated of all study sites reaches 20.7 ha of which 11.4 ha belong to *Collège Alfajiri* (S-CA), 2 ha to *Cathédrale Notre-Dame de la Paix* (S-ND) and 7.3 ha to *Institut Supérieur Pédagogique de Bukavu* (S-ISP). These values were useful for estimating tree density in each site as shown in Table 3.

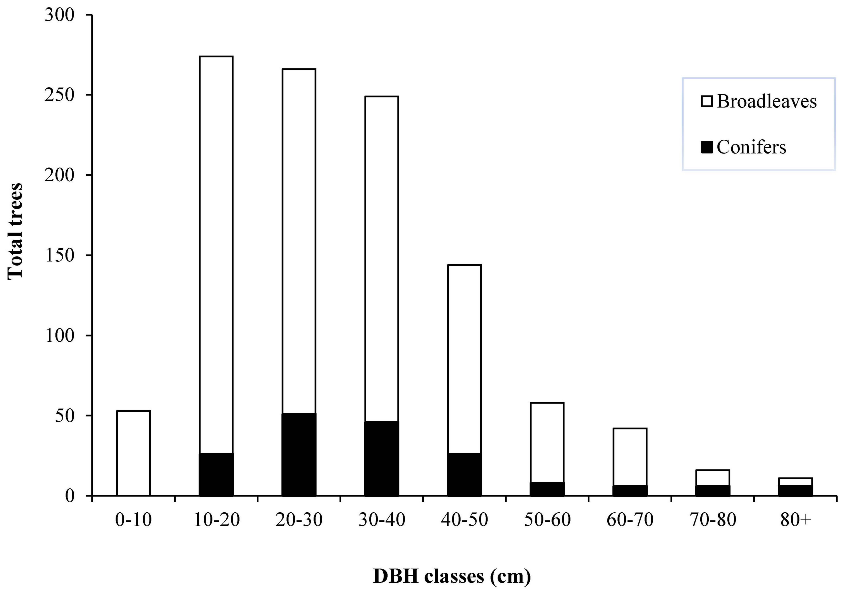

Fig. 1. Distribution of trees into diameter classes, Bukavu (October 2013).

Thus, the tree density both in terms of number per ha as well as of basal area varies widely among species and from one site to another in the city of Bukavu (Table 3).

In terms of number of trees per area, a wide variability prevailed among species to such an extent that it ranged from 0.0 to 31.8 trees ha^{-1}. In the S-ND, with a mean of 125 trees ha^{-1}, the most dominant species are *Cupressus lusitanica* and *Terminalia chebula*. *Eucalyptus globulus* is the species most represented in S-ISP with about 32 trees ha^{-1}, while *Jacaranda mimosifolia* and *Grevillea robusta* are densest in S-CA where the average is of 39 trees ha^{-1}.

The largest basal area up to 12.38 m^2 ha^{-1} is found in the S-ND against half of it in the S-ISP and about 3.6 times lesser in the S-CA. Furthermore, the most dominant species in stems per ha were not necessarily covering the greatest ground area. This situation is shown in Table 4 categorizing species according to the descending order of their relative density. The most abundant species is *Eucalyptus globulus* making up to 21.8% of total trees surveyed on each hectare of institutional site, then follows *Jacaranda mimosifolia* with 11.7% on average over all sites (Table 4). Moreover, beyond the average of 5.21 m^2 ha^{-1} of basal area occupied by trees in institutional lands, 34.93% of this ground area is covered by *Eucalyptus globulus* followed by *Cupressus lusitanica* with 13.6% (Table 4). Besides, species such as *Albizia gummifera*, *Melia azedarach* and *Podocarpus usambarensis* outpace by their percent of basal area others such as *Acacia spp*, *Cedrela serrata* and *Markhamia lutea* that ranked among the seven most abundant species per hectare.

Table 3. Tree density and basal area by species within institutional lands

		Density (trees/ha)				Basal area (m^2/ha)			
Conifers	*Araucaria araucania*	0.0	0.14	0.0	0.05	0.00	0.02	0.00	0.00
	Cupressus lusitanica	37	0.68	3.6	5.80	5.06	0.08	0.35	0.71
	Pinus patula	15.5	00	00	1.50	1.30	0.0	0.0	0.13
	Podocarpus usambarensis	8.0	0.27	0.44	1.11	1.14	0.02	0.24	0.25
Broadleaves	*Albizia gummifera*	0.0	0.0	4.82	2.66	0.00	0.0	0.54	0.30
	Albizia lebbeck	0.0	0.82	0.0	0.29	0.00	0.01	0.0	0.00
	Acacia spp	0.0	6.16	3.07	3.86	0.00	0.1	0.24	0.17
	A. reticulata	0.0	0.14	0.09	0.10	0.00	0.0	0.0	0.00
	Cedrela serrata	14.0	5.89	1.14	4.06	1.17	0.08	0.09	0.19
	Dracaena steudneri	0.0	00	0.09	0.05	0.00	0.0	0.0	0.00
	Eucalyptus globulus	0.0	31.78	0.96	11.74	0.00	4.96	0.13	1.82
	Euphorbia candelabrum	0.0	0.41	0.0	0.14	0.00	0.03	0.0	0.01
	Euphorbia tirucali	0.0	0.14	0.0	0.05	0.00	0.01	0.0	0.00
	Ficus exasperata	0.0	00	0.96	0.53	0.00	0.00	0.25	0.14
	Grevillea robusta	4.0	3.56	5.88	4.88	0.28	0.37	0.4	0.38
	Jacaranda mimosifolia	0.0	2.6	9.74	6.28	0.00	0.08	0.59	0.35
	Leucaena leucocephala	0.0	0.27	0.79	0.53	0.00	0.02	0.19	0.11
	Mangifera indica	0.0	0.27	0.0	0.10	0.00	0.01	0.0	0.00
	Markhamia lutea	12.5	0.41	4.56	3.86	0.38	0.00	0.18	0.13
	Melia azedarach	11.5	0.27	1.23	1.88	2.07	0.00	0.20	0.31
	Persea americana	1.0	0.55	0.18	0.39	0.06	0.10	0.01	0.05
	Plumeria alba	0.0	0.27	0.0	0.10	0.00	0.00	0.00	0.00
	Spathodea campanulata	2.5	0.41	1.49	1.21	0.20	0.02	0.07	0.07
	Terminalia chebula	18.5	1.92	0.0	2.46	0.72	0.02	0.00	0.08
	Vernonia amygdalina	0.0	0.0	0.26	0.14	0.00	0.00	0.01	0.01
	Total	124.5	56.96	39.30	53.77	12.38	5.93	3.49	5.21

Table 4. The most dominant species by percent of density as trees/ha and as basal area

N^0	Tree density		Basal area	
	Species	%	Species	%
1	*Eucalyptus globulus*	21.83	*Eucalyptus globulus*	34.93
2	*Jacaranda mimosifolia*	11.68	*Cupressus lusitanica*	13.63
3	*Cupressus lusitanica*	10.78	*Grevillea robusta*	7.29
4	*Grevillea robusta*	9.07	*Jacaranda mimosifolia*	6.72
5	*Cedrela serrata*	7.55	*Melia azedarach*	5.95
6	*Acacia spp*	7.19	*Albizia gummifera*	5.76
7	*Markhamia lutea*	7.19	*Podocarpus usambarensis*	4.80
8	Other	24.71	Other	20.92
	Total	100.00	Total	100.00

Table 5. Total carbon stored and CO_2 amount by species within urban sites of Bukavu

	Espèces	S-ISP	S-ND	S-CA	Total	
		Carbon (t)	Carbon (t)	Carbon (t)	Carbon (t)	CO_2 (t)
Conifers	*Araucaria araucania*	0.16	0.00	0.00	0.16	0.57
	Cupressus lusitanica	1.20	20.45	7.76	29.40	107.92
	Pinus patula	0.00	3.60	0.00	3.60	13.22
	Podocarpus usambarensis	0.19	4.45	6.50	11.14	40.89
	Total conifers	1.55	28.50	14.26	44.31	162.60
Broadleaves	*Acacia spp*	0.77	0.00	5.83	6.60	24.24
	Albizia gummifera	0.00	0.00	19.61	19.61	71.98
	Albizia lebbeck	0.08	0.00	0.00	0.08	0.31
	A. reticulata	0.05	0.00	0.04	0.09	0.34
	Cedrela serrata	1.38	7.12	2.96	11.45	42.04
	Draceana steudneri	0.00	0.00	0.11	0.11	0.40
	Euphorbia candelabrum	0.56	0.00	0.00	0.56	2.04
	Eucalyptus globulus	128.70	0.00	5.22	133.92	491.50
	Euphorbia tirucali	0.28	0.00	0.00	0.28	1.03
	Ficus exasperata	0.00	0.00	12.23	12.23	44.88
	Grevillea robusta	8.68	1.65	13.41	23.73	87.11
	Jacaranda mimosifolia	0.57	0.00	9.18	9.75	35.78
	Leucaena leucocephala	0.32	0.00	8.29	8.62	31.62
	Mangifera indica	0.21	0.00	0.00	0.21	0.76
	Markhamia lutea	0.01	1.96	5.49	7.47	27.40
	Melia azedarach	0.00	14.01	7.64	21.66	79.48
	Persea americana	2.74	0.34	0.00	3.09	11.33
	Plumeria alba	0.07	0.00	0.22	0.29	1.06
	Spathodea campanulata	0.40	1.21	2.57	4.18	15.33
	Terminalia chebula	0.33	3.91	0.00	4.24	15.57
	Vernonia amygdalina	0.00	0.00	0.32	0.32	1.16
	Total broadleaves	145.16	30.20	93.13	268.49	985.35
	Total	146.71	58.70	107.39	312.79	1,147.95

Species distribution in relation with allometric equations used

Total carbon was computed for 1,027 trees amounting to 92% of the whole sample. Thus, specific allometric equations of *Eucalyptus globulus* and *Jacaranda mimosifolia* were used to calculate carbon content in 320 trees, corresponding to 31% of all inventoried trees. Besides, allometric equations of *Acacia longifolia*, *Pinus radiata* and *Cupressus macrocarpa* allowed estimates of carbon fixed in 198 trees of their congeners, whose proportions are respectively 49 stems of *Acacia spp*, 119 of *Cupressus lusitanica* and 30 of *Pinus patula*. At last, trees for which generic equations of conifers and broadleaves were applied represent 49.5% of all trees surveyed, respectively 24 stems of 2 conifers species and 485 stems of 18 broadleaves.

Carbon stocks distribution per institutional sites and species

Carbon sequestered in the aboveground biomass of conifers and broadleaves and the amount of CO_2 fixed from the atmosphere in each institutional site are detailed in Table 5. Data reveal a wide variability of both parameters values within and among institutional sites. For the three study sites (S-ISP, S-ND and S-CA), the total carbon stored amounted to 312.8 tons, being equivalent to 1,147.9 tons of CO_2 fixed from the atmosphere (Table 5).

Likewise, the amount of carbon stored differs from one species to another due to their own characteristics, among which the DBH remains important (Table 5). Thus, the amount of carbon stored at the ISP site is the highest of all study sites and is more than twice that in S-ND. Species holding more carbon at S-ISP are *Cupressus lusitanica* with 77.5% of total stock of conifers and *Eucalyptus globulus* with 88.6% of total carbon fixed by broadleaves. Furthermore, in the S-ND, 70.8% of total carbon is stored by three species, namely *Cupressus lusitanica*, *Cedrela serrata* and *Melia azedarach*.

For *Collège Alfajiri* site, the equivalent of total CO_2 fixed from the atmosphere by conifers amounted to 52.3 tons mainly from two species, *Cupressus lusitanica* and *Podocarpus usambarensis*. However, broadleaves reveal a potential of carbon of nearly 93.1 tons equivalent to 341.8 tons of CO_2 (Table 5). Species with the greatest stocks in S-CA are *Albizia gummifera*, *Ficus exasperata* and *Grevillea robusta* holding 42.1% of total carbon storage within.

Overall, compared on the basis of carbon storage, conifers and broadleaves were similar in the S-ND. Elsewhere, broadleaves were by far superior. Thus, carbon storage ratios of broadleaves/conifers are 1.06, 6.53 and 93.6 re-

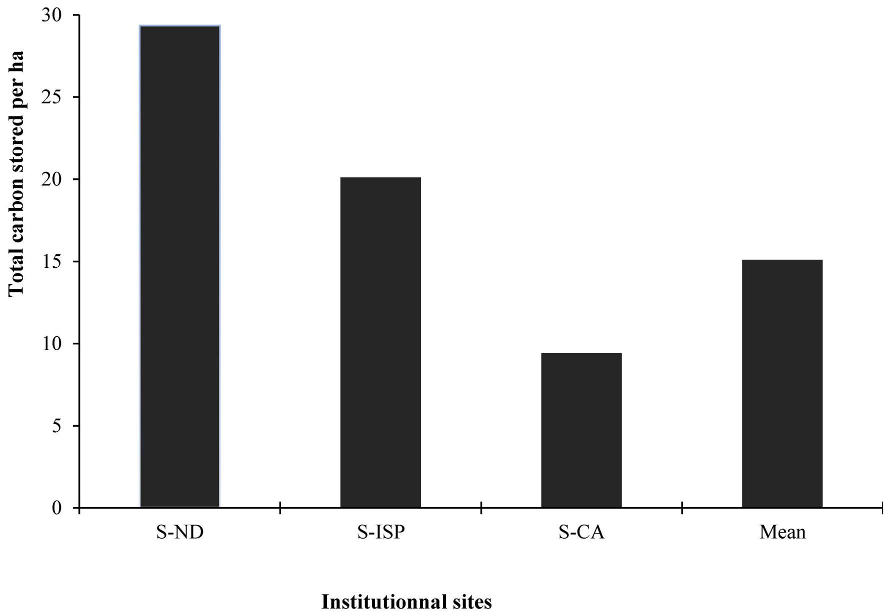

Fig. 2. Tons of carbon stored per hectare in institutional urban sites of Bukavu (October 2013).

spectively in the S-ND, S-CA and S-ISP.

Carbon density variation among sites

Total carbon stored per hectare widely varies from one institutional site to another in the city of Bukavu (Fig. 2). The greatest amount of carbon stored per ha occurs in the S-ND (29.3 tons C ha^{-1}) and is three-fold higher than that of the *Collège Alfajiri* site. For the three sites, the average is almost 15.1 tons of carbon accumulated per ha of institutional area.

Highest carbon sink species

The percent of carbon stored by species classified the most dominant is shown in Fig. 3. It is observed that the seven most successful species on all sites belong to both conifers and broadleaves. As shown, although present in two of three sites, *Eucalyptus globulus* has the largest carbon accumulation estimated at 43% of the total amount. It is far followed by *Cupressus lusitanica*. In addition, other species, even though widespread in all the three sites do not offer significant carbon stocks, especially *Podocarpus usambarensis* and *Jacaranda mimosifolia* (Fig. 3).

Discussion

Limitations and uses

Study sites were intentionally selected to belong to the institutional domain. Knowing that urban area comprises institutional, residential as well as street trees, data on tree density as well as carbon distribution in this study were not extrapolated to the entire city. Thus, with due caution, current results should be considered at the institutional scale while expecting that future studies have to expand the sample size to ensure generalizable conclusions.

Urban species composition

Based on the three study sites, the city of Bukavu is made of both native and exotic tree species. The presence of four species of conifers and other broadleaves such as *Eucalyptus globulus* from temperate zones explains the higher floristic diversity of the city. Specifically, conifers found are probably the work of White Catholic missionaries who managed all the three selected sites in Bukavu. Indeed, these forested lands rather result from artificial afforestation by institutional initiatives. Thus, this tree composition confirms (Nowak et al. 2007; Gulsvig et al. 2010) that the urban vegetation is a mix of native and non-native species introduced by residents or other means making a tree diversity often higher than in the surrounding native landscapes.

As for species nature, results reveal few fruit trees within institutional urban sites of Bukavu. In fact, of 25 species surveyed, only three are fruit trees, *i.e. Mangifera indica, Persea americana* and *Vernonia amygdalina* which, moreover, are not prevalent. This situation contrasts with that of

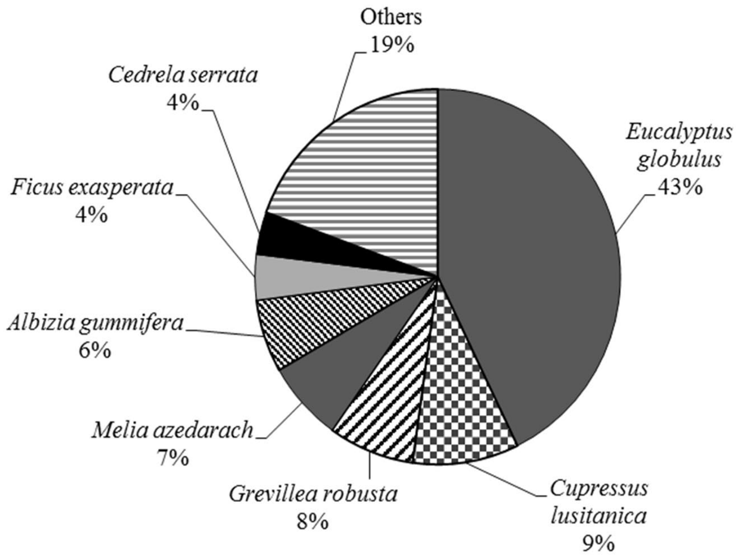

Fig. 3. Partitioning of carbon fixed by the most efficient species in urban area of Bukavu (October 2013).

the residential area of Kinshasa which is mainly populated by fruit trees. Indeed, Pauwels (1993) indicates that old cities are mainly planted to *Mangifera indica, Persea americana, Dacryodes edulis, Elaeis guineensis* and *Cocos nucifera*.

Moreover, results show around 12% of ramified trees in the city of Bukavu. The presence of abundant branched stems in urban areas should be a consequence of reduced competition for light as a result of their sparse distribution pattern on ground. In fact, McHale (2009) and Bruyat (2011) explain that low tree density in urban environments reduce competition for light and other resources surrounding trees. Thus trees, instead of producing a tapered trunk fetching light, tend to be wide by spreading their canopies. More likely however, this could also be a result of free growth due to poor tree management practice in these areas.

Diameter distribution and tree density

The pattern of tree distribution in diameter revealed a relatively young population. In fact, trees with a DBH less than 30 cm accounted for 62% of all trees surveyed in the study sites. This size distribution differs from that of the Oakland city where Nowak (1993) found approximately 61% of trees having less than 15 cm of DBH. On that, Nowak (1994b) explains that the distribution of tree sizes in urban area usually varies depending on the history and intensity of vegetation management.

Irrespective of sites, the density averages 54 trees per ha in Bukavu. This value is far less than estimates reported for african rainforest ranging from 300 to 700 trees per ha (Dupuy et al. 1998). It is still very low compared to the density of institutional lands in the Oakland city which reaches 111.9 trees per ha (Nowak 1993). Therefore, low presence of trees in the urban landscape of Bukavu is noteworthy, and then worrisome given the current climate change challenge.

As for the basal area, while Dupuy et al. (1998) report values between 30 and 35 m^2 ha^{-1} in the african rainforest, the average in the city of Bukavu was 5.21 m^2 ha^{-1}. This low basal area is explained by the extent of infrastructures and other dedicated spaces (streets, roads, sidewalks, lawns, playgrounds...) dominating in urban environment.

With regard to density, *Acacia spp*, *Cedrela serrata* and *Markhamia lutea*, although being among the most prevalent species in stems per ha do not cover necessary the largest basal area. This is due to their smaller girth at DBH despite their abundance as compared to some others like *Albizia gummifera, Melia azedarach* and *Podocarpus usambarensis*. Therefore, to identify species with the greatest diameter among urban trees of the same age can lead the choice for efficient species to plant in the city.

Assessing Carbon dioxide storage variation in Bukavu

Total carbon stored in the aboveground biomass of trees differed from one site to another. Thus 58.7 tons, 107.4 tons and 146.7 tons of carbon were recorded respectively in *Cathédrale Notre-Dame de la Paix, Collège Alfajiri* and *Institut Supérieur Pédagogique*. The average of carbon stored in these areas amounted to 15.1 tons ha^{-1}. This value is nearly 3.6-fold lesser than that reported by Imani et al. (2016) in the natural forest of the Kahuzi-Biega National Park (54 tons C ha^{-1}) located nearby the city of Bukavu. Thus it reveals the low tree density of urban forests as compared to that of natural forest vegetation outside urban area. The difference observed in carbon stock average could also be a consequence of the dissimilarity in species composition (Fayolle et al. 2013) between these artificial and natural ecosystems.

Results showed also that carbon density differs among sites with S-ND being significantly higher than S-CA ($p < 0.05$) (data not shown). This is essentially due to differences in current tree density in the three sites of Bukavu. Therefore, identifying tree optimal number per area as well as the nature of trees to plant in respect to their own characteristics, including size at maturity and carbon storage potential in any city is worthy of research.

Compared capacity of species in carbon storage

Most tree species holding the greatest carbon stock prevailed also in both density and basal area. These are mainly *Eucalyptus globus, Cupressus lusitanica, Grevillea robusta* and *Jacaranda mimosifolia* (Table 4). For some other species, however, relatively high density and or higher basal area did not account for greater carbon storage. Indeed, this is due to many factors such as species, age, size at maturity and tree growth rate which greatly influence carbon sequestration and storage (McPherson 1998; Nowak et al. 2002; Nowak and Crane 2002; Guarna 2012).

Moreover, tree diameter and moisture content do directly affect biomass calculation. Yet, conifers generally have lower moisture content than hardwood, 0.48 against 0.56 on average (Nowak 1994a). Thus, it is not surprising that a hardwood contains more carbon than a conifer of the same or lesser diameter girth. Hence, beside their abundance, hardwoods store nearly 6-fold much more carbon in Bukavu (268.4 tons C against 44.3 tons C for conifers) due to their own characteristics including their large size at maturity. This is also the reason why the average of carbon stored per ha under the tropics remains higher than that of woodlands dominated by conifers.

As regards species, *Eucalyptus globulus* particularly stores more carbon than any of the other species under study in Bukavu, making nearly half of total carbon stock of selected urban lands. This should be due to its great adaptability to the area as well as to its high growth rate beside its abundance in the landscape.

Environmental role of trees in institutional lands of Bukavu

According to Vergiette and Labrecque (2007), an automobile rejects about 4,500 kg of carbon after running 20,000 km. This ratio is equivalent, all other things being equal, to 225 kg of carbon released after 1,000 km of distance. The total carbon stored in the three institutional sites in Bukavu amounting to 312.8 tons, represents emissions of nearly 1,390 vehicles having traveled 1,000 km. This environmental service is not, in any case, negligible during this century given the global warming phenomenon already threatening human life and many natural ecosystems survival. No doubt, there is great need to increase the tree component in urban environments.

Conclusion

Assessing the ability of urban trees to reduce atmospheric gas emissions including CO_2 remains worthy of research given the current environmental challenge.

Based on the diameter at breast height of 1,113 trees inventoried, the potential of carbon storage varies from one species to another within each site, and among institutional sites in the city of Bukavu. Thus, 58.7 tons C, 107.4 tons C and 146.7 tons C are respectively stored in *Cathédrale Notre-Dame de la Paix, Collège Alfajiri* and *Institut Supérieur Pédagogique* of Bukavu. Of 312.8 tons of carbon stored by the three sites amounting to 1,147.9 tons of carbon dioxide equivalents, broadleaves store approximately 268.5 tons C representing 85.8% of the total storage while conifers store only 44.3 tons C. The greatest carbon-fixing tree species is *Eucalyptus globulus* storing about 134 tons C or 43% of total stock, followed by far by *Cupressus lusitanica*. The average of carbon stored per hectare reaches 15.1 tons.

Thus, trees surveyed in the urban area of Bukavu play a significant role in reducing atmospheric CO_2 and, thereby contributing to mitigate global warming effects. Given the imperative concern to combat climate change, more studies are needed to enrich tree database in Bukavu covering both institutional and residential lands as well as street trees. This need remains also crucial for other urban areas in DRC towards good management of urban forest in order to improve environmental quality and citizens' comfort. Programs to increase the potential for carbon sinks in urban areas are therefore required.

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