REPUBLIQUE DU CAMEROUN
Paix – Travail – Patrie
****
UNIVERSITE DE YAOUNDE I
FACULTE DES SCIENCES
DEPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE VÉGÉTALES
****

REPUBLIC OF CAMEROUN
Peace – Work – Fatherland
****
UNIVERSITY OF YAOUNDE I
FACULTY OF SCIENCE
DEPARTMENT OF PLANT BIOLOGY
****

Plant diversity, conservation concerns and carbon stock in the Doume Communal Forest of Cameroon: implication for sustainable forest management

Thesis submitted in partial fulfillment of the requirements for the degree of Philosophy Doctor in Plant Biology

Par : **ZEKENG Jules Christian**
Master of Science

Sous la direction de
MBOLO Marie Spouse ABADA,
Associate Professor, University of Yaoundé I

Année Académique : 2020

UNIVERSITE DE YAOUNDE I
THE UNIVERSITY OF YAOUNDE I

FACULTE DES SCIENCES
FACULTY OF SCIENCE

DEPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE VEGETALES
DEPARTMENT OF PLANT BIOLOGY

Yaoundé, the 12 JUIN 2020

ATTESTATION OF CORRECTION

****

We, the undersigned, members of the jury for the defense of the Doctorate/Ph.D. thesis in **Plant Biology**, option: **Botany-Ecology** defended on the 05th June 2020 by the student **ZEKENG Jules Christian**, Master es Sciences, Registration number **08S0347**, on the theme: **"Plant diversity, conservation concerns and carbon stock in the Doume Communal Forest of Cameroon: implication for sustainable forest management"**, hereby certify that he has made the corrections following the remarks and recommendations of the jury.

In witness whereof, this attestation of correction is made out and delivered to him to serve and enforce the purposes for which it was issued. /-

Le Chef de Département
The Head of Department

President:

YOUMBI Emmanuel
Professor

Member:

ZAPFACK

ZAPFACK Louis
Professor

Rapporteur:

MBOLO Marie Spouse ABADA
Associate Professor

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SONKÉ Bonaventure
Professor

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THE UNIVERSITY OF YAOUNDE I **Faculty of Science** Division of Programming and Follow-up of Academic Affairs		**UNIVERSITÉ DE YAOUNDÉ I** **Faculté des Sciences** Division de la Programmation et du Suivi des Activités Académiques
LIST OF PERMANENT TEACHING STAFF		**LISTE DES ENSEIGNANTS PERMANENTS**

ACADEMIC YEAR 2019/2020

(By Department and by Grade)

UPDATED ON: 19th January 2020

ADMINISTRATION

DEAN: TCHOUANKEU JEAN CLAUDE, *Associate Professor*
VICE-DEAN/DPSAA: DONGO Etienne, *Professor*
VICE-DEAN /DSSE: AJEAGAH Gideon AGHAINDUM, *Professor*
VICE-DEAN / DRC: ABOSSOLO Monique, *Associate Professor*
Head of Administrative and Financial Division: NDOYE FOE Marie C. F., *Associate Professor*
Head of Academic Affairs, Education and Research Division: MBAZE MEVA'A Luc Léonard, *Professor*

1- DEPARTMENT OF BIOCHEMISTRY (BC) (39)

N°	NAME AND FIRST NAME	GRADE	OBSERVATIONS
1	BIGOGA DIAGA Jude	Professor	In position
2	FEKAM BOYOM Fabrice	Professor	In position
3	FOKOU Elie	Professor	In position
4	KANSCI Germain	Professor	In position
5	MBACHAM FON Wilfried	Professor	In position
6	MOUNDIPA FEWOU Paul	Professor	**Head of Department**
7	NINTCHOM PENLAP V. spse BENG	Professor	In position
8	OBEN Julius ENYONG	Professor	In position
9	ACHU Merci BIH	Associate Professor	In position
10	ATOGHO Barbara Mma	Associate Professor	In position
11	AZANTSA KINGUE Gabin Boris	Associate Professor	In position
12	BELINGA née NDOYE FOE M. C. F.	Associate Professor	Head of DAF / FS
13	BOUDJEKO Thaddée	Associate Professor	In position
14	DJUIDJE NGOUNOUE Marcelline	Associate Professor	In position
15	EFFA NNOMO Pierre	Associate Professor	In position
16	MOFOR née TEUGWA Clotilde	Associate Professor	Service Inspector MINESUP
17	NANA Louise épouse WAKAM	Associate Professor	In position
18	NGONDI Judith Laure	Associate Professor	In position
19	NGUEFACK Julienne	Associate Professor	In position
20	NJAYOU Frédéric Nico	Associate Professor	In position
21	TCHANA KOUATCHOUA Angèle	Associate Professor	In position
22	AKINDEH MBUH NJI	Senior Lecturer	In Position
23	BEBEE Fadimatou	Senior Lecturer	In position
24	BEBOY EDZENGUELE Sara N.	Senior Lecturer	In position
25	DAKOLE DABOY Charles	Senior Lecturer	In position

26	DJUIKWO NKONGA Ruth Viviane	Senior Lecturer	In position
27	DONGMO LEKAGNE Joseph Blaise	Senior Lecturer	In position
28	EVEHE BEBANDOUE Marie-S.	Senior Lecturer	In position
29	EWANE Cécile Anne	Senior Lecturer	In position
30	FONKOUA Martin	Senior Lecturer	In position
31	KOTUE KAPTUE Charles	Senior Lecturer	In position
32	LUNGA Paul KEILAH	Senior Lecturer	In position
33	MANANGA Marlyse Joséphine	Senior Lecturer	In position
34	MBONG ANGIE M. Mary Anne	Senior Lecturer	In position
35	PECHANGOU NSANGOU Sylvain	Senior Lecturer	In position
36	Palmer MASUMBE NETONGO	Senior Lecturer	In position
37	MBOUCHE FANMOE Marceline Joëlle	Assistant	In position
38	OWONA AYISSI Vincent Brice	Assistant	In position
39	WILFRIED ANGIE Abia	Assistant	In position

2- DEPARTMENT OF ANIMALS BIOLOGY (BPA) (46)

1	AJEAGAH Gideon AGHAINDUM	Professor	*VDean / DSSE*
2	BILONG BILONG Charles-Félix	Professor	**Head of Department**
3	DIMO Théophile	Professor	In position
4	DJIETO LORDON Champlain	Professor	In position
5	ESSOMBA née NTSAMA MBALA	Professor	*VDean/FMSB/UYI*
6	FOMENA Abraham	Professor	In position
7	KAMTCHOUING Pierre	Professor	In position
8	NJAMEN Dieudonné	Professor	In position
9	NJIOKOU Flobert	Professor	In position
10	NOLA Moïse	Professor	In position
11	TAN Paul VERNYUY	Professor	In position
12	TCHUEM TCHUENTE Louis Albert	Professor	*Coord. Progr. MINSANTE*
13	ZEBAZE TOGOUET Serge Hubert	Professor	In position
14	BILANDA Danielle Claude	Associate Professor	In position
15	DJIOGUE Séfirin	Associate Professor	In position
16	DZEUFIET DJOMENI Paul Désiré	Associate Professor	In position
17	KEKEUNOU Sévilor	Associate Professor	In position
18	MEGNEKOU Rosette	Associate Professor	In position
19	MONY Ruth épse NTONE	Associate Professor	In position
20	NGUEGUIM TSOFACK Florence	Associate Professor	In position
21	NJATSA Hermine spse MEGAPTCHE	Associate Professor	In position
22	TOMBI Jeannette	Associate Professor	In position
23	ALENE Désirée Chantal	Senior Lecturer	In position
24	ATSAMO Albert Donatien	Senior Lecturer	In position
25	BELLET EDIMO Oscar Roger	Senior Lecturer	In position
26	DONFACK Mireille	Senior Lecturer	In position
27	ETEME ENAMA Serge	Senior Lecturer	In position
28	GOUNOUE KAMKUMO Raceline	Senior Lecturer	In position
29	KANDEDA KAVAYE Antoine	Senior Lecturer	In position
30	LEKEUFACK FOLEFACK Guy B.	Senior Lecturer	In position

31	MAHOB Raymond Joseph	Senior Lecturer	In position
32	MBENOUN MASSE Paul Serge	Senior Lecturer	In position
33	MOUNGANG LucianeMarlyse	Senior Lecturer	In position
34	MVEYO NDANKEU Yves Patrick	Senior Lecturer	In position
35	NGOUATEU KENFACK Omer Bébé	Senior Lecturer	In position
36	NGUEMBOK	Senior Lecturer	In position
37	NJUA Clarisse Yafi	Senior Lecturer	CD/UBa
38	NOAH EWOTI Olive Vivien	Senior Lecturer	In position
39	TADU Zephyrin	Senior Lecturer	In position
40	TAMSA ARFAO Antoine	Senior Lecturer	In position
41	YEDE	Senior Lecturer	In position
42	BASSOCK BAYIHA Etienne Didier	Assistant	In position
43	ESSAMA MBIDA Désirée Sandrine	Assistant	In position
44	KOGA MANG DOBARA	Assistant	In position
45	LEME BANOCK Lucie	Assistant	In position
46	YOUNOUSSA LAME	Assistant	In position

3- DEPARTMENT OF PLANT BIOLOGY (BPV) (33)

1	AMBANG Zachée	Professor	Head of Division/UYII
2	BELL Joseph Martin	Professor	In position
3	DJOCGOUE Pierre François	Professor	In position
4	MOSSEBO Dominique Claude	Professor	In position
5	YOUMBI Emmanuel	Professor	**Head of the Department**
6	ZAPFACK Louis	Professor	In position
7	ANGONI Hyacinthe	Associate Professor	In position
8	BIYE Elvire Hortense	Associate Professor	In position
9	KENGNE NOUMSI Ives Magloire	Associate Professor	In position
10	MALA Armand William	Associate Professor	In position
11	MBARGA BINDZI Marie Alain	Associate Professor	CT/MINESUP
12	MBOLO Marie spse ABADA	Associate Professor	PTA/*C2D-Project MINFOF*
13	NDONGO BEKOLO	Associate Professor	In position
14	NGODO MELINGUI Jean Baptiste	Associate Professor	In position
15	NGONKEU MAGAPTCHE Eddy L.	Associate Professor	In position
16	TONFACK Libert Brice	Associate Professor	In position
17	TSOATA Esaïe	Associate Professor	In position
18	DJEUANI Astride Carole	Senior Lecturer	In position
19	GOMANDJE Christelle	Senior Lecturer	In position
20	MAFFO MAFFO Nicole Liliane	Senior Lecturer	In position
21	MAHBOU SOMO TOUKAM. Gabriel	Senior Lecturer	In position
22	NGALLE Hermine BILLE	Senior Lecturer	In position
23	NGOUO Lucas Vincent	Senior Lecturer	In position
24	NNANGA MEBENGA Ruth Laure	Senior Lecturer	In position
25	NOUKEU KOUAKAM Armelle	Senior Lecturer	In position
26	NSOM ZAMO Annie Claude spse PIAL	Senior Lecturer	*National expert /UNESCO*
27	ONANA JEAN MICHEL	Senior Lecturer	In position
28	GODSWILL NTSOMBAH NTSEFONG	Assistant	In position

29	KABELONG BANOHO Louis-Paul-Roger	Assistant	In position
30	KONO Léon Dieudonné	Assistant	In position
31	LIBALAH Moses BAKONCK	Assistant	In position
32	LIKENG-LI-NGUE Benoit C.	Assistant	In position
33	TEMEGNE NONO Carine	Assistant	In position

4- DEPARTMENT OF INORGANIC CHEMISTRY (CI) (35)			
1	AGWARA ONDOH Moïse	Professor	*Vice Rector Univ. Bamenda*
2	ELIMBI Antoine	Professor	In position
3	Florence UFI CHINJE spse MELO	Professor	*Rector Univ.Ngaoundere*
4	GHOGOMU Paul MINGO	Professor	*Minister in Charge of Miss..PR*
5	NANSEU NJIKI Charles Péguy	Professor	In position
6	NDIFON Peter TEKE	Professor	*TA MINRESI/***Head of Department**
7	NDIKONTAR Maurice KOR	Professor	*Vice Dean Univ. Bamenda*
8	NENWA Justin	Professor	In position
9	NGAMENI Emmanuel	Professor	*Dean FS UDs*
10	NGOMO Horace MANGA	Professor	*VC/UB*
11	BABALE née DJAM DOUDOU	Associate Professor	*Head of Mission P.R.*
12	DJOUFAC WOUMFO Emmanuel	Associate Professor	In position
13	KAMGANG YOUBI Georges	Associate Professor	In position
14	KEMMEGNE MBOUGUEM Jean C.	Associate Professor	In position
15	KONG SAKEO	Associate Professor	In position
16	NDI NSAMI Julius	Associate Professor	In position
17	NJIOMOU C. spse DJANGANG	Associate Professor	In position
18	NJOYA Dayirou	Associate Professor	In position
19	YOUNANG Elie	Associate Professor	In position
20	ACAYANKA Elie	Senior Lecturer	In position
21	BELIBI BELIBI Placide Désiré	Senior Lecturer	CS/ ENS Bertoua
22	CHEUMANI YONA Arnaud M.	Senior Lecturer	In position
23	EMADACK Alphonse	Senior Lecturer	In position
24	KENNE DEDZO GUSTAVE	Senior Lecturer	In position
25	KOUOTOU DAOUDA	Senior Lecturer	In position
26	MAKON Thomas Beauregard	Senior Lecturer	In position
27	MBEY Jean Aime	Senior Lecturer	In position
28	NCHIMI NONO KATIA	Senior Lecturer	In position
29	NEBA nee NDOSIRI Bridget NDOYE	Senior Lecturer	CT/MINFEM
30	NYAMEN Linda Dyorisse	Senior Lecturer	In position
31	PABOUDAM GBAMBIE A.	Senior Lecturer	In position
32	TCHAKOUNTE KOUAMO Hervé	Senior Lecturer	In Position
33	NJANKWA NJABONG N. Eric	Assistant	In position
34	PATOUOSSA ISSOFA	Assistant	In position
35	SIEWO Jean Mermoz	Assistant	In position
5-DEPARTMENT OF ORGANIC CHEMISTRY (CO)(35)			
1	DONGO Etienne	Professor	Vice-Dean/PSAA

2	GHOGOMU TIH Robert Ralph	Professor	Dir. IBAF/UDS
3	NGOUELA Silvère Augustin	Professor	In position
4	NKENGFACK Augustin Ephreïm	Professor	**Head of Department**
5	NYASSE Barthélemy	Professor	*Director/UN*
6	PEGNYEMB Dieudonné Emmanuel	Professor	*Director/ MINESUP*
7	WANDJI Jean	Professor	In position
8	Alex de Théodore ATCHADE	Associate Professor	*DEPE/ Rectorate/UYI*
9	EYONG Kenneth OBEN	Associate Professor	*Chief of Service DPER*
10	FOLEFOC Gabriel NGOSONG	Associate Professor	*In position*
11	FOTSO WABO Ghislain	Associate Professor	In position
12	KEUMEDJIO Félix	Associate Professor	In position
13	KEUMOGNE Marguerite	Associate Professor	In position
14	KOUAM Jacques	Associate Professor	In position
15	MBAZOA née DJAMA Céline	Associate Professor	In position
16	MKOUNGA Pierre	Associate Professor	In position
17	NGO MBING Joséphine	Associate Professor	Sub/Director MINRESI
18	NGONO BIKOBO Dominique Serge	Associate Professor	In position
19	NOTE LOUGBOT Olivier Placide	Associate Professor	Chief of Service/MINESUP
20	NOUNGOUE TCHAMO Diderot	Associate Professor	In position
21	TABOPDA KUATE Turibio	Associate Professor	In position
22	TCHOUANKEU Jean-Claude	Associate Professor	*Dean /FS/ UYI*
23	TIH née NGO BILONG E. Anastasie	Associate Professor	In position
24	YANKEP Emmanuel	Associate Professor	In position
25	AMBASSA Pantaléon	Senior Lecturer	In position
26	KAMTO Eutrophe Le Doux	Senior Lecturer	In position
27	MVOT AKAK CARINE	Senior Lecturer	In position
28	NGNINTEDO Dominique	Senior Lecturer	In position
29	NGOMO Orléans	Senior Lecturer	In position
30	OUAHOUO WACHE Blandine M.	Senior Lecturer	In position
31	SIELINOU TEDJON Valérie	Senior Lecturer	In position
32	TAGATSING FOTSING Maurice	Senior Lecturer	In position
33	ZONDENDEGOUMBA Ernestine	Senior Lecturer	In position
34	MESSI Angélique Nicolas	Assistant	In position
35	TSEMEUGNE Joseph	Assistant	In position

6- DEPARTEMENT OF COMPUTER SCIENCE (IN) (26)

1	ATSA ETOUNDI Roger	Professor	*Chief of Div. MINESUP*
2	FOUDA NDJODO Marcel Laurent	Professor	*Head of Department ENS/Chief IGA.MINESUP*
3	NDOUNDAM Réné	Associate Professor	In position
4	ABESSOLO ALO'O Gislain	Senior Lecturer	In position
5	AMINOU Halidou	Senior Lecturer	In position
6	DJAM Xaviera YOUH-KIMBI	Senior Lecturer	In position
7	EBELE Serge	Senior Lecturer	In position
8	KAMGUEU Patrick Olivier	Senior Lecturer	In position
9	KOUOKAM KOUOKAM E. A.	Senior Lecturer	In position
10	MELATAGIA YONTA Paulin	Senior Lecturer	In position

11	MONTHE DJIADEU Valery M.	Senior Lecturer	In position
12	MOTO MPONG Serge Alain	Senior Lecturer	In position
13	OLLE OLLE Daniel Claude Delort	Senior Lecturer	C/D Enset. Ebolowa
14	TAPAMO Hyppolite	Senior Lecturer	In position
15	TINDO Gilbert	Senior Lecturer	In position
16	TSOPZE Norbert	Senior Lecturer	In position
17	WAKU KOUAMOU Jules	Senior Lecturer	In position
18	BAYEM Jacques Narcisse	Assistant	In position
19	DOMGA KOMGUEM Rodrigue	Assistant	In position
20	EKODECK Stéphane Gaël Raymond	Assistant	In position
21	HAMZA Adamou	Assistant	In position
22	JIOMEKONG AZANZI Fidel	Assistant	In position
23	KAMDEM KENGNE Christiane	Assistant	In position
24	MAKEMBE S. Oswald	Assistant	In position
25	MEYEMDOU Nadège Sylvianne	Assistant	In position
26	NKONDOCK MI. BAHANACK N.	Assistant	In position

7- DEPARTMENT OF MATHEMATICS (MA) (30)

1	EMVUDU WONO Yves S.	Professor	***CD Info***/ *CD/ MINESUP*
2	AYISSI Raoult Domingo	Associate Professor	**Head of Department**
3	MBEHOU Mohamed	Associate Professor	In position
4	NKUIMI JUGNIA Célestin	Associate Professor	In position
5	NOUNDJEU Pierre	Associate Professor	In position
6	TCHAPNDA NJABO Sophonie	Associate Professor	Director/AIMS Rwanda
7	AGHOUKENG JIOFACK Jean Gérard	Senior Lecturer	Chief Cell MINPLAMAT
8	CHENDJOU Gilbert	Senior Lecturer	In position
9	DJIADEU NGAHA Michel	Senior Lecturer	In position
10	DOUANLA YONTA Herman	Senior Lecturer	In position
11	FOMEKONG Christophe	Senior Lecturer	In position
12	KIANPI Maurice	Senior Lecturer	In position
13	KIKI Maxime Armand	Senior Lecturer	In position
14	MBAKOP Guy Merlin	Senior Lecturer	In position
15	MBANG Joseph	Senior Lecturer	In position
16	MBELE BIDIMA Martin Ledoux	Senior Lecturer	In position
17	MENGUE MENGUE David Joe	Senior Lecturer	In position
18	NGUEFACK Bernard	Senior Lecturer	In position
19	NIMPA PEFOUNKEU Romain	Senior Lecturer	In position
20	POLA DOUNDOU Emmanuel	Senior Lecturer	In position
21	TAKAM SOH Patrice	Senior Lecturer	In position
22	TCHANGANG Roger Duclos	Senior Lecturer	In position
23	TCHOUNDJA Edgar Landry	Senior Lecturer	In position
24	TETSADJIO TCHILEPECK M.	Senior Lecturer	In position
25	TIAYA TSAGUE N. Anne-Marie	Senior Lecturer	In position
26	MBIAKOP Hilaire George	Assistant	In position
27	BITYE MVONDO Esther Claudine	Assistant	In position
28	MBATAKOU Salomon Joseph	Assistant	In position
29	MEFENZA NOUNTU Thiery	Assistant	In position

30	TCHEUTIA Daniel Duviol	Assistant	In position

8- DEPARTMENT OF MICROBIOLOGY (MIB) (18)

1	ESSIA NGANG Jean Justin	Professor	DRV/IMPM
2	BOYOMO ONANA	Associate Professor	In position
3	NWAGA Dieudonné M.	Associate Professor	In position
4	NYEGUE Maximilienne Ascension	Associate Professor	In position
5	RIWOM Sara Honorine	Associate Professor	In position
6	SADO KAMDEM Sylvain Leroy	Associate Professor	In position
7	ASSAM ASSAM Jean Paul	Senior Lecturer	In position
8	BODA Maurice	Senior Lecturer	In position
9	BOUGNOM Blaise Pascal	Senior Lecturer	In position
10	ESSONO OBOUGOU Germain G.	Senior Lecturer	In position
11	NJIKI BIKOÏ Jacky	Senior Lecturer	In position
12	TCHIKOUA Roger	Senior Lecturer	In position
13	ESSONO Damien Marie	Assistant	In position
14	LAMYE Glory MOH	Assistant	In position
15	MEYIN A EBONG Solange	Assistant	In position
16	NKOUDOU Ze Nardis	Assistant	In position
17	SAKE NGANE Carole Stéphane	Assistant	In position
18	TOBOLBAÏ Richard	Assistant	In position

9. DEPARTMENT OF PHYSICS (PHY) (40)

1	BEN- BOLIE Germain Hubert	Professor	In position
2	ESSIMBI ZOBO Bernard	Professor	In position
3	KOFANE Timoléon Crépin	Professor	In position
4	NANA ENGO Serge Guy	Professor	In position
5	NDJAKA Jean Marie Bienvenu	Professor	**Head of Department**
6	NJANDJOCK NOUCK Philippe	Professor	*Sub Director/ MINRESI*
7	NOUAYOU Robert	Professor	In position
8	PEMHA Elkana	Professor	In position
9	TABOD Charles TABOD	Professor	Dean Univ/Bda
10	TCHAWOUA Clément	Professor	In position
11	WOAFO Paul	Professor	In position
12	BIYA MOTTO Frédéric	Associate Professor	**DG/HYDRO Mekin**
13	BODO Bernard	Associate Professor	In position
14	DJUIDJE KENMOE spse ALOYEM	Associate Professor	In position
15	EKOBENA FOUDA Henri Paul	Associate Professor	*Chief of Division. UN*
16	EYEBE FOUDA Jean sire	Associate Professor	In position
17	FEWO Serge Ibraïd	Associate Professor	In position
18	HONA Jacques	Associate Professor	In position
19	MBANE BIOUELE	Associate Professor	In position
20	NANA NBENDJO Blaise	Associate Professor	In position
21	NDOP Joseph	Associate Professor	In position
22	SAIDOU	Associate Professor	Director/MINRESI
23	SIEWE SIEWE Martin	Associate Professor	In position
24	SIMO Elie	Associate Professor	In position
25	VONDOU Derbetini Appolinaire	Associate Professor	In position
26	WAKATA née BEYA Annie	Associate Professor	*Sub Director/ MINESUP*

27	ZEKENG Serge Sylvain	Associate Professor	In position
28	ABDOURAHIMI	Senior Lecturer	In position
29	EDONGUE HERVAIS	Senior Lecturer	In position
30	ENYEGUE A NYAM spse BELINGA	Senior Lecturer	In position
31	FOUEDJIO David	Senior Lecturer	Chief of Service. MINADER
32	MBINACK Clément	Senior Lecturer	In position
33	MBONO SAMBA Yves Christian U.	Senior Lecturer	In position
34	MELI'I JORELLE LARISSA	Senior Lecturer	*In position*
35	MVOGO ALAIN	Senior Lecturer	*In position*
36	OBOUNOU Marcel	Senior Lecturer	DA/Univ Inter Etat/Sangmalima
37	WOULACHE Rosalie Laure	Senior Lecturer	In position
38	AYISSI EYEBE Guy François V.	Assistant	In position
39	CHAMANI Roméo	Assistant	In position
40	TEYOU NGOUPOU Ariel	Assistant	In position

10- DEPARTMENT OF EARTH SCIENCE (ST) (43)

1	BITOM Dieudonné	Professor	*Dean / FASA / UDs*
2	FOUATEU Rose spse YONGUE	Professor	In position
3	KAMGANG Pierre	Professor	In position
4	NDAM NGOUPAYOU Jules-Remy	Professor	In position
5	NDJIGUI Paul Désiré	Professor	**Head of Department**
6	NGOS III Simon	Professor	DAAC/Uma
7	NKOUMBOU Charles	Professor	In position
8	NZENTI Jean-Paul	Professor	In position
9	ABOSSOLO née ANGUE Monique	Associate Professor	*V-Dean/ DRC*
10	BISSO Dieudonné	Associate Professor	*Director/ Dam project Memve'ele*
11	EKOMANE Emile	Associate Professor	*In position*
12	GANNO Sylvestre	Associate Professor	In position
13	GHOGOMU Richard TANWI	Associate Professor	CD/UMa
14	MOUNDI Amidou	Associate Professor	*CT/ MINIMDT*
15	NGUEUTCHOUA Gabriel	Associate Professor	CEA/MINRESI
16	NJILAH Isaac KONFOR	Associate Professor	In position
17	NYECK Bruno	Associate Professor	In position
18	ONANA Vincent	Associate Professor	In position
19	TCHOUANKOUE Jean-Pierre	Associate Professor	In position
20	TEMDJIM Robert	Associate Professor	In position
21	YENE ATANGANA Joseph Q.	Associate Professor	*Chief of Div. /MINTP*
22	ZO'O ZAME Philémon	Associate Professor	*DG/ART*
23	ANABA ONANA Achille Basile	Senior Lecturer	In position
24	BEKOA Etienne	Senior Lecturer	*In position*
25	ELISE SABABA	Senior Lecturer	In position
26	ESSONO Jean	Senior Lecturer	*In position*
27	EYONG JOHN TAKEM	Senior Lecturer	In position
28	FUH Calistus Gentry	Senior Lecturer	*Sec. of State/MINMIDT*
29	LAMILEN BILLA Daniel	Senior Lecturer	In position

30	MBESSE CECILE OLIVE	Senior Lecturer	In position
31	MBIDA YEM	Senior Lecturer	*In position*
32	METANG Victor	Senior Lecturer	In position
33	MINYEM Dieudonné-Lucien	Senior Lecturer	*CD/Uma*
34	MOUAFO Lucas	Senior Lecturer	In position
35	NGO BELNOUN Rose Noël	Senior Lecturer	In position
36	NGO BIDJECK Louise Marie	Senior Lecturer	In position
37	NGUETCHOUA Gabriel	Senior Lecturer	CEA/MINRESI
38	NOMO NEGUE Emmanuel	Senior Lecturer	In position
39	TCHAKOUNTE J. spse NOUMBEM	Senior Lecturer	*Chief of Service / MINRESI*
40	TCHAPTCHET TCHATO De P.	Senior Lecturer	In position
41	TEHNA Nathanaël	Senior Lecturer	In position
42	TEMGA Jean Pierre	Senior Lecturer	In position
43	FEUMBA Roger	Assistant	In position
44	MBANGA NYOBE Jules	Assistant	In position

Numerical breakdown of the teachers of the Faculty of Science of the University of Yaoundé I

	NUMBER OF TEACHERS				
DEPARTMENT	Professors	Associate Professor	Senior Lecturer	Assistants	Total
BCH.	09 (01)	13 (09)	14 (05)	03 (02)	39 (16)
B.P.A.	13 (01)	09 (03)	19 (05)	05 (02)	46 (14)
B.P.V.	06 (00)	11 (02)	10 (07)	06 (01)	33 (10)
C.I.	10 (01)	09 (02)	13 (02)	02 (00)	35 (05)
C.O.	07 (00)	17 (04)	09 (03)	03 (00)	35(07)
I.N.	02 (00)	01 (00)	14 (01)	10 (02)	26 (03)
M.A.	01 (00)	05 (00)	19 (01)	05 (01)	30 (02)
M.B.	01 (00)	05 (02)	06 (01)	06 (02)	17 (05)
P.H.	11 (00)	16 (01)	10 (03)	03 (00)	40 (04)
S.T.	08 (01)	14 (01)	19 (04)	02 (00)	43 (06)
Total	68 (04)	99 (27)	132 (29)	45(10)	344 (70)

Total	**344 (70) with** :
- Professors	**68 (04)**
- Associate Professors	**99 (27)**
- Senior Lecturer	**132 (29)**
- Assistants	**46 (10)**
( ) = Number of women	**45**

DEDICATION

To

My mother Therese ZANGUIM

My father Armand E. NGUEFFA (of blessed memory)

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ACRONYMS AND ABBREVIATIONS

ADC	: Aboveground Dead Carbon
AGB	: Aboveground Biomass
AGC	: Aboveground Carbon
AgrL	: Agroforestry systems Land
APG	: Angiosperm Phylogeny Group
ARM	: “ Arbre de Régression Multivarié ”
BCI	: Bray–Curtis dissimilarity Index
BGC	: Belowground Carbon
CDB	: Convention on Biological Diversity
CEC	: Cation Exchange Capacity
COP	: Convention of the Parties
CF	: Communal Forest
CV	: Coefficient of Variation
CVRE	: Cross-Validated Relative Error
CWD	: Coarse Woody Debris
DBH	: Diameter at Breast Height
DCF	: Doume Communal Forest
DFHTD	: Dense Forest with High Tree Density
DFLTD	: Dense Forest with Low Tree Density
FPE	: Forest Permanent Estate
DHP	: “Diamètre à Hauteur de Poitrine”
EC	: Electrical Conductivity
ETM+	: Enhance Thematic Mapper Plus
FAO	: Food and Agriculture Organisation
FMUs	: Forest Management Units
FWD	: Fine Woody Debris
GHG	: Greenhouse Gas
GIS	: Geographic Information Systems
GPS	: Global Positioning systems
HV	: Herbaceous Vegetation
IPCC	: Intergovernmental Panel on Climate Change
ITTO	: International Tropical Timber Organisation
IUCN	: International Union for Conservation of Nature

LULC	: Land Use/Land Cover
MED	: Minimum Exploitable Diameter
MC	: Moisture Content
MLC	: Maximum Likelihood Classification
MRT	: Multivariate Regression Trees
MRV	: Monitoring, Reporting and Verification
NTFPs	: Non-Timber Forest Products
OLI/TIRS	: Operational Land Imager and Thermal Infrared Sensor
OSFACO	: « Observation Spatiale des Forêts d'Afrique Centrale et de l'Ouest »
PFD	: Permanent Forest Domain
REDD+	: Reducing Emissions from Deforestation and forest Degradation
RphSF	: Swampy *Raphia* Forest
SEM	: Structural Equation Model
SFM	: Sustainable Forest Management
SOC	: Soil Organic Carbon
SPOT	: « Satellite Pour l'Observation de la Terre »
STD	: Standing Dead Trees
SwFF	: Swampy Floods Forest
TAGC	: Total Aboveground Carbon
UNCED	: United Nations Conference on Environment and Development
UNFCCC	: United Nations Framework Convention on Climate Change
USGS	: United States Geological Survey
UTM	: Universal Transverse Mercator
UYI	: University of Yaounde I
WD	: Wood Density

ABSTRACT

The carbon stored by tropical forests and the enormous biodiversity they contain contribute to climate regulation and the balance of the living beings that inhabit them. Forest ecosystems such as forest management units and communal forests are habitats whose potential remains little explored. In Cameroon's Eastern region, a study aimed at understanding the impact of logging and abiotic factors on habitat-species associations and carbon stocks with a particular focus on biodiversity conservation and sustainable forest management was conducted in the Doume Communal Forest (DCF).

Remote sensing processing technics (i.e. maximum likelihood classification algorithm, the post-classification at per-pixel scale) were applied on three Landsat images from 2000, 2009 and 2018, to assess the Land Use and Land Cover (LULC), its spatio-temporal dynamics and change trajectories during the last two decades (2000-2018), and hence evaluate the state of this ecosystem management. This remote sensing stage and topographic maps were used to determine the sampling area and hence established the thirty 1 ha plots (100 m x 100 m). Each 1 ha plot was subdivided into 25 subplots of 20 m x 20 m, wherein all trees with a Diameter at Breast Height (DBH) ≥ 10 cm considered as large trees and all standing dead trees were measured while in thirteen of the twenty-five subplots, trees with DBH between 5 and 9.9 cm called understorey trees were inventoried and measured. Additionally, in five (the four sides and the center) of twenty-five subplots of 20 m x 20 m, two perpendicular transects of 15 m x 15 m, a subplot of 5 m x 5 m, two subplots of 50 cm x 50 cm and one subplot of 1 m x 1 m were installed to measure the diameter of dead woody debris, diameter at 30 cm aboveground level of small stems (1.0-4.9 cm), the biomass of litter and herbaceous vegetation respectively. Eleven soil variables were obtained after analyses of a composite sample of five soil samples per plot, while four topographic variables were collected for each plot. Multivariate Regression Trees (MRT) technique was used to determine habitat-species associations, and structural equation models were used to determine how abiotic and biotic factors drive aboveground carbon stocks. Moreover, variation partitioning analysis was used to determine how carbon pools contribute to total carbon stocks, and how different carbon components (e.g. large trees, understorey trees, dead woody debris) contribute to carbon pools as well as to total carbon stocks. All the analyses were done using the R statistical software program.

The results showed that 90 % of the DCF is occupied by terra-firme forest and that the different types of LULC changes increased and involved more diverse trajectories in 2009-2018 compared to 2000-2009. The degradation of dense forest with high tree density into a dense forest with low tree density and swampy *Raphia* forest has been dominant. The terra-firme forest plots inventoried host approximately 307 species with 16 % representing species with high priority for conservation. The MRT has shown that 37 % of the species variance was due to the influence of topographic and edaphic factors, which were grouped into four habitats each characterized by indicator species. This study revealed that the DCF terra-firme forest stores an average of 285.60 ± 51.19 Mg C ha^{-1}, and that aboveground live carbon pool, with an average of 182.62 ± 33.59 Mg C ha^{-1} mostly explained its variation ($R^2 = 0.79$). From all the aboveground carbon components, large trees' carbon stock was most strongly correlated with total carbon stocks. The second most important carbon pool was below ground carbon (on average 85.06 ± 15.86 Mg C ha^{-1}; $R^2 = 0.78$), mainly explained by coarse root carbon. Carbon in deadwood had only a small contribution to total carbon stocks ($R^2 = 0.04$). Across the site, topographic factors were positively related to aboveground carbon stocks across the tree size groups and the whole tree community. Different soil properties drive above ground carbon stocks across tree size classes and the whole tree community at different magnitudes and strengths. Taxonomic diversity indices had a positive relationship with aboveground live carbon stocks while diversity structural Gini index had the strongest relationships with aboveground carbon stocks.

This study showed that, in addition to wood production and the supply of non-timber forest products, communal forest also contributes to climate change mitigation and biodiversity conservation. The conservation and sustainable management of tropical forests given its rich biodiversity highlighted by many authors are and remain a challenge for the well-being of all living beings on earth, mainly humans.

Keywords: applied ecology, biodiversity-ecosystems functioning, Cameroon, Doume communal forest, modelling, semi-deciduous tropical rainforest.

RESUME

Le carbone stocké par les forêts tropicales et l'énorme biodiversité que recèlent celles-ci concourent à la régulation du climat et à l'équilibre des êtres vivants qui y habitent. Les écosystèmes forestiers comme les unités forestières d'aménagement, les forêts communales sont les habitats dont le potentiel reste peu exploité. Au Cameroun, région de l'Est, une étude visant à comprendre l'impact de l'exploitation forestière et les facteurs abiotiques sur les associations habitats-espèces et les stocks de carbone avec un accent particulier sur la conservation de la biodiversité et la gestion durable des forêts a été conduite dans la Forêt Communale de Doume (FCD).

Les techniques de traitement en télédétection (c'est-à-dire l'algorithme de classification par maximum de vraisemblance, la post-classification à l'échelle du pixel) ont été appliquées sur trois images Landsat de 2000, 2009 et 2018, pour évaluer l'Utilisation des Terres et la Couverture du Sol (UTCS), leur dynamique spatio-temporelle et les changements de trajectoires survenues durant les deux dernières décennies (2000-2018). Cette étape de télédétection et les cartes topographiques ont permis de déterminer les zones d'échantillonnages afin d'installer les 30 placettes de 1 ha (100 m x 100 m). Chaque placette d'un hectare a été subdivisée en 25 sous-placettes de 20 m x 20 m, où tous les arbres ayant un diamètre ≥ 10 cm à 1,30 m vivants ou morts sur pied ont été mesurés tandis que dans 13 des 25 sous-placettes, les arbres ayant entre 5 et 9,9 cm de diamètre appelés arbres de sous-bois ont été inventoriés et mesurés. En outre, dans cinq (quatre coins et au centre) des vingt-cinq sous-placettes de 20 m x 20 m de la placette de 1 ha, deux transects perpendiculaires de 15 m x 15 m, un quadrat de 5 m x 5 m, deux quadrats de 50 cm x 50 cm et un quadrat de 1 m x 1 m ont été installés pour mesurer le diamètre des débris de bois mort au sol, le diamètre à 30 cm au-dessus du sol des petites tiges (1,0-4,9 cm), la biomasse de la litière et la végétation herbacées.

Onze variables de sol ont été obtenues après analyse d'un échantillon composite de cinq échantillons de sol par placette, tandis que quatre variables topographiques ont été collectées pour chaque placette. La technique des Arbres de Régression Multivariée (ARM) a permis de déterminer l'association habitat-espèces et les modèles d'équation structurelle ont permis de déterminer l'influence des facteurs abiotiques et biotiques sur les stocks de carbone épigé. De plus, une analyse de répartition de la variance a permis de déterminer la contribution des pools de carbone au stockage total de carbone et celle des différentes composantes aux pools de carbone ainsi qu'au stockage total de carbone. Toutes les analyses ont été effectuées à l'aide du logiciel statistique R.

Les résultats ont révélé que 90 % de la FCD est occupé par des forêts de terre ferme et que les différents types de changements d'UTCS se sont multipliés et ont impliqué des trajectoires plus variées pendant la période 2009-2018 par rapport à 2000-2009. La dégradation des strates de forêt dense à forte densité d'arbres en des strates clairsemées d'arbres puis en forêts marécageuses à *Raphia* a été dominante. Les placettes de forêts de terre-ferme inventoriées abritent 307 espèces de plantes avec 16 % représentant des espèces à hautes priorités pour la conservation. L'ARM a montré que 37 % de la variance des espèces était due à l'influence des facteurs topographique et édaphique lesquelles étaient regroupées en quatre habitats caractérisés chacun par des espèces indicatrices. Cette étude a révélé que la forêt de terre ferme de la FCD stocke en moyenne 285,60 ± 51,19 t C ha^{-1}, et que le pool de carbone épigé avec une moyenne de 182,62 ± 33,59 t C ha^{-1}, explique principalement sa variation (R^2 = 0,79). Parmi toutes les composantes du carbone épigé, le carbone des grands arbres était fortement corrélé aux stocks de carbone totaux. Le deuxième réservoir de carbone le plus important a été le carbone hypogé (en moyenne 85,06 ± 15,86 t C ha^{-1}; R^2 = 0,78), principalement expliqué par le carbone des grosses racines. Le carbone de la necromass a contribué faiblement aux stocks de carbone totaux (R2 = 0,04). Dans l'ensemble du site, les facteurs topographiques ont été corrélés positivement avec les stocks de carbone de classes de diamètre ainsi que celle de l'ensemble de la communauté des arbres. Différentes variables du sol influencent les stocks de carbone des groupes de classes de diamètre ainsi que celle de l'ensemble de la communauté des arbres avec une force et magnitude différentes. La diversité taxonomique a été positivement corrélée, tandis que l'indice de diversité structurale de Gini a été significativement corrélé aux stocks de carbone des groupes de classes de diamètre ainsi que celle de l'ensemble de la communauté des arbres.

Cette étude a montré qu'en plus de la production de bois et de la fourniture en produits forestiers non ligneux, la forest communale contribution également à l'atténuation des changements climatiques et à la conservation de la biodiversité. La conservation et la gestion durable des forêts tropicales au vu de sa riche biodiversité soulignée par de nombreux auteurs restent et demeurent un défi à relever pour le bien-être de tous les êtres vivants sur la terre, principalement les humains.

Mots-clés: écologie appliquée, biodiversité-fonctionnement des écosystèmes, Cameroun, conservation, forêt communale de Doumé, modélisation et forêts tropicales semi-décidues humides.

CHAPTER I. GENERALITIES

I.1. INTRODUCTION

I.1.1. Background

Terrestrial ecosystems are responsible for a net reduction of 2.6 ± 1.2 petagrams of carbon from the atmosphere per year and therefore play a crucial role in the global carbon cycle by mitigating global warming (Stocker *et al.*, 2013). A large proportion of this reduction comes from tropical forests, where 55 % of global forest carbon stocks are stored (Pan *et al.*, 2011). Tropical forests are at the center of debates on climate change and sustainable forest management because of their dual roles in climate change mitigation and biodiversity conservation (Bodegom *et al.*, 2009; Bele *et al.*, 2015; Poorter *et al.*, 2016; Arasa-Gisbert *et al.*, 2018).

In addition to their important role in the global carbon cycle, tropical forests also provide a wide range of other ecosystem services that contribute to better livelihoods (Anonymous, 2019). This contribution includes: i) material contributions which are substances, objects or other material elements from nature that directly sustain people's physical existence and material assets; ii) Non-material contributions which are nature's effects on subjective or psychological aspects underpinning people's quality of life, both individually and collectively; iii) Regulating contributions which are functional and structural aspects of organisms and ecosystems that modify environmental conditions experienced by people, and/or regulate the generation of material and non-material contributions (Anonymous, 2019). These forests are subject to deforestation and degradation with a consequent major negative impact on terrestrial biodiversity, and thus on the provision of these ecosystem services closely linked to biodiversity.

Since it is irreversible, extinction is the major problem of the biodiversity crisis. Even though the conservation of biodiversity and reduction of its loss has been reasserted by the Aichi targets for 2020 by the Parties to the United Nations Convention on Biological Diversity (CBD) after failing to meet the 2010 target (Butchart *et al.*, 2010; Anonymous, 2011a), its loss does not seem to slow down. Anthropogenic disturbances have resulted in a loss of species diversity, with the current rate of extensions being at least 1000 times higher than natural extinction rates (De Vos *et al.*, 2015). Therefore, most obvious among them may be the lost opportunity for future resource use. Onana (2011) already noted the fact that some species lose their habitat and sometimes disappear definitively without being even known to science. With the loss of species, we lose the ultimate source and the basis of the structure and function of the ecosystems that support humans and all life on earth (Mittermeier *et al.*, 2011). Therefore, maintaining the biodiversity of forest ecosystems is essential to the supply of ecosystem services and not less important to support their health and resilience (Butchart *et al.*, 2010; Pereira *et al.*, 2013).

However, most of the studies carried out in Communal Forests (CF) and in Forest Management Units (FMUs) in tropical forests, it is observed that conservation issues and some sustainable management aspects are forgotten to the benefit of woody resources assessment (Tchouto, 2004; Anonymous, 2015). In most of these studies, floristic diversity is limited to tree species with a Minimum Exploitable Diameter (MED) for CF and FMUs and even for the management plan of protected areas. Therefore, this approach is not sufficient for plant diversity assessment because, most components of the diversity of the ecosystems such as shrubs, small trees, lianas, herbaceous plants, and epiphytic flora as well as their conservation status are not taken into account (Tchouto, 2004). Most African countries like Cameroon have decided as a biodiversity conservation strategy to erect large forest areas as protected areas (Mengue-Medou, 2002; Muhumuza & Balkwill, 2013). Terrestrial biodiversity is too widely dispersed to allow its measurement to be focused solely within strictly protected areas. Managed landscapes will continue to play vital roles as buffer zones and corridors supporting protected areas and more generally as habitat for wild species, some of which are likely to never be adequately represented within the protected area network (Dudley *et al.*, 2005). Measurement across the whole mosaic of land-cover types is therefore essential, including the areas of sustainable use, particularly forests inside and outside protected areas.

Moreover, tropical forests with their rich biodiversity also contribute to mitigating climate change and that is why the international community has recognized the important role of tropical forests and agreed that tackling deforestation and degradation of tropical forests is vital to fighting climate change (Anonymous, 2008). Therefore, under the United Nations Framework Convention on Climate Change (UNFCCC) in 2005, the international community put in place the program called “Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+)”. The REDD+ program aims at contributing to the reductions of carbon dioxide emissions while providing economic incentives for better management and protection of forests (Weatherley-Singh & Gupta, 2015; Vijge *et al.*, 2016; Ickowitz *et al.*, 2017; Rakatama *et al.*, 2017; Shrestha & Shrestha, 2017; Shrestha *et al.*, 2017). In addition to offsetting emissions, it could provide indirect support for biodiversity conservation through reduced habitat loss, thus providing a unique solution to the longstanding tension between conservation interests and other land-use needs in tropical forest regions (Baccini & Asner, 2013; Asner & Mascaro, 2014; Lund *et al.*, 2017; Mauerhofer & Essl, 2018).

However, the biomass maps produced for central Africa (Baccini *et al.*, 2008; Mitchard *et al.*, 2011) showed that there is still a lot of uncertainty about the amount and spatial variation in biomass and carbon stocks, both above- and belowground. These uncertainties are mainly due to the scarcity of reliable estimates of carbon pools and their variation across landscapes and forest types (Pan *et al.*, 2011). This limits the implementation of the measurement, reporting, and verification (MRV) protocol at the national level. Successful implementation of the REDD+ mechanisms depend on the monitoring of emission reductions, which also depends on mapping and monitoring the tropical forest carbon stocks over large geographic areas, and identifying the multiple drivers of land-use change and associated changes in the carbon budget (Maniatis & Mollicone, 2010). To improve the local and regional carbon estimates, it is urgent to provide essential data that enable the extrapolation of carbon stocks to ecosystems of biome-wide carbon cycle modeling (Urquiza-Haas *et al.*, 2007; Houghton *et al.*, 2009).

Few existing studies in Cameroon on the estimation of carbon stocks in the semi-deciduous rainforest (e.g. Fayolle *et al.*, 2016; Chimi *et al.*, 2018) as well as in evergreen rainforests (e.g. (Djomo *et al.*, 2011; Day *et al.*, 2013; Fayolle *et al.*, 2016; Tabue *et al.*, 2016; Kabelong *et al.*, 2018) have focused only on aboveground carbon stocks. Differences in carbon storage may be determined by forest type, with higher aboveground carbon in semi-deciduous forests than evergreen forests (Fayolle *et al.*, 2016). Besides forest type, also forest structure, such as the number of big-sized trees and the stand basal area, can be drivers of biomass stocks (Poorter *et al.*, 2015; van der Sande *et al.*, 2017b). Several studies in tropical rainforests elsewhere have shown that larger trees store more aboveground biomass than smaller trees (e.g. Chisholm *et al.*, 2013; Lutz *et al.*, 2018).

Deadwood is a major component of aboveground biomass (AGB) in tropical forests and is important for microorganisms and nutrient cycling and carbon storage (Carlson *et al.*, 2017). Very few studies have assessed carbon stored in deadwood for African tropical forests (but see Djomo *et al.*, 2011; Zapfack *et al.*, 2013; Carlson *et al.*, 2017; Kabelong *et al.*, 2018). It has been shown that coarse woody debris (CWD) is an important deadwood component of carbon storage in tropical forests (Gora *et al.*, 2019). In undisturbed moist forests, it may account for approximately 10 % of the total carbon storage (Pregitzer & Euskirchen, 2004) and can constitute up to 33 % of the forests' AGB (Baker *et al.*, 2007). A perturbation in the forest usually causes big changes in deadwood stocks. The increased mortality due to disturbance favors the flow of carbon from the living mass to the deadwood pool (Rice *et al.*, 2004) and the subsequent decomposition of dead trees increases the carbon emissions of the stand. Therefore, the quantification of deadwood stocks and flows helps us better understand the carbon balance of disturbed forests.

Furthermore, there is a poor understanding of belowground carbon storage (Doetterl *et al.*, 2015). Specifically, there is still a lack of knowledge on soil organic carbon (SOC) stocks in the tropical forest, their control and the relationship of biomass allocation and SOC stocks (Batjes, 2008; Malhi *et al.*, 2009; Saiz *et al.*, 2012). Available estimates suggest that soil carbon can contribute to as much as 32 % of the carbon stock in the total ecosystem in tropical forests (Pan *et al.*, 2011),

The present study focuses on the Doume Communal Forest (DCF) situated in eastern Cameroon and belonging to the guineo-Congolese domain (Letouzey, 1985) crucial for both national development and livelihoods of about 22763 local inhabitants (Anonymous, 2015). This forest is subject to intense pressure due to rapid population growth, logging, and hunting activities that exert diverse ecological impact on the forest ecosystems. Therefore, to address vulnerability, resilience and adaptative capacity of the forest ecosystem and hence improve the management and monitoring of natural resources at landscape scales, the main goal of the present study was to provide scientific tools and conservational information. Moreover, at the national scales, it could contribute to supply a database of international policies on biodiversity and GHG reduction signed by Cameroon.

I.1.2. Research Questions

The present study aims to answer the general research question of how logging disturbance and abiotic factors drive plant species association and carbon storage across the terra-firme forest of DCF, and that could contribute to biodiversity conservation and sustainable forest management.

Specifically, it aims to answer the following research questions:

- What are the dynamics and the trajectories (i.e. degradation, deforestation) of Land Use and Land Cover (LULC) in the DCF for the three periods of 2000-2009, 2009-2018 and 2000-2018?
- What is the potential of the terra-firme forest of the DCF in terms of plant diversity and species with high conservation priority?
- Does the forest show distinct habitats and to what extent variance in local plant species composition can be explained by habitat differentiation?

- What is the contribution of different carbon pools (aboveground, belowground, dead biomass) and underlying carbon components (large trees, understorey trees, small stems, palms, standing dead trees, woody debris, roots, and soil organic carbon) to total carbon?
- How do abiotic conditions determine carbon stocks directly and indirectly via biotic factors?
- How do biotic factors (i.e. taxonomic diversity and structural diversity) affect carbon stocks?

I.1.3. Hypotheses

The general hypothesis of this study is that logging disturbance and abiotic factors drive plant species association and carbon storage across the terra-firme forest of DCF and that their understanding contributes to biodiversity conservation and sustainable forest management.

This thesis addresses the following specific hypotheses:

- assuming sustainable forest management of the Doume Communal forest since 2008, dynamics and trajectories (i.e. deforestation, degradation, etc.) of LULC should improve from one decade to another;
- the potential of terra-firme forest of the DCF in terms of plant diversity and species richness with high priority for conservation is high;
- the terra-firme forest of the DCF does not show a detectable distinct topo-edaphic habitat differentiation;
- aboveground live carbon pool contribute most to the total carbon stock, and within this pool, large trees determine total carbon stocks;
- aboveground live carbon increases with increasing soil resource availability and decreases with increasing logging disturbance intensities;
- aboveground live carbon stock increases with increasing biotic factors (i.e. species diversity and structural diversity index).

I.1.4. Objectives of the study

I.1.4.1. General Objective

The general objective of this study is to understand how logging disturbance and abiotic factors drive plant species association and carbon storage across the terra-firme forest of DCF with a particular focus on biodiversity conservation and sustainable forest management.

I.1.4.2. Specific objectives

The specific objectives of this thesis are:

- to analyze the land use and land cover changes and trajectories that have occurred in DCF over the past two decades (2000-2018);
- to assess the plant diversity as well as their conservation values in the terra-firme forest of the DCF;
- to analyze topo-edaphic habitat-species associations in a terra-firme forest of DCF;
- to assess total carbon stocks and the contribution of different carbon pools as well as their components in explaining its variation;
- to analyze the relative and independent direct and indirect effects through biotic factors of abiotic factors on carbon stocks across tree size groups, as well as at the whole tree community;
- to analyze the relative and independent effects of biotic factors on carbon stocks across tree size groups, as well as at the whole tree community.

I.1.5. Outline of the thesis

This thesis consists of 4 chapters.

Chapter one presents generalities consisting of the general introduction (this part) and the literature review. The general introduction lays the foundation of this work by highlighting the background subtending this study and the problem it tries to solve. It ends with an enumeration of the research questions, the hypotheses and finally the research objectives. The second section presents the literature review in six sub-sections.

Chapter two presents the materials and methods employed to achieve each objective of the present study.

Chapter three presents in the first section the results obtained after using previous methodologies while in the second section consists of the discussion of the main results.

Chapter four presents the conclusion and perspectives. References and appendices close the present document.

I.2. LITTERATURE REVIEW

I.2.1. Presentation of the study area

I.2.1.1. Location, policy and administrative framework

Aware of conservation and the sustainable management of its resources and in compliance with the agreements and treaties signed or ratified, after the convention of Rio de Janeiro in 1992, Cameroon modified all its legal instruments, and put in place dispositions allowing for the contribution of all stakeholders to the sustainable management of its forest resources. To this end, the forestry, wildlife and fisheries regimes law No. 94/01 of 20th January 1994 and decree No. 95/531/PM of 20th August 1995 laying down the modalities of the forest Regime application made provisions for some forests to be managed by municipalities. In article 20 paragraph 2 of the forestry law, the Permanent Forest Estate (PFE) is defined as land permanently allocated to the forest and wildlife habitat. Article 21 (2) classifies communal forests as part of the permanent forest estate. Therefore, for a forest classified as a communal forest, the council wishing to exploit it must produce a management plan.

To cope with the responsibilities that the law of July 2004 on decentralization confers upon the council, and to stimulate its self-development, the Doume Council actively engaged in the diversification of its sources of income through, activities such as the exploitation of a communal forest. For this purpose, the Doume Council began a filing procedure in 2009 which ended in 2014 with the classification of 45 359 ha of the forest as DCF according to the decree N° 2014/3206/PM of 23rd September 2014 (Anonymous, 2015).

The Doume Council is located in the district of Doume, Department of Upper Nyong, in the East Region of Cameroon at ~58 km from Abong-Mbang and 57 km from Bertoua. Spread over an area of 2 500 km^2, it is bounded to the north by the district of Ndiang, to the south by the district of Abong Mbang, to the east by the district of Doumaintang and the southwest by the district of Angossas. The DCF is constituted of a forest area divided into two blocks of different surface areas (25 810 ha for block 1 and 19 549 ha for the block 2). The forest is located between latitudes 4°16'- 4°32' N and longitudes 13°16'-13°32' E for block 1. Whereas, for the block 2 is located between latitudes 4°8'-4°16' N and longitudes 13°12'-13°32' E. The DCF is bounded to the south by the agroforestry zone on the Doume-Doumaintang road axis, to the north by the agroforestry zone on the Diang-Bertoua road axis and to the west by the agroforestry zone on the Doume-Dimako axis (Anonymous, 2015).

I.2.1.2. Physical environment

I.2.1.2.1. Geology and soils

The geological bedrock of the entire area consists of metamorphic rocks, which are schists, micaschists and possibly melanocratic rocks. Some areas are characterized by the presence of migmatic gneisses and anatexis granites belonging to the Precambrian base complex dated between 2.5 and 1.8 billion years. In the area of Bertoua and Diang, the geology is composed of granites, syenites, diorites, syntectonic gabbros associated with the Precambrian base complex (Nougier, 1979 cit Anonymous, 2015).

Throughout the area, clay soils derived from the alteration of metamorphic rocks widely dominate. They are ferralitic red soils, loose and permeable, with little humus which can be several meters thick and the minerals are completely hydrolyzed with the removal of bases and silica. These soils are poor in nutrients, acids and fragile. In the swampy areas, the soils are hydromorphic to gley (Anonymous, 2015).

I.2.1.2.2. Topography

Relatively uniform, the relief of the forest can be described as slightly uneven. It presents two slightly low hills with generally gentle slopes interspersed with small well-marked streams and swampy depressions (several hundreds of meters) without a distinct watercourse. Steep slopes can be observed but they remain much localized on the edge of lowlands or rivers, and their difference in level seldom exceeds 20 to 30 m. The altitude varies from 605 to 740 m, with some particularly marked summits, culminating at less than 700 m of altitude (Anonymous, 2015).

I.2.1.2.3. Climate and hydrology

The climate of Doume locality is the Equatorial Guinean type (Anonymous, 2010; 2015) characterized by:

- an annual rainfall varying between 1300 and 1800 mm with two rainy seasons interspersed by two dry seasons and distributed as follows in the year: a long dry season from mid-November to mid-March, a short rainy season from the second half of March to the end of May, a short dry season from early June to the first half of August, and a long rainy season from the second half of August to November;
- an annual average temperature of 25 °C with an amplitude of 2.4 °C. It varies between 25 °C and 30 °C from March to November. Whereas, from December to February, the hottest months, the temperature can reach 35 °C;

- a seasonal cycle mainly governed by the annual movements of the intertropical front, between the convergences zones of the southern trade winds (wet monsoon, coming from the Saint Helena anticyclone) and the northern trade winds (dry harmattan, from the Saharan anticyclone). On the Nyong Basin these displacements result in dry winds from December to February, relatively wet winds from March to July, wet wings from August to October and relatively dry winds in November;

The hydrographic network is relatively dense and consists of several permanent watercourses most often unnamed. These are generally more apparent in the northern part of the massif than in the southern part characterized by the existence of many shallows which are sometimes very extensive where the water flows diffusely. A fairly dense hydrographic network supplies the massif with four main rivers: the Doume and its affluent Yompie, Byanté, Koum, Sès, and Sé; Ntel and its affluent Boughé and Angombe. The major affluents of these watercourses constitute a part of the natural boundaries of the DCF. Except for the Doume and Ntel rivers, most of the rivers present in the massif can be crossed without much difficulty in any season (Anonymous, 2010; 2015).

I.2.1.3. Socio-economic setting

I.2.1.3.1. Population, ethnicity, and settlements

Regarding the population of Doume, different statistics are given by different organizations. Indeed, the Doume Council during the preparation of its community development plan in 2011, and after the various participatory diagnoses in the 23 villages, estimated its population at about 39 000 people (Anonymous, 2011b). Effectively, during her last census in 2000, Plan Cameroon estimated the population of Doume at 22 763 people (Anonymous, 2010; 2015).

In the locality of Doume, the migratory phenomenon remained tiny. The number of inhabitants distributed among the communities settled in the 23 villages is composed of 02 large ethnic groups and 02 ethnic minorities (Anonymous, 2010; 2015):

- the Maka: it is the dominant ethnic group which is present in all the villages and constitutes more than 70% of the inhabitants of the locality;
- the Bakoum: present in the villages of Mendjim, Kobila, Sibita, Paki (the stronghold of the ethnic group), Mbama-Doume, Loumbou, Kempong, Goumbegeron, etc.). It constitutes about 20% of the population of the locality;
- the Baka settled in Bigoutcha, "Hausa" in Sibita and some Nigerians in Paki who constitutes the minority tribes.

I.2.1.3.2. Economic activities

The main village activities are agropastoral, hunting, artisanal fishing, the collection of secondary products, craft, and activities related to forest exploitation. These different activities are practiced both in the periphery and inside the DCF (Anonymous, 2010; 2015).

I.2.1.3.2.1. Agropastoral activities

Agriculture and rearing of livestock are practiced by more than 80 % of the active population. Subsistence agriculture holds the upper hand, although commercial farming is not to be neglected (Anonymous, 2011b)

Subsistence agriculture is practiced around village concessions in the agroforestry zone. Among the main products, we can mention groundnuts, cassava, maize, cocoyam but also banana plantain, sweet banana which are commercialized in local markets.

Cash crop farming is also practiced in the agro-forestry zone and occasionally in the communal forest. The main cash crops are cocoa, coffee, and oil palm. Cocoa-culture is an old practice of the people living in the DCF. Therefore, plantations are either aging or abandoned because of the lack of plant protection products and the absence of reconstitution. Cocoa cultivation is practiced in all villages bordering the DCF. However, although it is reserved for men, women intervene during harvest which is done in groups in the case of the big farmers (Anonymous, 2015).

Unlike subsistence agriculture, livestock farming is an accessory activity for local populations. In general, livestock farming is practiced by the Maka and Bakoum peoples and a little by Haoussa. Small livestock or poultry and small ruminants stray inside the village. The major part of products is intended for self-consumption during holiday celebrations and the rest for marketing in village markets (Anonymous, 2010; 2015).

I.2.1.3.2.2. Hunting and artisanal fishing activities

Mostly practiced by men, hunting is widespread in local customs and it is still very popular in the area; Doume being famous for its bush meat. Certainly, it tends to move away and become rarer, because of human activities and forest exploitation (Anonymous, 2011b). Here, subsistence hunting is practiced, which is sometimes the subject of heavy traffic, with large quantities of bush-meat that generate immediate profits. The hunting techniques used are the guns, more and more widespread, the individual trap or the trap associated with the barrier. This last hunting technique is most often used to protect crops from predators such as rodents. The barriers are also set in the bush, more than a hundred traps (Anonymous, 2010; 2015).

Fishing is practiced in the rivers near the villages and is done traditionally. The vast majority of about 90% of the fish derivatives is for self-consumption. The fishing techniques used are angling (by men and children), water barriers (by women) and nets (by men). Fishing products are usually smoked for preservation. The aquatic products are catfish, carp, crab, shrimp, and tilapia (Anonymous, 2010).

I.2.1.3.2.3. Collection of non-timber forest products

The collection of non-timber forest products (NTFPs) is an activity reserved for women and children. It is practiced seasonally according to the species of NTFP to harvest and extends into the area reserved for the communal forest. However, in general, the preferred period of NTFPs production/harvest is during the main rainy season. The harvested and collected products are tree barks, mushrooms, leaves, insects, caterpillars, fruits, seeds, and roots. These are used for self-consumption, traditional medicine, and marketing. NTFPs, being abundant in the forest, are harvested by any person originating from the village and wishing to do so (Anonymous, 2010).

Revenues derived from the exploitation of NTFPs, although not quantified, contribute significantly to the improvement of local living conditions. Indeed, we could say that it is the part of the forest that comes directly and daily to the people. These incomes are used daily to cover expenses related to schooling, health, clothing, household operations, etc. (Anonymous, 2010).

I.2.1.3.2.4. Artisanal activities

It is a very marginal activity in the locality; it is based on the manufacture of raffia mats, baskets, mortars, and other furnishing objects. The men and women are involved in the activity depending on the type of objects manufactured: women for baskets and men for the rest. Very few of these products are sold; they are almost entirely consumed locally. The raw material (raffia leaves, rattan, bamboo) comes from the forest and swamps (Anonymous, 2010).

I.2.1.3.2.5. Logging

Indigenous people generally exploit wood to meet their local construction needs or to make furniture. This activity is especially intense in the dry season. The presence of the community forest logging company in Bayong allows young people in the locality to have jobs and wood for construction. It should be noted, however, that illegal logging and the trafficking of certain species, in complicity with the villagers in the communal forest area was reported, not counting the artisanal sawing (which is not always declared by the population) (Anonymous, 2010).

I.2.1.4. Vegetation

From a phytogeography point of view, the Doume communal forest belongs to the dense semi-deciduous forest. Semi-deciduous forests refers to those forest types with about 70 % of the species losing their leaves during some periods of the year (Reich, 1995). These forest types occur in areas where yearly dry periods exceed three months. Tall canopy species are prominent in this forest type such as: *Staudtia kamerunensis* Warb., *Pausinystalia macroceras* (K.Schum.) Pierre ex Beille, *Celtis* spp., *Chrysophyllum* spp., *Terminalia superba* Engl. & Diels and *Antiaris toxicaria* (Engl.) C. C. Berg. etc.; while species with large trunks and undulating canopies (e.g. *Entandrophragma* spp., Triplochiton *scleroxylon* K.Schum. *Milicia excelsa* (Welw.) C.C.Berg) characterizes this forest type (Letouzey, 1985).

In this study area, semi-deciduous forests occur on terra firme, hence are called terra firme semi-deciduous forests where the forest understorey is dominated by *Anonidium mannii* (Oliv.) Engl. & Diels, *Baphia* spp., *Strombosiopsis tetrandra* Engl., *Aidia* spp. etc (Letouzey, 1968; 1985). Semi-deciduous forests also occur on hydromorphic soils and hence are called hydromorphic semi-deciduous forests.

I.2.2. Definitions of terminologies and concepts

I.2.2.1. Forests

Tropical forest ecosystems are globally significant; containing approximately 45% of all carbon in terrestrial vegetation (Anonymous, 2000) as well as high biodiversity (Myers *et al.*, 2000; Myers, 2017). They also provide ecosystem services such as timber, non -timber forest products provision (Smail & Lewis, 2009; Nasi *et al.*, 2012; Ranius *et al.*, 2018), and mitigate climate change (Le Toan *et al.*, 2011; Lewis *et al.*, 2013; Le Quéré *et al.*, 2016). Despite their importance, a globally agreed definition of forests is lacking (Putz & Redford, 2010). Therefore, sometimes forests are viewed, defined, assessed, and valued through different senses mostly according to the forest management objectives (Chazdon *et al.*, 2016). A commonly used definition is that of the Food and Agriculture Organisation (FAO), which states that forest is considered as land, over 0.5 ha, with a tree crown cover of over 10 percent and trees that (when mature) reach over 5m in height (Anonymous, 2000). A forest is considered to be tropical if it lies between the tropics of Cancer and Capricorn (Malhi & Grace, 2000; Pan *et al.*, 2011).

I.2.2.2. Communal forest

Belonging to the Permanent Forest Domain (PFD), a communal forest is a forest that has been the subject of an act of classification within the framework of a specific Council. The act of classification fixes the limits and the management objectives of the said forest which may be the same as those of state-owned forest, as well as the exercise of the right to access and use by indigenous peoples. It gives the right to the establishment of a land title in the name of the concerned Council. A decree fixes the procedure for the classification of communal forests that belong to the state domain states (Anonymous, 1994). Due to its permanent forest status, the management of the communal forest requires a management plan.

I.2.2.3. Management plan

The management plan is a long-term strategic document. It is generally revisable every fifteen years. Its decisions are ratified by the company and the administration in charge of the forests. The management plan is a document in which the potentialities of the resource are evaluated, the trade-offs among the ecological, economic, and social aspects of management are assessed, and balanced solutions are proposed. The management plan is the result of a thorough study of the potentialities of the massif to be developed, as well as the risks that may weigh on the forest and its functions (Anonymous, 2007). It is worth remembering that the management plan is the keystone of sustainable forest management (SFM). It is an essential management tool not only for day-to-day logging but also for investment policy and general planning of forest enterprises (Fobane, 2017).

I.2.2.4. Sustainable forest management

There are varying definitions of SFM. The Forest Stewardship Council defines it as the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality, and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems. However, for the United Nations Conference on Environment and Development (UNCED), SFM has to keep the balance between three main pillars: ecological, economic and socio-cultural. Successfully achieving sustainable forest management will provide integrated benefits to all, ranging from safeguarding local livelihoods to protecting the biodiversity and ecosystems provided by forests, reducing rural poverty and mitigating some of the effects of climate change (Anonymous, 1992). The International Tropical Timber Organisation (ITTO) defined SFM as the process of managing forests to achieve one or more specified objectives with regard to the production of a continuous flow of desired forest goods and services without undue reduction of its inherent values and future productivity and without undue undesirable effects on the physical and social environment (Anonymous, 1998). Within the framework of several international processes, initiated following UNCED, participating countries have defined criteria against which sustainability can be judged, and have specified corresponding indicators which help in monitoring the effects of forest management interventions over time. Criteria and indicators are today commonly recognized as appropriate tools for defining, assessing and monitoring progress towards sustainable forest management (Kotwal *et al.*, 2008).

I.2.2.5. Forest structure

Forest structure usually refers to how the attributes of trees are distributed within a forest ecosystem. However, we distinguish the vertical and horizontal structure of the forest. The structure is a fundamental notion referring to patterns and relationships within a more or less well-defined system (Gadow *et al.*, 2012). According to Delang & Li (2013), forest structure is a complex system considered as a whole rather than of any single part. It is meaningless to add together the various measures and produce some average quantification of forest structure. There is no overall measure to quantify or express forest structure, and foresters measure a variety of attributes such as aboveground biomass, abundance, basal area, stem diameter, canopy height, plant density each of which contributes to the overall structure, but do not, individually, describe it completely (Gadow *et al.*, 2012; Delang & Li, 2013; van der Sande, 2016).

I.2.2.6. Carbon pools

The carbon pool designates a system with the capacity to accumulate or release carbon. More specifically, the IPCC defines five terrestrial carbon reservoirs namely: aboveground carbon (AGC); litter; coarse woody debris (CWD); below ground carbon; soil organic matter (SOM) and the soil organic carbon (SOC). Aboveground Biomass carbon entails all the carbon contained in living vegetation, both woody and herbaceous, above ground, including stems, stumps, branches, bark, seeds, and foliage (Anonymous, 2006). The carbon litter represents any non-living organic carbon that is larger than the soil organic matter limit (2 mm) and less than the minimum diameter chosen for dead wood, in various decomposition states above or below the interior of the mineral or organic soil (Anonymous, 2006). Coarse woody debris (CWD) comprises all non-living woody carbon that is absent in the litter, whether it is standing, lying on the ground or in the soil, while belowground carbon represents all the carbon contained in living roots. Finally, soil carbon includes organic carbon in mineral soils at a specified depth chosen by the country (Anonymous, 2006).

I.2.3. Definition and drivers of deforestation and degradation of tropical forests

Historically, deforestation is the result of a local change in the nomadic way of life of hunter-gatherers to sedentary agriculture (often resulting in an increase in population and thus an increase in the demand for food and fuel). However, in the tropics, the majority of LULC change is considered relatively recent, having occurred over the last 100 years (Fearnside, 2005; Rudel *et al.*, 2009; Efroymson *et al.*, 2016). Tropical deforestation is estimated at ~ 13 million ha^{-1} between 2000 and 2010, a decrease in deforestation rates in the 1990s (Achard *et al.*, 2002; Asner *et al.*, 2009), even though these estimates are highly uncertain, with secular trends based on unclear data (Grainger, 2008) and scale-dependent (Pan *et al.*, 2010). Thus, given the uncertainty surrounding tropical deforestation rates, is it possible to determine what leads to modern tropical deforestation?

Deforestation is defined by Kanninen *et al.* (2007) as the conversion of forest into another form of spatial occupation or as the long-term reduction of forest cover under a threshold of ten percent. The erosion of biodiversity is one of the most important environmental effects of deforestation. Indeed, tropical forests contain the greatest known specific diversity (Puig, 2001). The latter states that the decrease in the area of tropical forests and their fragmentation are responsible for the disappearance of 7 % of the non-exploited species subservient to these habitats. Forests in the Congo Basin are now among the lowest deforestation areas in the world (De Wasseige *et al.*, 2014). According to Bellassen *et al.* (2008), deforestation accounts for 0.15% of the forest area of the Congo Basin compared to 0.51 % in tropical America or 0.58 % in tropical Asia. Currently, the loss of biodiversity is low in the Congo Basin forests compared to other large tropical forest areas (De Wasseige *et al.*, 2014). The processes that destroy forest cover elsewhere in the world are also at work in the sub-region. These "drivers of deforestation" have been defined as elements having an explicit and direct cause-consequence link with the destruction of forest cover (Pfaff *et al.*, 2007).

Deforestation can occur as one sole action, leading to a change in land cover. However, it could also occur gradually, with forests being slowly degraded over time until achieved LULC change. Up until the point at which the land cover exceeds the respective definitions of forest, this change would not be recorded as deforestation (Putz & Redford, 2010), but instead termed degradation. Specifically, degradation is the ‘temporary or permanent deterioration in the density or structure of vegetation cover or its species composition (Grainger, 2008). This process is most commonly a result of human actions but covers a range of activities, from selective logging and short rotation shifting cultivation to over-hunting and pollution but is thought to have already impacted up to one -third of today’s tropical forest (Lambin *et al.*, 2001).

In general, degradation can be considered a precursor to deforestation as prolonged periods of degradation may eventually result in LULC change and thus a deforestation event. Thus, it has been suggested that the factors driving forest degradation are similar to those driving deforestation (Liu *et al.*, 2016). Like deforestation, the process can be need-driven, whereby the local populations utilize forest resources to address their immediate needs and this disturbance degrades the forest over time, or profit-driven. Although understanding the drivers and extent of degradation is somewhat limited, attempts to quantify its effects have occurred. The latest FAO deforestation estimates, covering the period between 2000 and 2010, do not contain any estimates of rates of degradation. However, estimates of degradation have been made for previous periods. Between 1990 and 1997, 2.3 ± 0.7 million hectares of forest were visibly degraded, with 47% occurring in Asia and 36% and 17% occurring in Amazonia and Africa respectively (Achard *et al.*, 2002). Current estimates suggest that carbon emissions as a result of degradation are about 25 - 47% of those estimated for deforestation (Asner *et al.*, 2010). Thus, current carbon emission as a result of degradation is estimated at ~0.5 Pg C yr^{-1} approximately half the amount that is absorbed by current tropical regrowth (Pan *et al.*, 2011).

Hence, the impacts resulting from degradation are substantial. However, most ongoing REDD+ research and discussions focus on deforestation while mostly disregarding the effects of degradation (Gullison et *al.*, 2007; da Fonseca et *al.*, 2007). This disregard is shortsighted since degradation is often a precursor to deforestation (Nepstad *et al.*, 1999; Asner *et al.*, 2005). An increased focus on estimating the carbon emissions from degradation and understanding the proximate and underlying drivers of such changes is vital to decrease the uncertainty surrounding REDD+ emission estimates.

I.2.4. Community ecology

I.2.4.1. Definition

Community ecology is an expanding and rich subfield of ecology, studying organization and functioning of communities, which are assemblages of interacting populations of the species living within a particular area or habitat (Looijen & van Andel, 1999). Alternatively, it has been defined as the study of the processes that shape the identity (traits) and abundance of species within limited space (Kraft & Ackerly, 2014). Species composition of a local community is the result of several processes and factors that act at different scales, none of them being mutually exclusive. This encompasses from features and processes that act at global and regional scales, such as randomness, historical patterns of speciation, extinction, migration as well as dispersal processes, to abiotic factors (physical constraints of the environment) and biotic interactions (both positive and negative) that act at the local scale (Fig. 1). Thus, community assembly may unite evolutionary, biogeographical and environmental processes (Kraft & Ackerly, 2014).

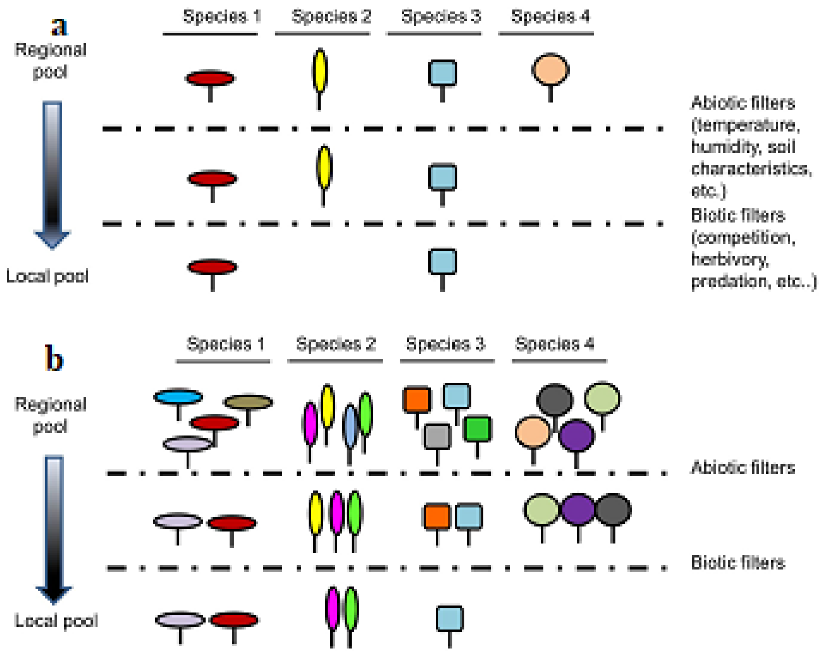

Fig. 1. Influence of intraspecific variability in the filtering of potential species integrating a community: a) classical community assembly theory without taking into account intraspecific variability and b) community assembly theory incorporating intraspecific variability (Valladares *et al.*, 2015).

I.2.4.2. Competition and related mechanisms explaining species co-occurrence

Several alternatives have been proposed to explain coexistence and diversity when classic niche theory fails (Barot, 2004; Wildová *et al.*, 2012). Under this emergent scenario, classic ideas on competition are being reshaped in a more mechanistic framework giving new perspectives that reconcile neutral and niche theories (Adler *et al.*, 2007), often treated as mutually exclusive explanations.

This new mechanistic framework is explicitly addressed by combining the two concepts of Chesson (2000) framework: the so-called “niche differences” and “fitness differences.” Note that fitness is used as an ecological term, referring to the average competitive ability of a species, and not in an evolutionary context. Although complementing niche theory, niche differences do not determine the outcome of interactions alone. They are only a stabilizing mechanism favoring coexistence by limiting species abundance when they rise to dominance and buffering them against exclusion when they become rare (Adler *et al.*, 2007). Differences in fitness favor dominance, and, in the absence of niche differences, they determine the species that exclude the rest. The key message of Chesson (2000) framework is that the outcome of species interaction is jointly determined by the relative strength of niche differences versus fitness differences between species. In this context, coexistence will be fostered when niche differences overcome fitness differences (Fig. 2).

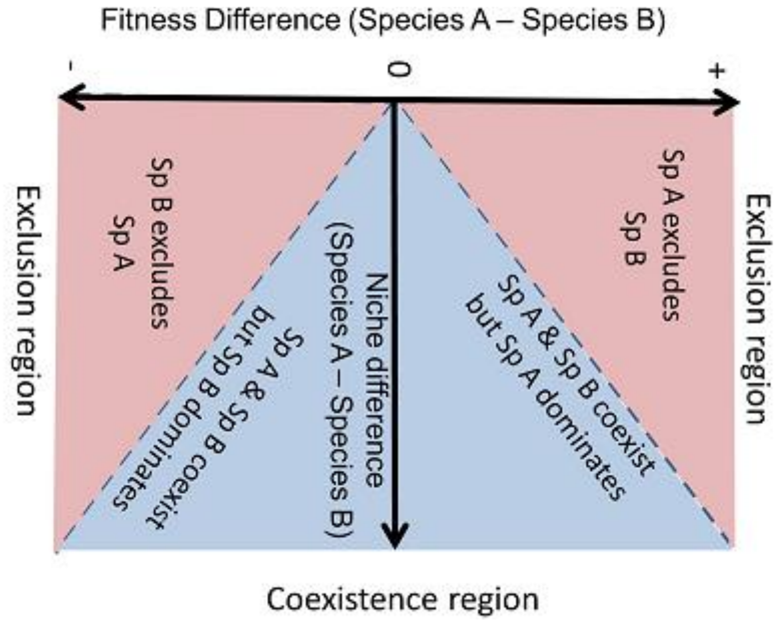

Fig. 2. Theoretical scheme of coexistence and competitive exclusion between two species (Valladares *et al*., 2015).

I.2.4.3. Niche and neutral theory

The classical exclusion principle by Chapman (1935) states that a large number of species competing for the same resources cannot stably coexist because the number of limiting resources often exceeds the number of competing species (Hutchinson, 1961; Connell, 1978). Several hypotheses such as classical niche theory (Pimm, 1983) and the neutral theory of biodiversity (Hubbell, 2001) have been developed to resolve this enigma.

Depending on the neutral theory, functionally, species are equivalent and diversity is controlled by stochastic processes such as drift and dispersal limitation (Hubbell, 2001; McGill, 2003). Functional equivalence of plant species would mean that segregation along environmental niche axes is not the primary driver of species assembly. According to Hubbell (2001), pervasive dispersal limitation, ecological drift and a balance between random extinction and speciation could explain a wide variety of ecological patterns:

- dispersal limitation; i.e. the capacity of a plant species to disperse its seeds to reach unoccupied sites (Ehrlén & Eriksson, 2000);
- ecological drift; i.e. the abundance of a particular species can either increase or decrease through time controlled by births, deaths and the outcome of the competition (Purves & Turnbull, 2010).

In contrast to neutral theory, classical niche theory states that competing for plant species can avoid competitive exclusion by relying on different, spatially segregated, resources (Harms *et al.*, 2001; Sugihara *et al.*, 2003; Pavoine & Bonsall, 2011; Valladares *et al.*, 2015). Its prominence depends on the primary spatial scale under investigation. Its development (Grinnell, 1917) and later modification (Hutchinson, 1957) is thought to have inspired pioneering concepts. For instance, MacArthur (1957) viewed the relationships between species or species trait with the environment and also interspecific trade-offs as being paramount for co-occurrence at the local scale.

I.2.4.4. Influence of abiotic drivers on diversity

Tropical forests have a complex composition and structure. Mechanisms contributing to maintaining high diversity and multispecies coexistence in these forests remain debated (Ricklefs, 1977; Wright, 2002; Leibold, 2008; Couvreur *et al.*, 2011). An understanding of the driving factors of spatial heterogeneity will determine the functional plant types. Vegetation structures are necessary for projecting consequences of climate and land-use changes, and for designing effective conservation and forest management strategies (Loreau *et al.*, 2001; Andrew *et al.*, 2012; Fayolle *et al.*, 2012; Mishra *et al.*, 2013).

Abiotic factors determine the distribution of tree species diversity and forest structure in tropical forests at the continental, regional and local scales (Swaine, 1996; Clark *et al.*, 1998a; Clark & Clark, 2000; Webb & Peart, 2000; Harms *et al.*, 2001; Pyke *et al.*, 2001; Phillips *et al.*, 2003; Tchouto, 2004; Toledo *et al.*, 2011a; Toledo *et al.*, 2011b; Fayolle *et al.*, 2012; Li *et al.*, 2015; Ricklefs & He, 2016). The most important ones of proposed factors to be strong drivers of composition and structure of tropical rain forests at regional scales are rainfall (Swaine, 1996; Pyke *et al.*, 2001; Li *et al.*, 2015; Ricklefs & He, 2016) and soil factors or topography (Tuomisto *et al.*, 1995; Clark *et al.*, 1998a; ter Steege *et al.*, 2006). Among local abiotic factors that are directly related to species distribution in tropical forests, soil properties, topography, canopy cover, temperature, seasonality, and rainfall stand out as filters or promoters to the establishment (Lebrija-Trejos *et al.*, 2010; Paine *et al.*, 2011; Lasky *et al.*, 2013).

At local scales, abiotic factors such as topography and soil factors have been reported as factors influencing the distribution of species in tropical forests worldwide (Harms *et al.*, 2001; Phillips *et al.*, 2003; Palmiotto *et al.*, 2004; Tchouto, 2004; John *et al.*, 2007; Toledo *et al.*, 2011a; Toledo *et al.*, 2011b). This could be explained by the fact that topography and soil texture are related to the soil moisture availability, and that the availability of soil nutrients depends on topography and climate (Fayolle *et al.*, 2012). For example, Fayolle *et al.* (2012) have shown that sandy soils have more drought-tolerant species than clay soils. van der Sande *et al.* (2018) in the Guyanese tropical rainforest have found that soil fertility increased species richness. Even the most fertile portion of this forest is still relatively poor in nutrients. It is possible that an increase in soil fertility will also be an opportunity for non-N2-fixing species to establish, and thus has a positive effect on species richness. In contrast to results obtained by van der Sande *et al.* (2018); Toledo *et al.* (2011a) found that soil fertility has negative effects on the emergent layer and tree density.

Besides the soil and topography such as abiotic factors driving the distribution of the species, it is largely argued that there are strong relationships between trees species distribution and rainfall in the tropical rainforests. Indeed, Tchouto (2004) in the Campo Ma'an area in southern Cameroon has shown that rainfall positively influences the community and structure of vegetation. That study revealed a gradual variation in dominant species and an increase in species richness with increasing distance from the sea and decreasing annual rainfall. Toledo *et al.* (2011a) arrived at the same conclusions following similar work carried out in the tropical forests of Bolivia. Many other studies also found rainfall as a good predictor of species distributions in tropical rainforest worldwide (e.g. Swaine, 1996; Bongers *et al.*, 1999; Pyke *et* *al.*, 2001; Engelbrecht *et al.*, 2007). Meanwhile, in a study done in the Congo basin forest, Fayolle *et al.* (2012) found results in contrast to those mentioned and they attribute them to the small range of rainfall (1200-1700 m).

Species richness sometimes shows a hump-disturbed relationship (i.e., the "intermediate disturbance" hypothesis, (Connell, 1978), although it is generally low for tropical forests (Bongers *et al.*, 2009). van der Sande *et al.* (2018) found a marginally significant negative effect of forest disturbance on species richness which according to de Avila *et al.* (2015), an increase in species diversity due to increased light availability and larger differences could appear on longer timescales. On the other hand, the recruitment of pioneer species, which is normally favored by the increased availability of light, maybe inhibited by the low availability of nutrients in the forest, and the low abundance of pioneer species in the landscape surrounding the area (Steege & Hammond, 2001). In the tropical rainforest of Cameroon, many studies have evaluated the impact of human disturbance on tree species diversity and composition (e.g., Tchouto, 2004; Beina, 2011; Fayolle *et al.*, 2012).

I.2.5. Conservation and endemism

Endemism is a situation in which a species is restricted to a particular geographic region as a result of factors such as isolation or in response to abiotic conditions. It is referred to as the uniqueness of the biota of a particular place. The restriction of taxa to particular areas is a consequence of both historical and ecological factors (Morrone, 2008; Prawiradilaga, 2017). The former is invoked to explain how a taxon becomes confined to its present range and the latter to explain the present limits of endemic taxa. Endemic taxa can be classified into autochthonous, allochthonous, taxonomic relicts, biogeographic relicts, neo-endemics, and paleo-endemics (Morrone, 2008).

Areas where the distribution areas of two or more taxa overlap are called areas of endemism. They reflect an ancestral biotic component. If we map the distributional ranges of relatively well-known taxa, the substantial overlapping in their ranges determines an area of endemism (Kerr, 1997). Areas of endemism are successively nested, which means that within larger areas of endemism smaller ones are recognized, and within the latter, there are even smaller ones. This gives the possibility of proposing a hierarchic biogeographical classification employing the following subdivisions: realms, regions, dominions, provinces, and districts.

To reconstruct the historical relationships of areas of endemism, cladistic or vicariance biogeography assumes that the correspondence between taxonomic relationships and area relationships is biogeographically informative (Sanmartín, 2012). It is based on an analogy between biogeography and systematics, where taxa are treated as characters. Patterns of area relationships derived from a cladistic biogeographic analysis are interpreted as secondary biogeographical homology (Kerr, 1997; Morrone, 2008).

Biogeography is the discipline that studies present and past distribution patterns of biological diversity and their underlying environmental (ecological) and historical causes (Sanmartín, 2012). It is known that different geological and climatic events occurring in the past affect the distribution of co-existing taxa over time, establishing correlated diversification patterns and groups of taxa from different time scales (divergence times) in a single area of endemism (Noguera-urbano, 2016; Gámez *et al.*, 2017). Areas of endemism are the basic units in historical biogeographic studies (Morrone, 1994), as well as for conservation biology (Whittaker *et al.*, 2005), and are the result of taxa evolutionary processes (e.g. vicariance/allopatric speciation). An area of endemism is identified by the congruent distribution of two or more taxa (Morrone, 1994; Szumik *et al.*, 2002). Thus, taxa that have similar geographical distributions may have been influenced by common historical factors (Szumik *et al.*, 2002).

I.2.6. Carbon stocks in tropical forest

I.2.6.1. How abiotic factors drive carbon stock

Abiotic conditions designate a nonliving condition such as climate, physical environment, edaphic conditions, and social factors, etc., which influence or affect an ecosystem and its living organisms. They impose physiological limits or can determine which species will survive in a given environment (Soberon & Peterson, 2005; van der Sande, 2016).

Several studies across tropical forests have highlighted that biomass stocks depend on abiotic drivers, in terms of resource availability (water, nutrients, and light), and on forest structure, in terms of vegetation quantity and quality (Lohbeck *et al.*, 2015). The disturbance may modify the vegetation, by removing biomass and opening up the forest canopy, leading to increased light availability, hence enhanced rates of carbon gain in the remaining forest stand (Toledo *et al.*, 2012). Moreover, natural and anthropogenic disturbances, such as logging, have been hypothesized to both enhance and limit species diversity through changes in habitat heterogeneity, shifts in competitive balances among species, the creation of otherwise-rare habitats, and hence light availability (Denslow, 1995). Low disturbance rates over preceding decades are likely to result in greater biomass allocated to fewer stems because when disturbance events are rare, larger older trees should dominate, shading out and thus reducing the growth rates and survival probability of smaller trees (Lewis *et al.*, 2013; Holm *et al.*, 2014).

Moreover, disturbance might affect the physical, chemical and biological characteristics of soils which in turn may have long term consequences for the soil's productivity, nutrient regime, and capability. Temporarily, however, it may increase soil fertility due to increased litter input and increased species diversity due to the establishment of light-demanding species (van der Sande *et al.*, 2018). On a small scale, the heterogeneity within soil types and topography can also influence the variation of soil conditions. Several studies highlight soil texture as a factor that directly and indirectly influences a cascade of relationships between organic matter, ions, and soil drainage. Thus, it was noted as a factor limiting the accumulation of biomass in Amazonian growth forest soils that are sandier and characterized by lower productivity (Zarin *et al.*, 2001). Thereby, this influence on productivity by soil texture may be related to moisture, nutrient availability, and nutrient cycling.

Besides, in tropical forests, aboveground biomass is influenced directly and indirectly (via biotic factors) by local abiotic factors (i.e., climate, soils, topography) (Poorter *et al.*, 2017; van der Sande *et al.*, 2018). For example, topographic heterogeneity and diversity, functional identity, and structural complexity of overstorey trees can influence the variation in light capture by the species that compose it (Ali & Yan, 2017). In the meantime, as soil fertility hypothesis suggested, the physicochemical properties of the soil can strongly influence plant growth (Quesada *et al.*, 2012), species diversity, stand structure and above-ground biomass across forest layers.

I.2.6.2. How biotic factors drive carbon stock?

Biotic conditions are comprised of the set of interactions with other species that modify the species’ ability to maintain populations. These interactions can be either positive (e.g., mutualists seed dispersers, pollinators, etc.) or negative (e.g., competitors, predators, diseases). By limiting or enhancing population processes, interactions can affect distributions (Soberon & Peterson, 2005). According to van der Sande (2016), it refers to vegetation attributes such as taxonomic diversity, trait diversity, community mean trait values and structural attributes.

The diversity and species richness can affect carbon stocks through a variety of mechanisms: (1) niche complementary or facilitation among species is thought to be a key mechanism by which biodiversity affects the rates of resource use that govern the efficiency and productivity of ecosystems (Tilman *et al.*, 2001); (2) the selection effect hypothesis suggesting that diversity effects are caused by a greater chance of one or a few dominant, high biomass species being present in the community (Loreau & Hector, 2001); (3) insurance effect, where more diverse communities have been shown to have higher and more temporally stable ecosystem functioning than less diverse ones, suggesting they should also have a consistently higher level of functioning over time (Allan *et al.*, 2011). Because high productivity could lead to faster accumulation of biomass and these are positively correlated in forests. Thereby, these assumptions about the relationship between species richness and productivity could also be applied to standing biomass (Chisholm *et al.*, 2013).

Besides taxonomic attributes, forest structure attributes, such as stem diameter, tree density, and leaf area index, determine biomass, resource, and productivity (Poorter *et al.*, 2015; Fotis *et al.*, 2018; Ali *et al.*, 2019). Vegetation structure as biotic driver contributes directly to the biomass, but variations in the structure such as leaf stratification could also improve the light capture and hence biomass gain (Poorter *et al.*, 2015). Within communities, structural attributes may vary more strongly than taxonomic attributes due to disturbance while across communities due to environmental gradients, it may have a larger direct impact. Serving as a mechanism for regulating species diversity through plant-plant interactions in natural forests (i.e., niche differentiation based on tree size), variation in tree size could also constitute a potential ecological mechanism for mediating a positive response of aboveground biomass to species diversity (Yachi & Loreau, 2007; Zhang & Chen, 2015). As a result, in natural forests, the effect of species diversity on productivity depends largely on the stand basal area (Bohn & Huth, 2017).

Because the density of high stands induced by biodiversity may result in greater interception of light, aerial biomass could, therefore, be influenced by species diversity and structural complexity of stands by their feedbacks or interactions (Brockerhoff *et al.*, 2017). For instance, species diversity has indirect positive effects on aboveground biomass via tree diameter and height diversity or variation within forest stands (Lewis *et al.*, 2013; Meakem *et al.*, 2018). The abundance of large tree sizes and maximum tree height has a strong positive association with aboveground biomass (Slik *et al.*, 2013; Stephenson *et al.*, 2014)

Forest vertical stratification influences plant light capture and usage (Laurans *et al.*, 2014), thereby shaping species diversity, functional diversity, and aboveground biomass between overstorey and understorey strata. Indeed, light is more plentiful in the overstorey stratum as compared to understorey, whereas the overstorey stratum imposes competitive constraints on the understorey light availability in natural forests (Brenes-Arguedas *et al.*, 2011). As a result, understorey species may adopt a complementarity or conservative strategy, while functional dominance (adult stature) may be more apparent in the overstorey in structuring aboveground biomass (Bartels & Chen, 2010).

I.2.6.3. Spatial variation of carbon stock

There is a strong spatial variation in carbon within tropical forests and particularly between the three tropical forest basins with higher values in tropical Africa and Asia, respectively 197 ± 43 and 185 ± 51 Mg C ha^{-1}, than in South American forests, 135 ± 49 Mg C ha^{-1} (Slik *et al.*, 2013). These variations are explained by the higher frequency of trees over 70 cm in diameter in palaeotropical forests (Africa and Asia). Within the African continent, there are also important spatial variations in carbon stocks. Lewis *et al.* (2013), indicate biomass estimates in Central Africa (202 Mg C ha^{-1}) significantly higher than those of West (143 Mg C ha^{-1}) and Eastern Africa (129 Mg ha^{-1}). These differences in biomass can be explained by the high presence of hyper dominant species in Central Africa, which contribute more than 50% of the world's carbon stocks (Bastin *et al.*, 2015).

At the local level, several authors have also shown significant variations in biomass between different types of African tropical forests. Day *et al.* (2013), indicate variations in aboveground carbon between the different types of dense humid forest in Central Africa and Kuyah *et al.* (2014) between the Miombo forest types in East Africa. These variations are mainly explained by structural differences related to anthropogenic disturbances and/or edaphic and altitudinal gradients. However, floristic composition and structural variables (basal area, height-diameter allometry, etc.) explain a larger part of the spatial variation in carbon in African tropical forests (Marshall *et al.*, 2012; Shirima *et al.*, 2015).

On the one hand, spatial variations in biomass are explained by specific compositions different from forest types (Zapfack, 2005; Fayolle *et al.*, 2012; Zapfack *et al.*, 2013; Bastin *et al.*, 2015; Shirima *et al.*, 2015; Fayolle *et al.*, 2016; Tabue *et al.*, 2016; Zapfack *et al.*, 2016; Fobane, 2017; Bastin *et al.*, 2018; Kabelong *et al.*, 2018). Mature forests where *Gilbertiodendron dewevrei* (Fabaceae - Caesalpinioideae) form single-dominant stands store as much or more above-ground biomass than younger mixed forests in Cameroon (Djuikouo *et al.*, 2010) and the Democratic Republic of Congo (Makana *et al.*, 2011; Kearsley *et al.*, 2013). According to Maniatis *et al.* (2011), forests dominated by trees of the families Olacaceae, Caesalpiniaceae and Burseraceae have a much higher aerial biomass than forests dominated by the families Burseraceae, Myristicaceae and Euphorbiaceae.

CHAPTER II. MATERIAL AND METHODS

II.1. MATERIAL

II.1.1. Location of the study site

The study was conducted within the Doume Communal Forest (DCF) in eastern Cameroon located between 459933.04 Y (S) and 295737.04 X (W). Managed by the Doume municipality, mapping of the area using remote sensing revealed that it is an area of 40402 ha divided into two blocks of different size (22 987.6 ha for block 1 and 17 412.4 ha for block 2; Zekeng *et al*., 2019). The first block shares boundaries with the Doumaintang Communal Forest and Bayong Community Forest while the second block shares boundaries with the Angossas Communal Forest (Fig. 3).

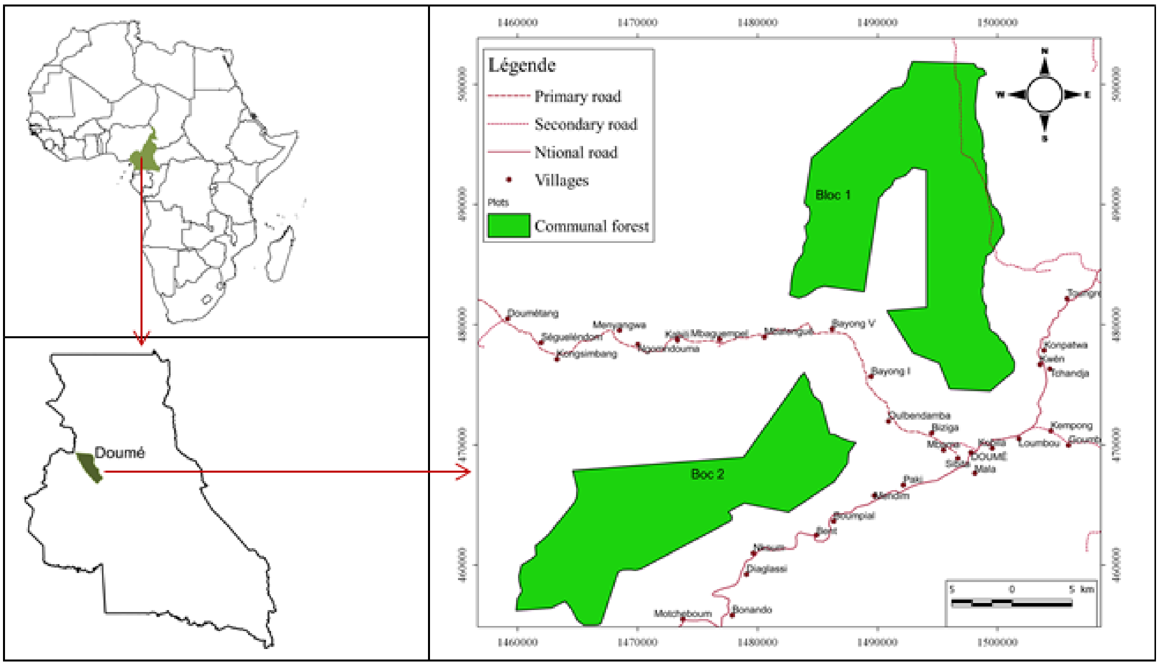

Fig. 3. Map and location of the Doume Communal forest, showing the two blocks

II.1.2. Material for remote sensing, Geographical Information Systems analysis and field inventory

In this study, remote sensing and GIS materials were essentially the GPS used to collect truth ground data and software such as ERDAS 15 and ArcGIS 10.1. The plots installation required the use of materials such as machetes, compasses, GPS, decameter tape. Details of the material used to ensure the success of the fieldwork are given in Table I while the uses of these materials are explained in the corresponding stages of the method.

Table I. List of material used during fieldwork

Material	Use	Quantity
Plot demarcation		
GPS (Garmin 62s)	For prospecting, locating geographic coordinates of plots and different types of land use and land cover.	2
Digital camera	Photographing plants and landscapes	2
Supplementary batteries	for the flashlight, the GPS and digital camera,	20
Compass	To orientate and give the azimuth of the transects	3
Machetes	To delimit the transects	6
Decameters	To measure the length of the transects	4
DBH meter	Measure the tree diameter	4
Clinometer	To record the slope of the plot	4
Botanical inventory		
Scisors	Cut leaf and small branches of botanical samples	2
Newspapers	To conserve botanical specimens	5 kg
Plant press	Press vouchers	2
Alcohol 95°C	To conserve botanical specimens	5 liter
Markers, and ordinary pencils	To mark and take notes	6
Notebook	Take notes in the field	2
Soil collection		
Ziplock plastic paper bags	Pack and conserve soil samples in the field	5 per plot
100 kg bag	Carrying botanical samples	20
Soil auger	Soil sampling	1
Datasheet	To record the field data	150
Camping		
Tents of 6 places	Use for housing in the forest	02
Tents of 5 places	Use for housing in the forest	01
Sleeping bag	To sleep on	10
Flashlight	For lighting	08

II.1.3. Materials for laboratory analyses of soil samples

The material used in the laboratory for analysis constituted equipment and reagents. The details of the equipment and reagents used in this study are given in Table II.

Table II. Material used in the laboratory for soil analysis

Glassware	Apparatus
Crucible	pH meter
Desiccator	Reciprocating shaking machine
Metal sieves 2 mm	Conductivity meter
Pipette 1, 5 and 10 ml	Balance (accuracy 1/1000 of measurement value)
Beakers	Analytical balance
Dispensers	Oven Box
Plastic bottles of 100 ml	Muffle furnace
Buchner funnels	Magnetic stirrer
Filter paper	Malvern Mastersizer Hydro 3000
Spatulas	Refrigerator Thermo Scientific
Test tubes	Shimadzu UV Spectrophotometer 1800
500 ml Erlenmeyer flasks	Kjeldahl digestion and distillation unit
Volumetric flask 1000 and 2 000 ml	
50 ml burettes	
Measuring cylinder	
Reagents	
Hydroxide peroxide (H_2O_2)	
Ammonium acetate	
Concentrated Sulphuric acid 98%	
Reagent grade $K_2Cr_2O_7$	
Ferrous ammonium sulfate ($Fe(NH4)2(SO_4)2.6H_2O$	
Barium diphenylamine sulfate	
$BaCl_2.2H_2O$	
Phosphoric acid	
Copper Sulphate ($CuSO_4.H_2O$)	
Potassium sulfate or anhydrous sodium sulfate	
35% Sodium hydroxide solution	

II.2. METHODS

II.2.1. Sample design and plot demarcation

The inventories were focused only in terra-firme forest avoiding rivers and swampy vegetation types because terra-firme forests represent the majority of the forests in the locality. Remote sensing and GIS were used to select representative and homogeneous vegetation types of terra-firme across forest cover types. The 1 ha (100 x 100 m) plots were subdivided into 25 subplots of 20 m x 20 m following the field protocols of Libalah (2018) described below. However, it should be noted that the 1 ha plot was chosen for this study because of its widespread use in tropical forests across worldwide (Lewis *et al.*, 2013). Furthermore, it allows to obtain results per unit area that are easily comparable to those obtained in other studies. Its use will also reduce the uncertainty associated with extrapolating carbon stocks at the hectare level.

The demarcation of each 1 ha plot involved the use of a compass for orientation in the direction of preference. Following this direction, two baselines of 100 m each were demarcated, one towards the North direction and the other towards the East direction. The two directions were named Y for the North-South axis and X for the East-West axis. In other words, these two baselines were the axes of an orthonormal frame and the insertion point is the origin of the frame (Fig. 4a). A 20 m distance was measured from the origin of the marker (point 0:0) and a pole was planted at this position. The pole was marked with a ribbon depending on the location along with the XY position. The position of the quadrat (a quadrat measuring 20 m x 20 m called S1 in the entire methodology) in the space were numbered according to the XY coordinates of the southwest corner of the quadrat (Fig. 4b).

Once the 1 ha plot was established, five subplots of 5 m x 5 m (S2) were installed in four corners and the center subplots S1 (1, 5, 13, 21 and 25; Fig. 4) to evaluate diameter at 30 cm aboveground level of small stems (1.0-4.9 cm). Additionally in these five subplot S1 (1, 5, 13, 21 and 25; Fig. 5), additional subplots were installed: i) two subplots of 50 cm x 50 cm (S4) at the midpoint of the southern and western margins to evaluate the biomass data of litter and ii) a subplot of 1 m x 1 m (S3) within subplot S2 to collect biomass data of herbaceous plants.

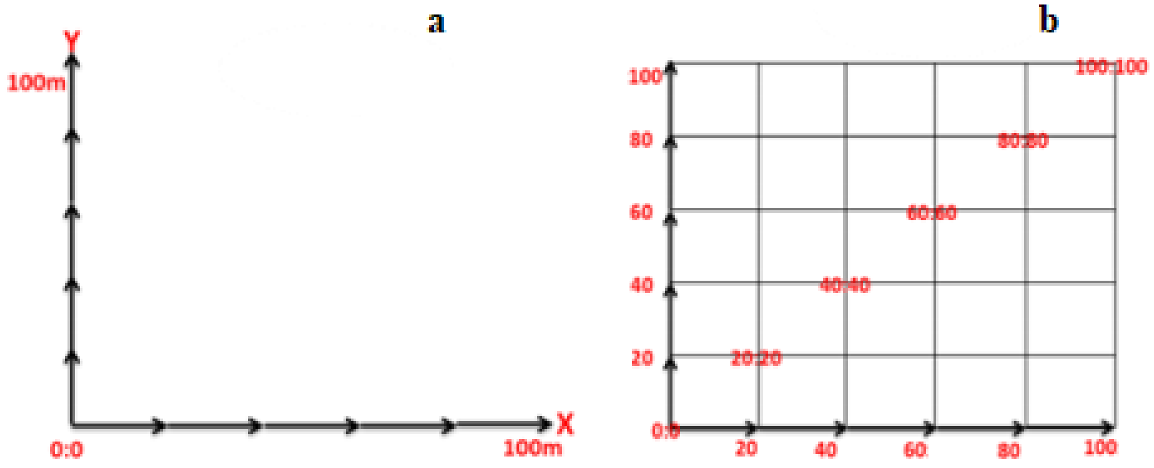

Fig. 4. Demarcation of a one ha plot: a) length and direction of first baselines; b) complete demarcation of quadrats (Libalah, 2018).

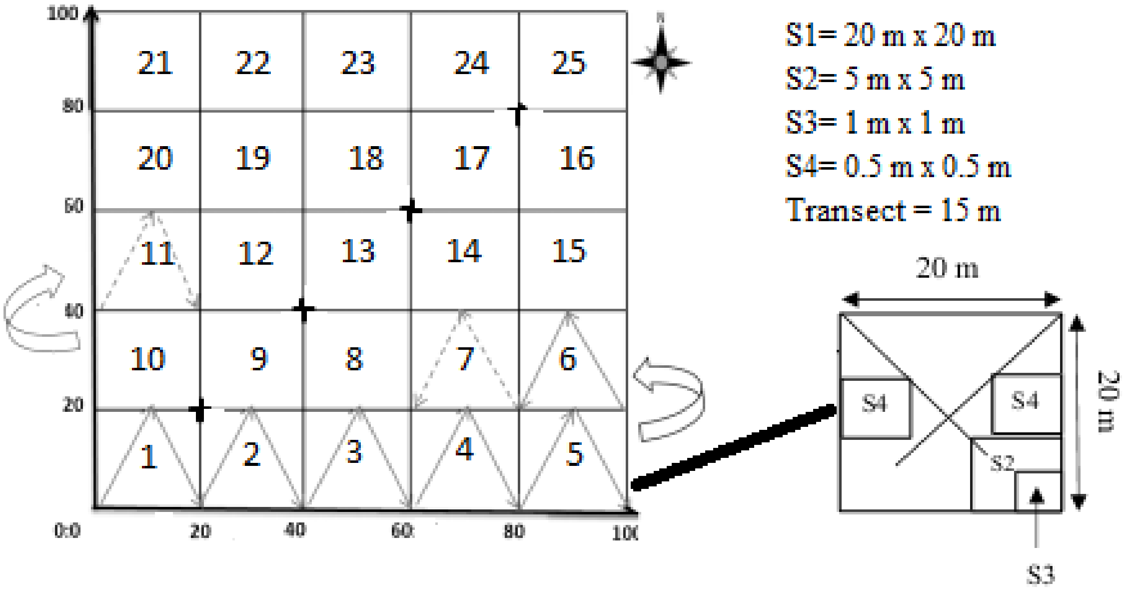

Fig. 5. Complete design sampling plot for field inventory

II.2.2. Data collection

II.2.2.1. Data collection using computer software

II.2.2.1.1. Remote sensing data acquisition

Free cloud cover Landsat 7 Enhance Thematic Mapper Plus (ETM+) images for the years 2000 and 2009, and Landsat 8 Operational Land Imager and Thermal Infrared Sensor (OLI/TIRS) 8 images for the year 2018 were obtained (Table III). The images scenes were designated by path 184/row 057 and acquired from https://earthexplorer.usgs.gov, the United State Geological Survey (USGS) Landsat archive. Furthermore, "Satellite Pour l'Observation de la Terre" (SPOT) 7 images for the study area from Airbus Defence and Space, which were available through the project "Observation Spatiale des Forêts d'Afrique Centrale et de l'Ouest" (OSFACO), http://www.osfaco.org were obtained. However, these SPOT images did not cover the entire study area and were therefore only used to obtain additional reference data to validate further classification.

Table III. Characteristics of remote sensor images used in this study

Path and row	Sensor	Band	Wavelength (µm)	Spatial Resolution
Path 184 rows 57	Landsat 7 Enhanced Thematic Mapper for 2000 and 2008/2009	Band 1-Blue	0.45-0.52	30 m x 30 m
		Band 2-Green	0.52-0.60	
		Band 3-Red	0.63-0.69	
		Band 4-Near Infrared	0.77-0.90	
		Band 5- Shortwave infrared	1.55-1.75	
		Band 6-Thermal infrared	10.40-12.50	
		Band 7- Shortwave infrared	2.09-2.35	
		Band 8-Panchromatic	0.52-0.90	15 m x 15 m
	Landsat 8 OLI/TIRS for 2018 period	Band 1-Coastal aerosol	0.43-0.45	30 m x 30 m
		Band 2-Blue	0.45-0.51	
		Band 3-Green	0.53-0.59	
		Band 4-Red	0.64-0.67	
		Band 5-Near-infrared (NIR)	0.85-0.88	
		Band 6- Shortwave infrared (SWIR) 1	1.57-1.65	
		Band 7-Shortwave infrared (SWIR) 2	2.11-2.29	
		Band 8- panchromatic	0.50-0.68	15 m x 15 m
		Band 9-cirrus	1.36-1.38	30 m x 30 m
		TIRS 1	10.60-11.19	
		TIRS2	11.5-12.51	

II.2.2.1.2. Topographic variables

Topographic variables consisted of elevation, slope, and aspect. In each plot, elevation was recorded at four corners and the center subplots of 20 m x 20 m. Mean elevation was calculated as the mean of the elevation measurements at the four corners and the center of a one ha plot. The slope was calculated as the average angular deviation from the horizontal plane of each of the four triangular planes formed by connecting three of its four corners. Aspect is the direction of a slope's faces; cos (aspect) and sin (aspect) were calculated to make aspect data usable in linear models (Baldeck *et al.*, 2013b; Wang *et al.*, 2017). Elevation and slope variables were obtained in the field using GPS and clinometer, respectively while aspect was obtained by analyzing digital model elevation images in ArcMap 10.5.

II.2.2.2. Field data collection

II.2.2.2.1. Ground truth or reference data for land use/land cover classification

To classify the landscape into different LULC classes, the classification scheme developed by the DCF, derived from earlier field observations in the landscape was used. These included the following LULC classes: swampy *Raphia* forest (RphSF), swampy flooded forest (SwFF), fallow, dense forest with low tree density (DFTLD), dense forest with high tree density (DFHTD), agroforestry systems land (AgrL).

Field surveys were performed to categorize the landscape into the abovementioned LULC classes, for two applications: as training samples for landscape classification (see 'Supervised classification'), and as reference data for accuracy assessment (see 'Post classification'). Four hundred ground-truthing data was collected using a Garmin 62s GPS for all LULC types. The GPS point was taken at the center of the LULC type. The great challenge in tropical dense forests is the accessibility of remote areas of the forest interior. Therefore, the obtained SPOT 7 images over the study area were used to collect fifty sampling points in the remote areas where the field team could not access. To collect the reference data for the 2000-2009 period, Google Earth Pro was used. Additionally, to describe the LULC classes, the management plan of the Doume communal forest was used.

II.2.2.2.2. Tree species inventory

The communal forest of Doumé is spread over an area of 40403 ha with an area of 34778 ha representing the terra-firme forest (Zekeng *et al.*, 2019). A total of 30 plots of 1 ha distributed in the terra-firme forest taking into account the topography and logging factors were installed. This sampling represents a sampling rate of 0.09% of the terra-firme forest of the whole DCF. Within each 1 ha plot, all vascular plants with a DBH ≥ 10 cm hereafter considered as large trees were identified and measured at 1.3 m breast height or, if applicable, 50 cm above the top end of the buttresses or 2 cm above the deformity (Fig. 6a and c) (Condit, 1998). Moreover, within the 1 ha plot, only the height of all palms was carefully measured as it is the only parameter required for estimating their biomass. To ensure nearly uniform coverage of the plot, in every odd-numbered plots (in a checker-board pattern; Fig. 5), trees with a diameter between 5 and 9.9 cm hereafter denoted as understorey trees were identified and measured. Moreover, stems (trees with a diameter between 1 and 5 cm) hereafter considered as small stems, were identified and their diameter at 30 cm ($D_{30\ cm}$) aboveground level was measured (Fig. 6c) in five 5 m x 5 m quadrats of five subplots (the four corners and center) per 1 ha plot (Fig. 5). During the fieldwork, a direct identification was performed by two expert botanists at the time of tree mensuration by observing the leaves, flowers, habit, slash and other diagnostic characters. During the inventory, a unique code was attributed to unidentified species for re-use if encountered later within the plot or locality. Also, a single ecological specimen was collected for further checking and identification at the National Herbarium of Cameroon. A datasheet of each specimen was filled out describing its vegetative characters.

Fig. 6. Tree dendrometric mensuration: a) diameter at breast height; b) diameter at 50 cm above the top of the buttresses; c) diameter of small stems at 30 cm aboveground level.

II.2.2.2.3. Samples of herbaceous vegetation biomass, fine roots and soil

In the five subplots (1, 5, 13, 21, 25; Fig. 5) per 1 ha plot, samples of herbaceous vegetation were collected using a quadrat of 1 m x 1 m. In each quadrat, all the herbaceous vegetation was cut, weighed and packaged. Samples of litter were also collected in the same five subplots up cit. using two quadrats of 50 cm x 50 cm. The litter was collected, weighed in the field using 1 kg spring scales and packaged. The fine roots were collected using destructive methods. Fine roots were collected from one sample with a radius of 2.5 cm and a depth of 20 cm in the five 20 m x 20 m subplots per 1 ha plot. All the samples packaged were carried to the laboratory of Botany and Ecology at the University of Yaounde I in Cameroon.

Moreover, the soil samples were collected using a soil auger at five specific locations of the one ha plot (1, 5, 13, 21, 25; Fig. 5). For each point of soil collection, soil cores were dug at 20 cm depth. In this study it was decided, to sample the soil at the depth of 20 cm because some studies (e.g. Kotto-Same *et al.*, 1997) showed that there is no difference between carbon at 20 cm and 30 cm depth. All samples were bulked, crushed and all organic non-decomposed material (stubbles, roots, stems and rubbish) were removed. Also, five soil cores were collected at five positions to determine their bulk density. All the samples collected were stored in zip-lock bags before shipped to the soil laboratory of the Department of Environmental Science at the University of Botswana.

II.2.2.2.4. Woody debris mensuration

Mensurations of woody debris were measured using the planar-intersect method (Van Wagner, 1968; Brown, 1974). Fine (2.5–9.9 cm diameter) and coarse (≥10 cm diameter) woody debris fractions were measured separately within five 20 m x 20 m subplots using two 15 m long perpendicular transects per subplot (Fig. 5). For each transect, fine debris was sampled along the first 5 m while coarse debris was sampled along the entire transect. Deadwood density (Table IV) was assigned, based on the resistance of wood to the penetration of a metal (in our study a cutlass) into the body of the woody debris (Lambert *et al.*, 1980; Clark *et al.*, 1998b) using the three following decomposition stages (Delaney *et al.*, 1998; Pearson & Brown, 2005):

- class 1 (sound): the sound state included logs that had little or no surface breakdown, intact branches and bark, strong wood structure, and the ability to support its weight;
- class 2 (Intermediaire): the intermediate state included logs that had some surface breakdown, the bark was not always present, and wood structure was weaker, but the bole could support its weight;
- class 3 (Rotten): the rotten state included logs that had an extensive surface breakdown, no bark, poor wood structure, and often could not support their weight.

Table IV. Decomposition state and corresponding wood density (Pearson & Brown, 2005).

Decomposition state	Description	Deadwood density (Mg m^{-3})
Class 1	The sound state included logs that had little or no surface breakdown, intact branches and bark, strong wood structure, and the ability to support its weight	0.43
Class 2	Logs that had some surface breakdown, the bark was not always present, and the wood structure was weaker, but the bole could support its weight.	0.34
Class 3	Logs that had an extensive surface breakdown, no bark, poor wood structure, and often could not support their weight	0.19

II.2.2.2.5. Inventory of standing dead trees

During the botanical inventory and within the 1 ha plot, the DBH and height of standing but dead trees were systematically recorded. Each standing dead tree was assigned to one of the following four decomposition states: 1) snags with branches and twigs resembling a living tree (except for foliage); 2) standing dead trees without twigs but still with large and small branches; 3) standing dead trees with large branches only, and 4) trunk only without branches.

II.2.2.2.6. Disturbance data

The Doume Communal Forest was subject to normal and legal exploitation under the licensing regime between 1971 and 1980. It was also illegally exploited from 2009 to 2014 in the form of wild sawing (Anonyme, 2015). Therefore, some plots were found to have experienced logging of varying intensity, mirroring the status of a large fraction of forests in the Congo basin (Doetinchem *et al*., 2013). During field inventory, in some plots, the diameter of trees stumps showing logging disturbance was estimated, and hence it wasn't possible to account directly for the trees damage due to logging. Therefore, to take into account the entire disturbance (i.e. logging + damage), the basal area of trees damages was quantified using the equation : $\alpha_B = 0.01439 * exp^{(0.1829 * N_{log})}$ (Durrieu de Madron *et al.*, 1998), where α_B is the proportion of damaged basal area and $N_{log,}$ is the number of trees logged.

Logging disturbance was computed as a continuous disturbance variable because logging disturbance depends on the distribution and density of commercial species and is therefore not evenly distributed in space and didn't vary strongly within plots. The relative logging disturbance (in %) was computed per ha, based on the basal area of all trees that were logged + damaged basal area divided by the total pre-logging basal area of the plot.

II.2.2.3. Species identification and taxonomy

The names of each species identified during the fieldwork were corrected/homogenized for synonymies and orthographic problems using several plant databases such as the Plant list database (Hassler, 2018). The Angiosperm Phylogeny Group IV (APG IV) (Byng et *al*., 2016) was used for the botanical nomenclature of families. However, to be able to make a direct comparison with previous studies and according to the specificities of each of the Fabaceae *sensu* subfamilies, APG III (Bremer et *al*., 2009; Caesalpinioideae, Mimosoideae, Faboideae), and the ecological importance of Caesalpinioideae in Central African forests were considered, for each of them separately (Letouzey, 1985; Doucet, 2003; Gonmadje, 2012).

II.2.2.4. Soil analysis in the laboratory

Once, at the University of Botswana, one composite of the soil sample using an equal volume of the five subplots of each 1 ha was made. After determining the soil moisture, all the soil samples were air-dried and then ground to pass a 2 mm mesh sieve. The composite soil sample was used to assess the electrical conductivity (EC), pH, soil moisture content, texture, cation exchange capacity (CEC), soil organic carbon (SOC), Nitrogen (N) and Phosphorus (P).

II.2.2.4.1. Electrical conductivity and pH

Electrical conductivity (EC) and pH were determined using distilled water. For each sample already passed through a 2 mm sieve, 10 g was weighed and put into well-labeled 100 ml plastic bottles. Then 25 ml of H_2O was added into the bottles using dispensers and the bottles were sealed, put on the shaker and secured. It was shaken for two hours at a speed of about 150 rpm after which the sample was removed from the shaker and allowed to settle for one hour. The sample was collected in a beaker. Once the sample solution was obtained, the pH meter and the conductivity meter were calibrated each using a standard solution. The probe was then submerged into the sample and allowed until the pH or the EC reading on the meter was stabilized. This operation was made successively for pH and EC for each of the thirty samples and after each process, the probes of pH meter or EC meter were rinsed with distilled water.

II.2.2.4.2. Soil moisture content

Soil moisture contents (MC) were evaluated successively.

Crucibles were cleaned and dried for 1 hour. The well-marked empty crucible was weighed (W_1); then 10g (W_2) of wet soil was put into the crucible. The crucible containing a moist sample was placed in an oven box at 100 ° C for 48 hours or more until a constant weight was obtained. The crucibles were cooled in a desiccator and the weight (W_3) at room temperature was recorded.

The MC was calculated as a percentage of the dry soil weight as follows:

$$\%MC = \frac{W_2 - W_3}{W_3 - W_1} * 100,$$

where: W_1= Weight of crucible (g); W_2 = Weight of moist soil + crucible (g); W_3 = Weight of dried soil + crucible (g).

II.2.2.4.3. Texture analyses

Particle size was measured using a Malvern Mastersizer 3000E laser particle size analyzer with a Hydro 3000MU pump accessory (Miller & Schaetzl, 2012). Before, beginning the analysis, the software was set according to the particle size and their names.

For our analysis, the refractive index and absorption index values of the soil materials to be 1.520 and 1.000, was assumed respectively. Distilled water was used as the dispersant; it was assumed to have a refractive index of 1.33. A subsample of 0.3 to 0.5 g was removed from a sample bag, using a spoon, and placed into a 500 ml beaker containing distilled water. The Mastersizer 3000E uses the technique of laser diffraction to measure the size of particles. It does this by measuring the intensity of light scattered as a laser beam passes through a dispersed particulate sample. This data is then analyzed to calculate the size of the particles that created the scattering pattern. This is done in less than 10 seconds for one sample.

II.2.2.4.4. Cation exchange capacity

The Cation Exchange Capacity was evaluated using Ammonium Acetate at pH= 7 (Westerman, 1990). In this study, we obtained the CEC by summing the values obtained from the individual determinations of the four elements, Ca^{2+}, Mg^{2+}, K^+, Na^+, extractable acids. Twelve point five g of air-dried soil samples were weighed and put into a well-labeled 100 ml plastics bottles, 25 ml of neutral ammonium acetate solution was added and the bottles were tightly sealed and put on the shaker. After shaking for one hour at a speed of about 155 rpm, the samples were removed from the shaker and allowed to settle for one hour. Each sample mixture was transferred to a Buchner funnel filtered with a moist Whatman filter paper n°. 42 under gentle suction. We continued to leach the soil slowly with small quantities of ammonium acetate until approximately 100 ml of leachate was collected. The leachate was transferred into a 100 ml volumetric flask. A blank solution constituted only of ammonium acetate solution was also prepared. An Agilent 4100 Microwave Plasma Atomic Emission Spectrometer was used to determine the concentrations of the four elements mentioned above. The CEC (cmol+/kg) was estimated by adding together concentrations of exchangeable K (ppm/390), Ca (ppm/200), Mg (ppm/120), Na (ppm/230) and extractable acids.

II.2.2.4.5. Bulk density

At the same sampling points as fine root sampling described above, two soil samples were taken between 0-20 cm depth, for soil organic carbon (SOC) and bulk density using a cylinder of 392.6991 cm^3 (r = 2.5 cm and h = 20 cm). Soil samples were collected at the same time as the field inventory. The soil samples collected for bulk density were oven-dried for 48 hours at

104 ºC, after which dry mass was measured and divided by 392.6991 cm^3 to obtain bulk density in g cm^{-3}.

II.2.2.4.6. Soil organic carbon

The soil organic carbon was analyzed using the Walkley-Black method (Nelson & Sommers, 1982). A weighed amount (1 g) of the air-dried soil sample with a variable quantity of organic matter (3-16 %) was treated with 10 ml of 1.00 N potassium dichromate solution ($K_2Cr_2O_7$) followed by addition of 20 ml of concentrated sulfuric acid. The mixture was gently swirled and left at room temperature in a fume hood for 30 minutes. When the mixture became greenish, a further 10 ml of $K_2Cr_2O_7$ and 20 ml of concentrated sulfuric acid were added and then, 10 ml phosphoric acid was also added. The excess of dichromate was back-titrated potentiometrically with the standard 0.5 N ferrous ammonium sulfate ($Fe(NH_4)_2(SO4)_2*6H_2O$) solution adding 5 ml of the redox indicator when the solution became greenish. Blank titration of the acidic dichromate with ferrous ammonium sulfate solution was performed at the beginning of the batch analysis using the same procedure with no soil sample.

II.2.2.4.7. Available phosphorus

The available Phosphorus in soil was analyzed using the Ascorbic Acid color development method (Westerman, 1990). A weighed amount (5 g) of the air-dried soil samples was put into a 100 ml plastic bottle and then, 50 ml of 0.5 M of sodium bicarbonate ($NaHCO_3$) was added. The mixture was shaken for 30 min and filtered through Whatman paper n°5. One ml of the soil aliquot was pipetted into a test tube and successively 8 ml of distilled water, 1 ml of color solution, and 0.5 ml of ascorbic acid solution were added into the test tube. At each time the test tube was shaken and after putting ascorbic acid, it was allowed to react for 15 minutes.

In parallel, standard P stock solution 100 ppm was prepared by dissolving 0.439 g of KH_2PO_4 in distilled water and diluted to 100 ml volumetric flask. Then, the standard P working solutions were prepared by pipetting 0, 2.0, 4.0, 8.0 ml of 100 ppm standard P stock solution into four 100 ml volumetric flasks and the volume was completed with distilled water. The Standard P curve was prepared by pipetting 1 ml of 0, 2.0, 4.0 and 8.0 ppm standard P working solutions respectively into 4 test tubes and successively 8 ml of distilled water, 1 ml of color solution, and 0.5 ml of ascorbic acid solution were added. At each time the test tube was shaken and after putting ascorbic acid, it was allowed for 15 minutes. The color intensity was then measured using Shimadzu UV Spectrophotometer 1800 with an 880 nm wavelength.

II.2.2.4.8. Total nitrogen

Total Nitrogen was determined using Classical Kjeldahl Methods (Marcó *et al.*, 2002) briefly described as follows: 1 g of air-dried soil sample and 2 g of catalyst mixture (potassium sulfate/ copper sulfate 10:1 m/m) was put into a 100 ml Kjeldahl flask, and 5 ml of concentrated sulfuric acid was added into the flask. The flask was put into an oil bath. The mixture was heated at 150°C for 30 minutes, after which temperature was raised to 360°C, and maintained at this temperature for 90 minutes. At the end of the digestion, the Kjeldahl flask was cooled down to room temperature and the digested solution was transferred to a 100 ml round-bottom flask. The solution was distilled with sodium hydroxide (added in small quantities), which converted the ammonium salt to ammonia. The amount of ammonia present (i.e., the amount of N present in the sample) was determined by back titration. The condensate was absorbed by a solution of boric acid. The ammonia reacted with the acid, the remainder of the acid was titrated with sodium carbonate solution using a methyl orange pH indicator.

II.2.3. Data analysis

II.2.3.1. Determination of land use and land cover change and trajectories

To determine LULC change and trajectories, remote sensing, GIS techniques, and field data were used. The overview of the research design is summarized by the flow chart (Fig. 7).

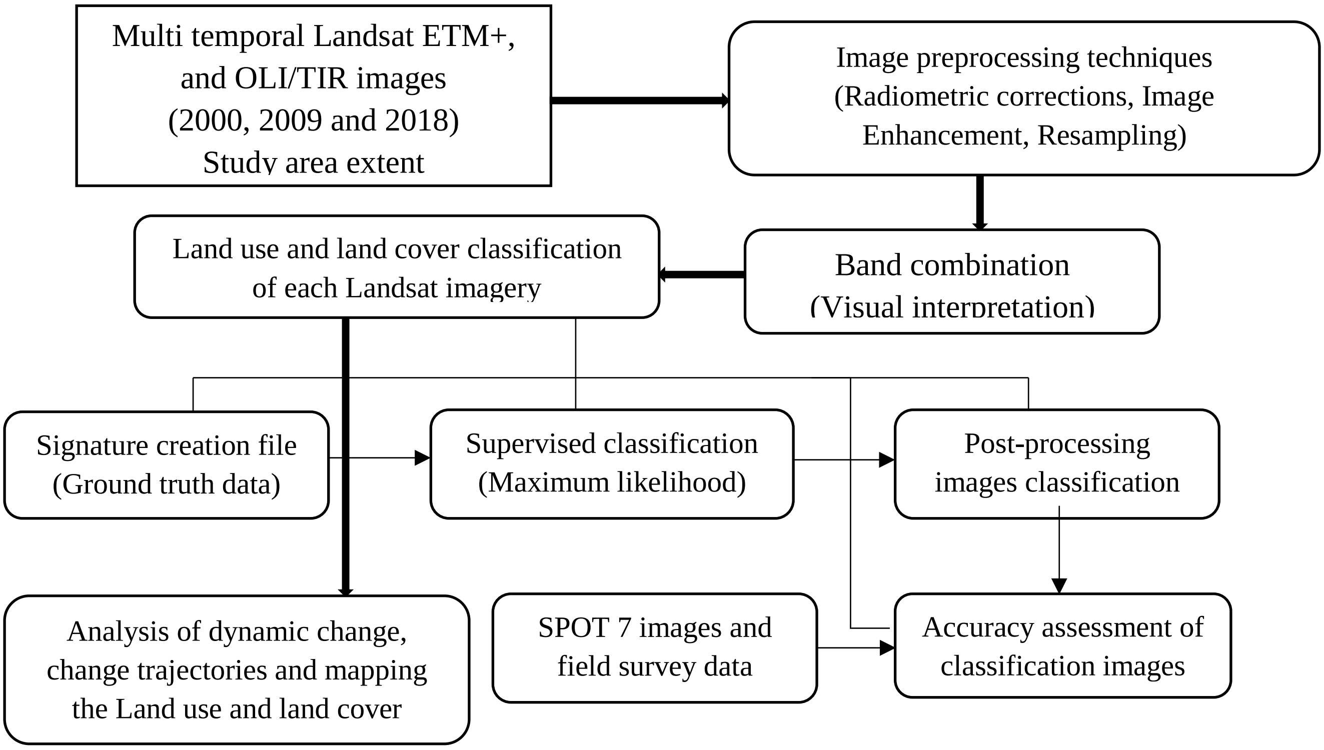

Fig. 7. Flow chart of the remote sensing research methodology

II.2.3.1.1. Images pre-processing

The pre-processing of the Landsat images was done in three steps. Firstly, we had to make sure that information from all bands to be used (seven first bands; Table III) had the same spatial resolution so that their information could be combined. Furthermore, as all the images had previously been related to the Universal Transverse Mercator (UTM) coordinate system 33N, and that their geometric accuracy met our research requirement, there was, therefore, no need for any further geometric correction. Secondly, as the Landsat 7 ETM+ and Landsat 8 OLI/TIRS, did not have the same spatial resolution, there was a need to improve the Landsat 7 ETM+ with 30 m x 30 m so that it had the same spatial resolution of Landsat 8 OLI/TIRS. For that, the image enhancement Ehlers fusion resolution merge technic (Ehlers, 2004), which has the aptitude for creating multispectral images of higher spatial resolution while preserving the spectral characteristics of the lower resolution multispectral images was used (Lu *et al.*, 2011; Chitade & Katiyar, 2012). To avoid the change of digital numbers and keep the images at the same pixel size of 30 m by 30 m, during image-to-image registration, the nearest neighbor resampling algorithm was used to resample (Li *et al.*, 2011) the TM+ and OLI images. Therefore, the spatial resolution of all products was improved from 30 m x 30 m into 15 m x 15 m. Thirdly, for each year's images, the first seven bands were combined into a composite image using the layer-staking function of the remote sensing software ERDAS v.14 The raster images obtained were sub-set to the study area using a boundary vector file.

II.2.3.1.2. Landscape classification

II.2.3.1.2.1. Supervised classification

To classify Landsat pixels into different LULC classes, the often-used maximum likelihood supervised classification (MLC) was used (Lu *et al.*, 2004; Zhang *et al.*, 2016). The MLC is the most common parametric classifier that assumes a normal or near-normal spectral distribution for each feature of interest and equal prior probability among the classes. The MLC is based on the probability that a pixel belongs to a particular class. It assumes that these probabilities are the same for all classes and that the input bands have normal distributions (Li *et al.*, 2011; Lu *et al.*, 2012).

To specify the various pixel values or spectral signatures that should be associated with each LULC, 170 GPS data points were randomly selected and used as training samples, and hence the MLC used the spectral signatures from these training areas to classify the whole image (Lu *et al.*, 2005; Lu *et al.*, 2012; Zhang *et al.*, 2016). Depending on the homogeneity of the LULC type, a polygon of 8 to 40 pixels for each GPS was selected. The selection of training samples was followed by an evaluation of the spectral separability of the training samples to obtain more accurate values of the training samples where necessary. According to literature, the classification could be reasonably made only if the separability of two training samples is sufficient (≥ 10) (Zhang *et al.*, 2016). Finally, the MLC and parallelepiped decision rules were applied to the training samples to analyze each pixel and aggregate the pixels into different LULC types of training samples, and the landscapes were preliminarily classified into different LULC types on a map.

II.2.3.1.2.2. Post classification

To assess the accuracy of the LULC classifications from Landsat images, the level of error contributed by the LULC image, the producer's accuracy, user's accuracy, overall accuracy and kappa coefficient statistics based on a pixel to pixel comparison for the years 2000, 2009 and 2018 were used (Congalton & Green, 2009). The producer's accuracy explains how well a certain LULC type was classified, i.e. how often real features on the ground were correctly shown on the classified map or the probability that a certain land cover type on the ground was classified as such. The producer's accuracy was computed as the number of reference sites classified accurately divided by the total number of reference sites for that class (Congalton & Green, 2009). In contrast, the user's accuracy essentially tells the user how often the class on the map will be present on the ground, which refers to reliability. This was computed as the fraction of the total number of pixels classified on the total number of correct classifications for a particular LULC for a particular class and was used to examine the reliability of classified LULC. The overall accuracy often used to assess the performance of each LULC was computed as the fraction of the total number of correctly identified pixels on the total number of pixels (Congalton & Green, 2009). The kappa statistics is another accuracy indicator, which measures how the classification results compare to values assigned by chance.

II.2.3.1.2.3. Quantification of changes and trajectories

To quantify the LULC change processes and trajectories in DCF during the two periods, a two-stage analysis was performed. Trajectories in this study refer to the pathway taken by a LULC in a specific period. First, a quantification of the area per land cover type for 2000, 2009 and 2018 based on the attribute tables of the land cover maps in ArcGIS 10.5.1 was conducted. In this way, what LULC types increased and what LULC types decreased in land area between 2000–2009 and 2009–2018 and during the whole period 2000–2018 was quantified. The following parameters were computed for each LULC between 2000-2009, 2009-2018 and the whole period (2000-2018): the absolute change in total area (Ci), the proportional change in the area, relative to the initial area (C %), and the annual rate of relative area change (Ar).

This analysis provided the gain or loss for specific LULC types but did not allow us to quantify the LULC change processes and trajectories or to identify what LULC types had replaced the previous LULC. Therefore, in the second stage, to characterize and analyze the LULC change processes and trajectories, which was called trajectory analyses, a change detection at per-pixel using cross-tabulations of the LULC maps. Furthermore, to examine the detailed LULC change trajectories at the per-pixel scale for the three periods following Lu *et al.* (2013), the post-classification approach was used. More specifically, these trajectories analyses consisted of identifying the changes of one Land cover into another land cover and the process implying it. In this study, the following trajectories were identified:

- degradation was defined as the process of decreasing canopy cover or decreasing carbon stocks due to human activities in forests that are remaining forests (Nasi et *al*., 2009);
- deforestation was defined as the direct anthropogenic conversion of forest to non-forest or more clearly a change from forest to either fallow;
- restoration of degraded forest can occur, for instance from the dense forest with low tree density to a dense forest with high tree density;
- abandonment and regeneration of degraded or deforested vegetation cover can occur;
- conversion was defined as the change from any land cover type to a land cover type that is used for the production of commodities or extraction of natural resources;
- such land uses can subsequently be abandoned and regenerated into natural land cover types under certain climatic conditions such as flood period, the area of swampy floods forest increase.

II.2.3.2. Determination of plant diversity and their conservation values

II.2.3.2.1. Plant diversity

II.2.3.2.1.1. Taxonomy diversity

In ecology, diversity implies a measure of both species number and evenness. To describe the diversity patterns across the Doume communal forest plots, alpha diversity indices were used. It represents the number of species in a chosen community (Kent & Coker, 1992), or a set of samples (Magurran, 2004). Diversity indices consider not only the number of species but also whether species are more or less equally abundant or if, on the contrary, one or more species dominate. Diversity of the whole tree community and the tree size groups was assessed using species richness, rarefied species richness, Shannon-Weaver (Shannon & Weaver, 1949), Simpson (Simpson, 1949) and α-Fisher (Fisher *et al.*, 1943) diversity indices, which are the most widely used.

Species richness refers to the number of species present, without any particular regard for the exact area or number of individuals examined. Nevertheless, it is useful to distinguish between numerical species richness, the number of species present in a collection containing a specified number of individuals (Hurlbert, 1971).

Rarefied species richness is the number of species observed when a fixed number of trees are randomly drawn from a plot, therefore removing the confounding influence of tree density on species richness (Porter *et al.*, 2017). Rarefied species richness was calculated here as the number of species at a random draw of 469 stems for the whole tree community, 458 stems for large trees, 62 stems for understorey trees and ten for small stems, as these numbers of individuals were found in all 1 ha plots according to the sampling design and the tree size groups. To determine also how smaller the sample included in this study, the sample-based rarefaction curve was plotted.

The Shannon-Weaver index (Shannon & Weaver, 1949) which assumes that individuals are randomly sampled or distributed from an indefinitely large population and that all species are represented in the sample. The Shannon-Weaver index was computed from the following equation below:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Where P_i is the proportion of individuals belonging to the ith species found in a sample.

The Simpson index (Simpson, 1949) is a measure of the number of species present as well as the relative abundance of each species taken into account. It represents the probability that two randomly selected individuals in the area belong to the same species. It measures how individuals were distributed among species of a population and it is given by:

$$\gamma = \sum_i P_i^2$$

Where Pi is the proportion of individuals belonging to the ith species found in a sample.
Due to its reciprocal character, it starts with the value 1 and rises to the total number of species. Therefore, it lies between 0 and 1.

Trees diversity was also estimated using a common diversity index, the α-Fisher indices (Fisher *et al.*, 1943) which assume that samples are reasonable fit to a log-series. It is independent of sample size and it describes how the individuals are divided among the species.

Fisher-α indices provide good discrimination between sites, it is not very sensitive to density fluctuations and it is normally distributed.

$\alpha = \frac{N(1-x)}{x}$, with x estimated from $\frac{S}{N} = \frac{(1-x)}{x\left[-\ln(1-x)\right]}$

Where N represents the total number of individuals and S the total number of species (Magurran, 1988).

The calculation was done using the R package vegan (Oksanen *et al.*, 2018).

II.2.3.2.1.2. Structural diversity

Previous studies have highlighted that forest structure such as trees density (e.g. Lewis *et al.*, 2013; Porter *et al.*, 2015) and basal area (van der Sande *et al.*, 2017a) drive biomass, and hence this study chooses to determine the relationship between structural diversity and carbon stocks. Therefore, for each tree size group and the whole trees community per plot, the diversity Gini index was calculated using the Gini coefficient (Gini) of tree basal area. The diversity Gini index measures the inequality among values of tree size groups. A diversity Gini index value of zero expresses perfect equality while the value of 1 expresses maximal inequality among values of the tree size distribution (Weiner & Solbrig, 1984).

For each 1 ha plot, and each tree size groups and the whole tree community, stand basal area were calculated. For calculations of stand basal area, all individuals' were included. However, calculations of stand basal area of trees with understorey and small trees were done by averaging the basal area of the thirteen and five subplots respectively to obtain a value which represents the value of 20 x 20 m and 5 x 5 m. Then the average value was multiplied by 25 for understorey trees and by 80 for small stems in order to obtain the stand basal area at the 1 ha plot scale. The stand basal area of trees with DBH ≥ 10 cm was obtained by summing the basal area of all trees. The stand basal area at the whole tree community was obtained by summing the stand basal area at the 1 ha plot of all tree size groups. The basal area of a tree is expressed in m^2 while the stand basal area is expressed in m^2/ha and was calculated using the following formula (Bisseleua & Vidal, 2008):

$$BA = \frac{1}{40000}\left(\pi * DBH^2\right),$$

where DBH is the diameter at breast height of trees given in cm and BA the stand basal area.

II.2.3.2.2. Assessment of plants conservation value and endemism status

Priority species for conservation are defined as species with high conservation value, such as Cameroon's endemic species, rare species, or endangered species (Tchouto *et al.*, 2006; Onana & Cheek, 2011; Onana, 2013). For the establishment of this priority species list, several steps were followed. First, using a management plant of the Doume communal forest and our 30 1 ha plots field inventory, a plant checklist was generated. Secondly, to determine the potential taxa of high conservation priority, several criteria were used: recognized and scientific criteria as determined by the endemicity, and threatened species status and that was done using existing floras and monographs (Onana, 2011; Onana & Cheek, 2011), the IUCN (2019) red data list, the CJB (2019) database (conservatoire du Jardin Botanique de Genève: http://www.villege.ch/musinfo/bd/cjb/africa/recherche.php) and the Plant list database (Hassler, 2018). The notion of rarity is understood differently according to the authors who worked on it, often according to the objectives sought (Tchouto *et al.*, 2006; Gonmadje *et al.*, 2012; Onana, 2013). In this work, the notion of rarity is defined according to the forestry law of Cameroon. Indeed, the forest law of 1994 and its application decree considered that all species with less than one trees per 100 ha are rare. The major African phytochoria (White, 1979; 1983) were used to determine the distribution patterns of the plant check-list. Therefore, each species was assigned to one of the following categories: (1) Widespread (Ws) including pan-African and paleo-tropical, (2) Guineo-Congolian (Gc), (3) Upper and Lower Guinea (Gu), (4) Lower Guinea (Lg), and (5) Cameroon (Cam). Based on the species information above, a list of species of high conservation priority was produced with priority given to taxa that are endemic to Cameroon.

II.2.3.3. Determination of habitat types and their species indicators

Multivariate regression trees technique (MRT) (De'ath, 2002; Larsen & Speckman, 2004) was used to group plots with similar species composition according to topographic variables and soil conditions. Multivariate regression trees technique represents a constrained clustering method that can explore the relationships between multispecies and environmental data (De'ath, 2002). In this study, the MRT was based on a recursive algorithm and the root note consisted of all 30-ha plots (100 x 100 m). The algorithm determines the environmental value threshold that splits the plots into several groups by minimizing the species dissimilarity within groups (Larsen & Speckman, 2004). The MRT used the Bray–Curtis dissimilarity (BCI) index to represent the species dissimilarity between two plots j and k:

$BCI = \sum_i \left(y_{ij} - y_{ik}\right) / \sum_i \left(y_{ij} + y_{ik}\right)$, where y_{ij} is the abundance of the *i*th species in the *j*th plot. Tree size was selected by minimizing the cross-validated relative error (CVRE) with 1 SE rules in all the cases to avoid over-fitting the data. The CVRE ranged from 0 (best predictors) to 1 (poorest predictors). The MRT analysis was performed using 'mvpart' package in R.

It is important to investigate which species are most important for habitat classification. Therefore, indicator species analysis (Dufrene & Legendre, 1997) was used to identify species that were statistically significant indicators of habitat types. The indicator value is defined as the product of the frequency and fidelity for each habitat type, ranging from 0 (species does not occur in a habitat) to 1 (species occurs in all plots of one habitat type and none of the plots of other habitat types). Species with high indicator values for particular habitat types are considered as indicator species. Indicator species analysis was performed using 'labdsv' package in R.

II.2.3.4. Assessment of the contribution of carbon pools and their components to total carbon stocks

To assess the relative contribution of each of the three-carbon pools to total carbon stock (see next section for assessment), a variation partitioning analysis was used. Variation partitioning analysis attempts to partition or resolve the explanatory power of different explanatory variables (i.e. the main pools, aboveground live carbon (AGC; large trees, understorey trees and small stems), aboveground dead carbon (ADC; standing dead trees, fine and coarse woody debris) and belowground carbon (BGC; Fine and coarse roots, Soil organic carbon) in relation to the response variable (i.e. total carbon stock). A first variation partitioning analysis was run using all carbon pools including all its components as explanatory variables in relation to the same response variable (total carbon stock) and then a second variation partitioning analyses was run using only the significant components of each carbon pool (i.e. AGC, ADC and BGC) in relation to the total carbon stock. How components within each carbon pool were correlated, and how all components correlated with total carbon stock were tested.

A tree's size distribution of aboveground carbon stock was calculated and drawn using a bar chart with a distribution range of 10 cm. Linear regression was used to evaluate the contribution of the density of big size trees (>70 cm DBH) on the aboveground and total carbon stocks.

All analyses were performed in R.3.5.1 (R Development Core Team, 2018). Variation partitioning analyses were computed using the varpart function in the vegan package (Oksanen *et al.*, 2018). Pearson correlations were evaluated using the rcorr function of the Hmisc package.

II.2.3.4.1. Carbon stock

This study evaluated 3 carbon pools (aboveground, belowground, and dead carbon), together composed of 12 components: palms, herbaceous vegetation, fine woody debris (2.5-9.9 cm DBH), coarse woody debris (≥ 10 cm), standing dead trees, litter, fine and coarse roots, soil organic carbon, large trees, understorey trees and small stems. The biomass of all components (see next sections) was converted to carbon using conversion factors according to the recommendation of Anonymous (2006). A conversion factor of 0.47 widely used in most studies in tropical African countries (Zapfack *et al.*, 2013; Zapfack *et al.*, 2016; Zekeng *et al.*, 2020) was used for aboveground live biomass (large trees, understorey trees, small stems, palms, herbaceous vegetation) and the default value of 0.50 for the rest of the biomass components (Anonymous, 2006).

II.2.3.4.1.1. Aboveground biomass of large trees

The Aboveground biomass (AGB) for large trees was obtained by converting the DBH into AGB using Eq. (1) of Chave *et al.* (2014) but see Réjou-Méchain *et al.* (2017). This equation is a refinement of a Chave *et al.* (2005) earlier model developed for humid forest using data from multiple sites but that did not include data of African sites. Nevertheless, this allometric equation was used to facilitate the comparisons of our results with those of other studies.

$$AGB = \exp\left[-2.024 - 0.896E + 0.920\ln(WD) + 2.795\ln(DBH) - 0.0461\left[\ln(DBH)^2\right]\right] \qquad (1)$$

Where E is a measure of environmental stress of the site, which depends on temperature seasonality and water deficit and is extracted from http://chave.ups-tlse.fr/pantropical_allometry/readlayers.r with the retrieve_raster function in R. DBH is the diameter at breast height (cm), and WD is the wood density (g cm^{-3}). WD was based on local wood density if available, and otherwise on wood density obtained from the Global Wood Density Database (Chave *et al.*, 2009; Zanne *et al.*, 2009). For 61.5% of the species in the plots species-level, WD was used while for 31.9% of the species-genus- or family-average WD was used. For the few cases (forty-six species) without genus- or family-level WD (5.6%), WD averaged (of species where wood density is available) per plot was used. Note that this wood density assignation also included understorey trees and small stems, of which AGB estimation is explained in the next section. The AGB for the large trees of the twenty-five 20 m x 20 m subplots were summed to give the AGB in Mg ha^{-1}.

II.2.3.4.1.2. Aboveground biomass of understorey trees and small stems

The DBH of understorey trees was converted to AGB using Eq. (1), while D_{30} cm of small stems was converted to AGB using Eq. (2) developed by Ntonmen Yonkeu (unpublished data). That equation was developed using a sample of 793 trees of diameter range between 1 to 5 cm and the model performance criteria were the relative root mean square error (0.200), residual standard error of the estimate (0.433), adjusted coefficient of determination (0.852), Akaike Information Criterion (928) and correction factor (CF; 0.09). The AGB of understorey trees in the 13 subplots was averaged and multiplied by 25 to provide AGB in Mg ha^{-1}, and the AGB of small stems in the five subplots was averaged and multiplied by 400 to scale it to Mg ha^{-1}.

$$AGB_{Small\_stems} = \exp\left[-2.145 + 2.451 * \ln(D) + 1.120 * \ln(WD)\right] * CF \qquad (2)$$

II.2.3.4.1.3. Aboveground biomass of palms

The height of palms collected in the field was converted to AGB using the Eq. (3) developed by Frangi & Lugo (1985). As there are no available allometric equations developed destructively for palms in the Congo basin, equation (3) developed for Amazonian (Neotropical) forest was used.

$$AGB_{Palms} = (10.0 + (6.4 * H)) \qquad (3)$$

II.2.3.4.1.4. Aboveground biomass of herbaceous vegetation

The Samples of herbaceous vegetation were oven-dried at a temperature of 75 °C until a constant dry mass was obtained (Segura & Kanninen, 2005) in the laboratory of Botany and Ecology at the University of Yaounde I. The average biomass per plot was expressed in Mg ha^{-1}.

II.2.3.4.1.5. Necromass of fine and coarse woody debris

Necromass of deadwood debris previously measured was estimated using Eq. (4) from Pearson & Brown (2005) as follows:

$$Necromass(Mg.ha^{-1}) = \frac{\pi^2 WD \sum_{i=1}^{n}\left(d_1^2 + d_2^2 + ... + d_n^2\right)}{8L} \qquad (4)$$

Where WD is wood density (g cm^{-3}), d_1, d_2,…, dn represent the diameters of the intersected pieces of dead wood given in m, and L is the total length of the transect in m.

The necromass of each state was summed to obtain necromass woody debris.

II.2.3.4.1.6. Necromass of standing dead trees

Necromass of standing dead trees was estimated according to the decomposition states of the three. Dry necromass of snags with intact crowns (decomposition states 1-3) was estimated using allometric Eq. (5) of Djomo & Chimi (2017), with values reduced by 2.5 % for state 1 and 17.5% for states 2 and 3, to compensate for the loss of leaves, twigs and small branches (Pearson & Brown, 2005; Pearson *et al.*, 2007). The allometric model developed by Djomo & Chimi up cit., which requires only tree diameter, was used to estimate the AGB because dead trees could not be identified to the species level. For the standing dead trees without crowns (decomposition state 4), necromass was estimated using Eq. (6) (Graça *et al.*, 1999). The mass of the standing dead tree at the scale of hectare was obtained by summing the values obtained in all 20 m x 20 m plots.

$$AGB = \exp^{(-2.688+2.578*\ln(DBH))} \qquad (5)$$

$$Necromass = BA*h*WD*F \qquad (6)$$

Where BA is the basal area ($m^{2.}$), ***h*** is the commercial height (m), ***F*** is the form factor (0.78) and WD is the wood density (Mg m^{-3}). Here, as all the dead trees inventoried have the sound characteristic, the wood density of 0.43 Mg m^{-3} was used (Brown & Pearson, 2005).

II.2.3.4.1.7. Litter

Biomass of the litter was estimated using two quadrats of 50 cm x 50 cm within five 20 m x 20 m subplots of 1 ha used for herbaceous inventory. The litter was collected, weighed using 1 kg spring scales in the field, packaged and oven-dried at 80 °C until the constant dry weight was obtained (Pearson & Brown, 2005; Pearson *et al.*, 2007). The average biomass of litter was scaled to Mg ha^{-1}.

II.2.3.4.1.8. Fine and coarse roots biomass

Coarse root biomass was estimated based on published root: shoot biomass ratios, and fine root biomass was sampled from the field. Biomass of coarse root trees with DBH $\geq$ 5 cm corresponds to 0.235 AGB of the corresponding tree (Mokany *et al.*, 2006; Nasi *et al.*, 2009) while for trees with diameter < 5 cm it corresponds to 0.32 AGB (Djomo *et al.*, 2011). Fine root biomass was estimated using destructive methods. The fine roots collected during the fieldwork were oven-dried for 48 hours at 80 ºC and weighted. The fine root mass of the five sampling points per ha was averaged and scaled to Mg ha^{-1} of 20 cm depth (i.e. 2000 m^3), to compare values with aboveground biomass stocks that were also expressed in Mg ha^{-1}.

II.2.3.4.1.9. Soil organic carbon

The percentage of soil organic carbon was obtained using the following formula:

$$\text{SOC }(\%) = \frac{0.396}{m} * [a * molarity] - [b * molarity],$$

where: the letters a and b represent the volume of 1.00 N $K_2Cr_2O_7$ and 0.5 N ferrous ammonium sulfate solution respectively; m represent the mass of the soil sample.

As this method suffers from some limitation to extract stable and recalcitrant carbon forms (Allison, 1960; De Vos *et al.*, 2007; Lettens *et al.*, 2007), and hence may result in an underestimation of the carbon concentration, a correction factor of 1.32 to compensate the incomplete oxidation was used (Walkley & Black, 1934). The volume of 2000 m^3 was multiplied by the percentage of SOC and the dry bulk density of the soil to obtain Mg C ha^{-1} in the upper 20 cm depth.

II.2.3.4.2. Uncertainty estimates of carbon pools and components

For each carbon pool and its components, the total uncertainty was estimated in two ways: the uncertainty of each pool within plots due to measurement errors (S_{within}) and the spatial variation among plots ($S_{between}$). For all components, the spatial variation ($S_{between}$) was calculated as the mean standard deviation of the mean among plots. For all trees with DBH ≥5 cm, the AGBmontecarlo function available in the BIOMASS library (Réjou-Méchain *et al.*, 2017) was used to assess the S_{within} uncertainty due to error propagation of the measurements of DBH, WD and allometric model. As different equations to AGB for all trees with diameter between 1 and 4.9 cm was used, their S_{within} uncertainty was calculated as $\sigma_A = B\sqrt{\exp(MSE) - 1}$ (Sierra *et al.*, 2007), with *B* as the estimate of the average carbon for small stems, and MSE the mean square error from the biomass equation 3. To estimate the S_{within} uncertainty of all dead carbon components, fine roots, and soil carbon components, the average variation between the subplots within the plot was used. The spatial variation ($S_{between}$) was estimated as the standard deviation of the mean carbon among plots. According to Sierra *et al.*

(2007), using the estimated uncertainty of each component and assuming normal distributions for the averages, a Monte Carlo procedure to estimate the uncertainty of the final estimates of each carbon pools (i.e. AGC, ADC, BGC, TAGC and Total carbon) were used. Total uncertainty (S_{total}), was estimated as the square of the sum of the S_{within} and $S_{between}$ uncertainties for every pool and component ($S^2_{total} = S^2_{within} + S^2_{between}$; Sierra *et al*., 2007).

II.2.3.5. Assessment of abiotic and biotic effects on aboveground carbon stocks

The Structural Equation models (SEMs) offers the possibility to test multivariate and hierarchical of direct and indirect relationships among the measured variables (Shipley, 2016). Therefore, this study examined both direct and indirect relationships through taxonomic diversity and diversity Gini causal effects of abiotic factors (topography, soil conditions and logging disturbance) on AGC stocks of small stems, understorey trees, large trees and the whole tree community (Fig. 8) using SEMs. It also examined the relationships between biotic variables (taxonomic diversity and diversity Gini) and AGC stocks of small stems, understorey trees, large trees and the whole tree community using also SEMs. Because many interactions among the predictive variables could be detected (e.g. as the topography variables influencing soil texture or soil fertility), the number of possible models and the number of explanatory variables per model were limited by evaluating only the framework corresponding to our *a priori*, as simple as possible hypothesis (see Fig. 8).

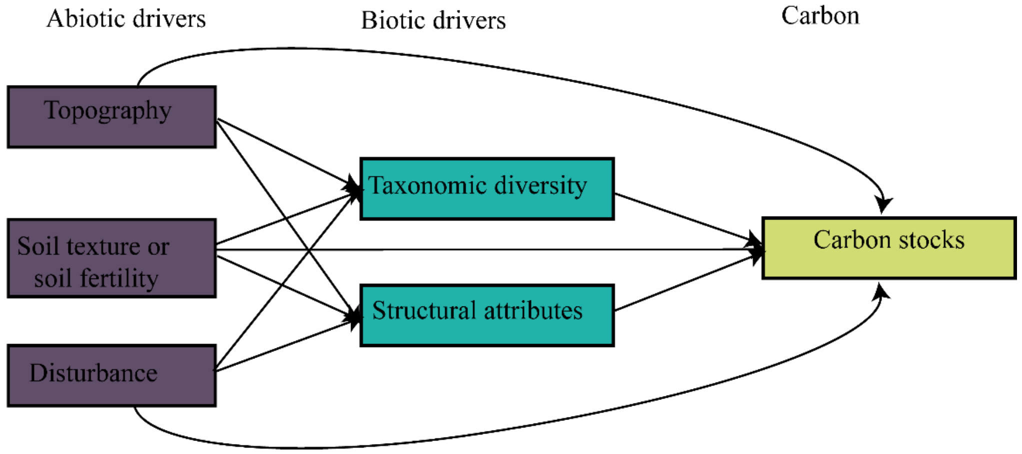

Fig. 8. Conceptual framework linking abiotic drivers (topography, soil texture/fertility and disturbance) and biotic drivers (taxonomic diversity and structural attributes) to carbon stocks. Disturbance is included as abiotic drivers because it affects forest (modify from Poorter *et al*., 2015).

Due to the multiple variables used as an indicator for abiotic variables (soil and topographic variables) and taxonomic diversity, subsets regression analyses to select one for topographic and taxonomic variables or two variables for soil with the highest relative importance value for aboveground carbon stocks were first performed. Soil variables were represented by soil texture (i.e. the proportion of clay, silt, and sand), soil fertility (i.e. CEC, $C:N_{soil}$, EC, MC, MC, $N:P_{soil}$, $N_{soil,}$ $P_{soil,}$ pH), while topographic was represented by five variables (sine and cosine of aspect, elevation, terrain curvature, and terrain slope) and taxonomic diversity, was represented by three (richness, rarefied richness, and Shannon-Weaver index). Disturbance and structural diversity were included in all SEMs. Then per carbon stock variable, a maximum of several SEMs was tested, from which the SEM with the highest explained variation (R^2) of the carbon stocks was selected. The overall fit of the SEMs was assessed using χ^2 – square test (a p-value > 0.05 would indicate an absence of significant deviations between data and model).

All analyses were performed in R 3.5.1. The lme function of the nlme package, and structural equation models with the sem function of the lavaan package were used (Rosseel, 2012). For all subsets regression analyses and model averaging, the lm function for the linear regression models, the dredge function and the model.avg function of the MuMIn package (Barton, 2015) were used respectively.

CHAPTER III. RESULTS AND DISCUSSION

III.1. RESULTS

III.1.1. Land use and land cover dynamics

III.1.1.1. Classification accuracies

The computed error matrices for the classified images revealed an overall accuracy of over 80 % for the three classification dates and an overall kappa statistics of over 74 % in the classification of the three periods (Table V). The Classification of LULC using the Landsat 8 OLI for the year 2018 gave the highest classification accuracy (89.45 %) and kappa statistics (0.87) compared to the Landsat 7 ETM+ images used for the years 2000 and 2009 (Table V).

Table V. Accuracy assessment results for the three periods in the study area.
LULC types – AgrL, DFHTD, DFLTD, RphSF and SwFF represent agroforestry systems Land, dense forest with high tree density, dense forest with low tree density, swampy *Raphia* forest and swampy flooded forest respectively. RT and CT represent row total and column total respectively.

Accuracy assessment for the 2000 classified image										
LULC types	AgrL	DFHTD	DFLTD	RphSF	SwFF	fallow	RT	CT	Producers Accuracy (%)	Users Accuracy (%)
AgrL	24	0	0	4	0	0	28	26	92.31	85.71
DFHTD	0	15	3	0	2	0	20	17	88.24	75.00
DFLTD	0	1	70	10	7	0	88	90	77.78	79.55
RphSF	2	0	12	48	1	0	63	65	73.85	76.19
SwFF	0	1	4	3	45	0	53	55	81.82	84.91
Fallow	0	0	1	0	0	3	4	3	100.00	75.00
Overall Classification Accuracy = 80.08 % ; kappa statistics: 0.74										
Accuracy assessment for the 2009 classified image										
AgrL	9	7	0	0	0	2	18	86	95.35	50.00
DFHTD	1	46	3	1	2	2	55	22	77.27	83.64
DFLTD	1	3	17	0	0	0	21	62	88.71	80.95
RphSF	1	1	1	5	0	0	8	61	75.41	62.50
SwFF	4	3	0	2	82	3	94	9	55.56	87.23
Fallow	0	1	1	1	2	55	60	16	56.25	91.67
Overall Classification Accuracy = 83.59 % ; kappa = 0.78										
Accuracy assessment for the 2018 classified image										
AgrL	3	0	0	0	0	0	3	6	50.00	100.00
DFHTD	0	41	1	0	1	0	43	51	98.15	94.64
DFLTD	1	2	53	0	2	1	59	54	80.39	89.13
RphSF	2	1	0	51	1	0	55	54	94.44	92.73
SwFF	0	5	0	3	61	4	73	66	92.42	83.56
Fallow	0	2	0	0	1	20	23	25	80.00	86.96
Overall Classification Accuracy = 89.45 % ; kappa statistics = 0.87										

III.1.1.2. Status and dynamics of land use and land cover in Doume Communal forest

The LULC map comparisons showed that in 2000, most of the areas in the DCF were covered with forest (39520 ha; 98 %) and that about 256.94 ha representing 0.65 % of this forest area was lost between 2000 and 2009 (Fig. 9; Table VI).

Table VI. Land use and land cover changes from 2000 to 2009 in the Doume Communal forest. LULC types – AgrL, DFHTD, DFLTD, RphSF, and SwFF represent agroforestry systems Land, dense forest with high tree density, dense forest with low tree density, swampy *Raphia* forest, and swampy flooded forest respectively.

LULC type	Area (ha)	%	Area (ha)	%	Area (ha)	%	Annual Change rate (ha)	%
	2000		2009		LULC change between 2000 and 2009			
AgrL	882.54	2.18	1139.48	2.82	256.94	29.11	28.55	3.23
DFHTD	23943.03	59.26	22843.50	56.54	-1099.54	-4.59	-122.17	-0.51
DFLTD	12239.92	30.30	13308.69	32.94	1068.76	8.73	118.75	0.97
RphSF	2010.26	4.98	1934.33	4.79	-75.93	-3.78	-8.44	-0.42
SwFF	1170.93	2.90	900.95	2.23	-269.98	-23.06	-30.00	-2.56
Fallow	155.37	0.38	275.55	0.68	120.18	77.35	13.35	8.59
Total	40402.50	100	40402.50	100	-	-	-	-
	2009		2018		LULC change between 2009 and 2018			
AgrL	1139.48	2.82	2561.10	6.34	1421.62	124.76	142.16	12.48
DFHTD	22843.50	56.54	18979.44	46.98	-3864.06	-16.92	-386.41	-1.69
DFLTD	13308.69	32.94	15799.00	39.10	2490.31	18.71	249.03	1.87
RphSF	1934.33	4.79	1731.31	4.29	-203.02	-10.50	-20.30	-1.05
SwFF	900.95	2.23	875.88	2.17	-25.07	-2.78	-2.51	-0.28
Fallow	275.55	0.68	455.77	1.13	180.22	65.40	18.02	6.54
Total	40402.50	100.00	40402.50	100.00	-	-	-	-
	2000		2018		LULC change between 2000 and 2018			
AgrL	882.54	2.18	2561.10	6.34	1678.56	190.20	88.35	10.01
DFHTD	23943.03	59.26	18979.44	46.98	-4963.59	-20.73	-275.76	-1.09
DFLTD	12239.92	30.30	15799.00	39.10	3559.08	29.08	187..32	1.53
RphSF	2010.26	4.98	1731.31	4.29	-278.94	-13.88	-14.68	-0.73
SwFF	1170.93	2.90	875.88	2.17	-295.05	-25.20	-15.53	-1.33
Fallow	155.37	0.38	455.77	1.13	300.40	193.35	15.81	10.18
Total	40402.50	100	40402.50	100	-	-	-	-

During the two decades, it was observed that the forest land cover was facing deforestation and degradation. It was found that:

- dense forest with high tree density (~22943 ha representing 59 % of the total forest) lost about 5 % of its area between 2000 and 2009 (Fig. 9, Table VI). This loss continued to increase from 2000-2009 (~1099 ha; ~5 %) and 2009–2018 (~3864 ha; ~17 %). This increased loss corresponded to an annual loss of 0.51 and 1.69 % respectively for 2000–2009 and 2009–2018 periods (Table VI);

- not only the dense forest with high trees density surfaces decreased but also the swampy *Raphia* and swampy flooded forests in terms of canopy cover. Swampy *Raphia* forest declined from the 2000–2009 period by ~4 % to ~11 % in the 2009-2018 period while swampy flooded forests declined from the 2000-2009 period by 270 ha (~23%) to 295 (~25 %) (Fig. 9; Table VI).

In contrast, at the same time, significant improvements in other LULC (e.g. agroforestry areas, fallow areas and dense forest with low trees density areas) were observed:

- dense forest with low tree density increased between 2000-2009 and 2009-2018 in terms of land area from 1069 ha (9 %) to 2490 ha (19 %), respectively (Fig. 9, Table VI);
- It was also observed that the area of agroforestry systems had almost tripled from 882 ha in 2000 to almost 2561 ha in 2018 (Table VI). This expansion of agroforestry systems was observed with an annual rate of 10 % during the two decades;
- fallows also increased from 120 ha (78 %) up to 180 ha (65 %) between the first period (2000-2009) and the second period (2009-2018). The changes occurred in the dense forest with high tree density areas over time which are a direct effect of the changes in agroforestry systems land, dense forest with low density and fallow in 19 years (Table VI).

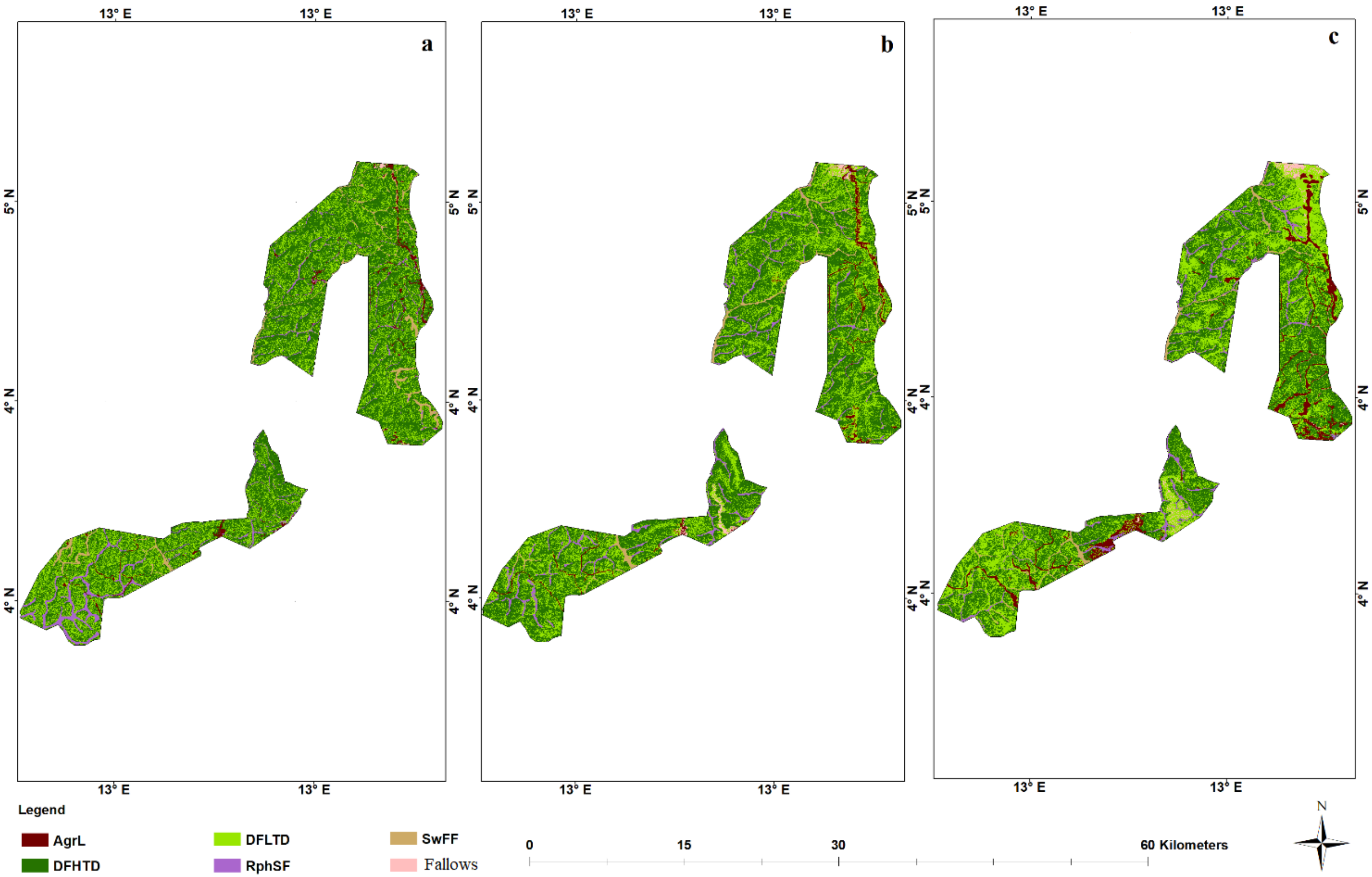

Fig. 9. Spatio-temporal land use and land cover type: a) 2000; b) 2009; and c) 2018 in the study area.

LULC types – AgrL, DFHTD, DFLTD, RphSF, SwFF and Fallow represent agroforestry systems Land, dense forest with high tree density, dense forest with low tree density, swampy *Raphia* forest and swampy flooded forest, respectively.

III.1.1.3. Quantification and schematic presentation of land use and land cover change processes and trajectories

III.1.1.3.1. First period 2000 -2009

The quantification of LULC change during the first decade showed that 20366 ha of the area was changed into different LULC (Table VII). This change occurred through multiple-step trajectories (Fig. 10), meaning that land cover changed from one type to several other LULC types.

Degradation represents the dominant trajectory (see thick arrows Fig. 10), with 38.81 % and an annual change rate of 3.88 % (Table VII). It occurred when dense forest with high trees density changed into the dense forest with low trees density and swampy *Raphia* forest, as well as a dense forest with low trees density, changed into swampy *Raphia* forest (A: green arrows; Fig. 10).

The results of change and trajectories analyses also showed that, during the first decades, 7372 ha of dense forest with low trees density representing 36.20 % of the study area was restored into the density of high trees with high density (B: pink arrows; Fig. 10).

Deforestation of 1377 ha of the forest to fallows (E: yellow arrows; Fig. 10) represent 6.76 % with an annual rate of 0.68 % of the study area change (Table VII). It was also found that 734 ha of LULC was converted into agroforestry systems (D: red arrow; Fig. 10) which represents 3.60 % with an annual rate of 0.36 % of the study area change (Table VII).

Moreover and surprisingly, some changes were found but it was difficult to explain the mechanism by which they occur. Indeed, it was found that swampy flooded forest, swampy *Raphia* forest, fallows and agroforestry systems were turned into the dense forest (high and low trees density; C: Orange, Fig. 10). It was also found that dense forest (high and low trees density) turned into a swampy flooded forest that occurred under specific climatic conditions.

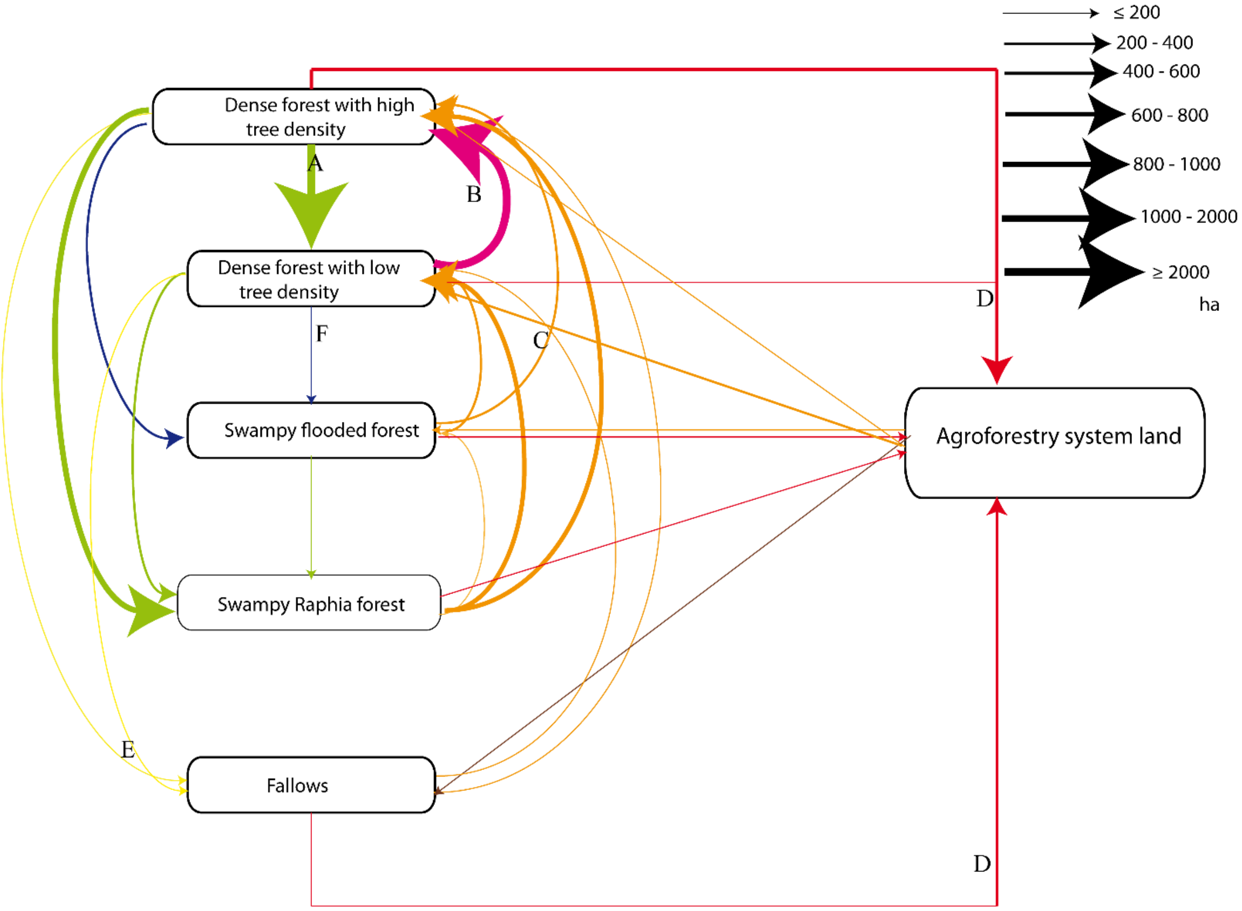

Fig. 10. Quantification and schematic presentation of the land use and land cover change processes and trajectories in the Doume communal forest for the period of 2000-2009. The trajectories: (A: green) degradation; (B: pink) restoration; (C: orange) abandonment and regeneration; (D: red) conversion; (E: yellow) deforestation; (F: blue) the passage of dense forests into swampy flood forest which occurred under specific climatic conditions.

III.1.1.3.2. Second period 2009 -2018

The same change and trajectories were found for the second decades. However, the increase of arrows in Fig. 11 compared to Fig. 10 clearly shows that the area and the different types of land cover changes increased but kept the same set of trajectories in the period 2009–2018 compared to 2000–2009.

Even it represents also the main trajectory, in terms of superficies, the change reduces but in terms of annual change rate, degradation increases during the second decades compared to the first period (Table VII). It occurred when dense forest with high trees density changed into the dense forest with low tree density and swampy *Raphia* forest, as well as a dense forest with low tree density, changed into swampy *Raphia* forest (A: green arrows; Fig. 11).

The results of change and trajectories analyses also showed that, during the first decades, 4283 ha of dense forest with low trees density representing 24.59 % of the study area was restored into a density of high trees with high density (B: pink arrows; Fig. 11).

The same trends as deforestation were also found for deforestation. Indeed, deforestation of 1191 ha of the forest to fallows (E: yellow arrows; Fig. 11) represent 6.84 % with an annual rate of 0.76 % of the study area change (Table VII). Contrary to other trajectories, it was found that conversion has increased approximately three times in the second-decade compared to the first second. Conversion of 1916 ha of LULC into agroforestry systems (D: red arrow; Fig. 11) represent 11 % with an annual rate of 1.20 % of the study area change (Table VII).

During the first decades, it was found out that it was difficult to explain the mechanisms by which some changes occur. Indeed, it was found that swampy flooded forest, swampy *Raphia* forest, fallows and agroforestry systems were turned into the dense forest (high and low trees density; C: Orange, Fig. 11). It was also found that dense forest (high and low trees density) turned into a swampy flooded forest that occurred under specific climatic conditions.

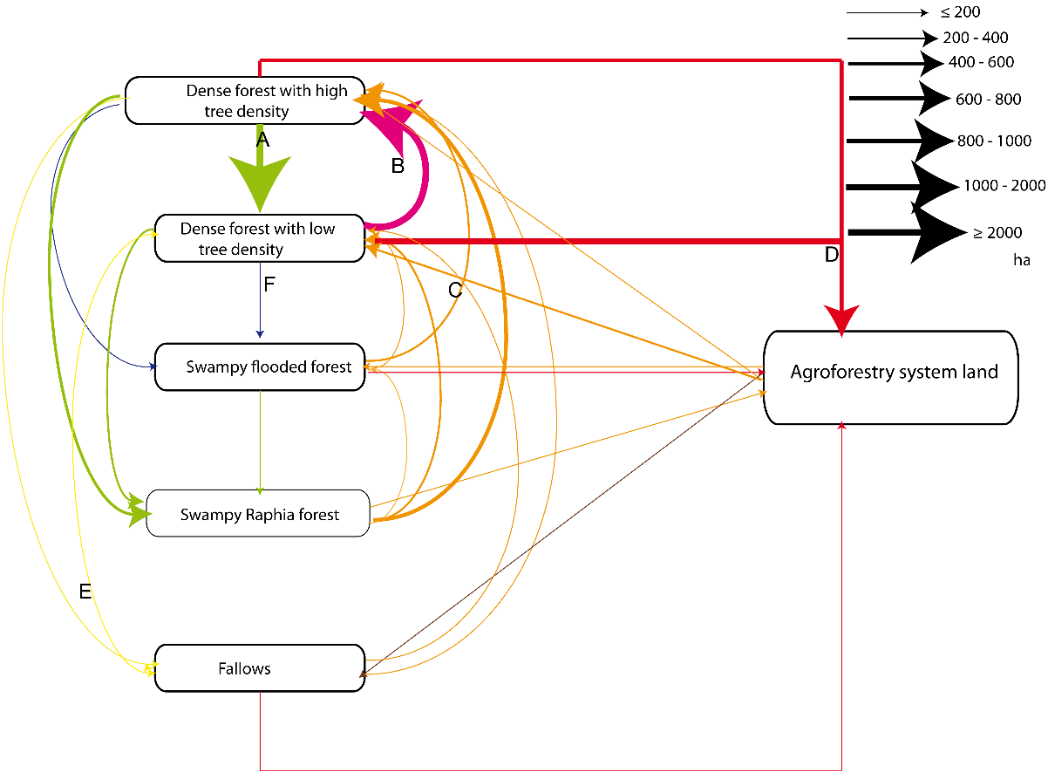

Fig. 11. Quantification and schematic presentation of the land use and land cover change processes and trajectories in the Doume communal forest for the period, 2009-2018. Trajectories: (A: green) degradation; (B: pink) restoration; (C: orange) abandonment and regeneration; (D: red) conversion; (E: yellow) deforestation; (F: blue) the passage of dense forests into swampy flood forest which occurred under specific climatic conditions.

III.1.1.3.3. Synthesis of the entire study period 2000 -2018

Quantification of LULC change showed that, between 2000 and 2018, about 53.45% (~21583 ha) of the study area had changed (Fig. 12; Table VII).

Between 2000 and 2018, about 99 % of the total area of land cover change had changed through multiple-step trajectories (Fig. 12; Table VII), meaning that land cover had changed from one type to several other land cover types within the total study period. Only ~1 % of the total area of land cover change had changed through two-step trajectories between 2000 and 2018, indicating that land cover had changed from one type to a second type and further to a third type.

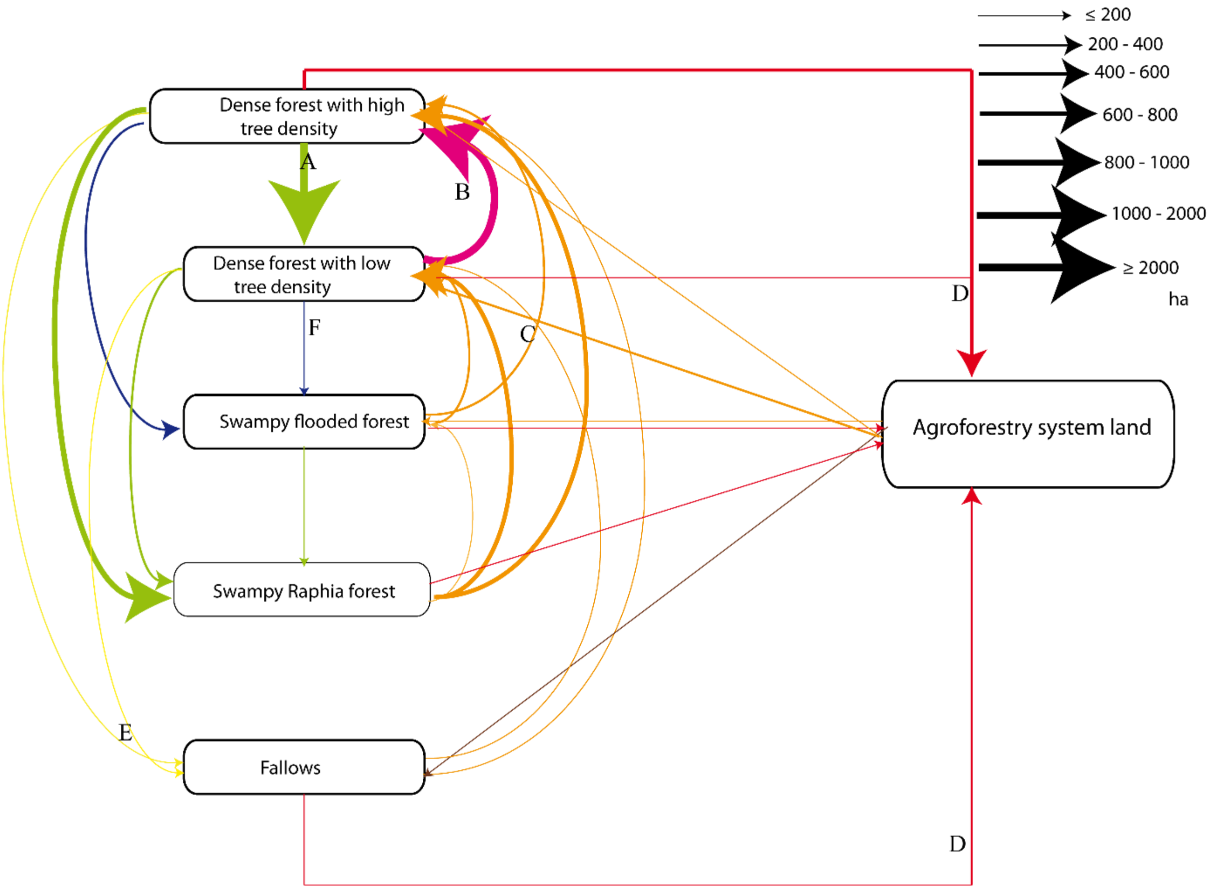

Fig. 12. Quantification and schematic presentation of the land use and land cover change processes and trajectories in the Doume communal forest for the period, 2000-2018. Trajectories: (A: green) degradation; (B: pink) restoration; (C: orange) abandonment and regeneration; (D: red) conversion; (E: yellow) deforestation; (F: blue) the passage of dense forests into swampy flood forest which occurred under specific climatic conditions.

The first type of multiple-step trajectories that had occurred in the landscape (in terms of land area, ~11743 ha in total) involved forest degradation (from the more dense forest with high tree density to more dense forest with low tree density types and swampy *Raphia* forest), deforestation (from the dense forest with high tree density to fallow), and conversion (from the dense forest with high tree density to agroforestry systems.

The second type of multiple-step trajectories involved changes from the dense forest with low tree density (6983 ha in total) to a dense forest with high tree density (i.e., restoration) to swampy *Raphia* forest (i.e. degradation) or fallow (i.e., deforestation), and further to agroforestry systems (i.e., conversions).

The third type of multiple-steps, trajectories involved changes from swampy *Raphia* forest (2008 ha in total) to agroforestry systems (i.e. conversions), and to a dense forest (i.e. abandonment and regeneration);

The four types of multiple steps trajectories involved degradation of agroforestry systems (882 ha in total) into fallow, and abandonment and regeneration (dense forest, and swampy flood forest); and the last multiple steps trajectories involved the conversion of fallow (161 ha) into agroforestry system land, and abandonment and regeneration (dense forest).

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Table VII. Quantification of land use and land cover change trajectories based on remote sensing data that occurred in the periods 2000–2009, 2009–2018 and 2000–2018.

Trajectories	Area (ha)			Area (%)			Annual change rate (%)		
	2000-2009	2009-2018	2000-2018	2000-2009	2009-2018	2000-2018	2000-2009	2009-2018	2000-2018
Deforestation	1377	1191	1481	6.76	6.84	6.86	0.68	0.76	0.38
Degradation	7904	7757	9240	38.81	44.54	42.81	3.88	4.95	2.38
Conversion	734	1916	2164	3.60	11.00	10.02	0.36	1.20	0.55
Restauration	7372	4283	5645	36.20	24.59	26.15	3.62	2.73	1.45
Abandonment, and regeneration	2491	1976	2820	12.23	11.35	13.07	1.22	1.26	0.72
Species colonisation and climatic conditions	488	293	233	2.40	1.68	1.08	0.24	0.19	0.06
Total land Change	20366	17416	21583						
No change land	20016	22966	18799						
TOTAL	40382	40382	40382	100.00	100.00	100.00			

III.1.2. Plant diversity, conservation and endemism

III.1.2.1. Species diversity in the Doume communal forest plots

A total of 22100 stems with a diameter ≥ of 1 cm were recorded within the 30 1 ha total sampling plots. representing 307 species divided into 194 genera and 72 families. Among the total number of stems recorded, 15 168 trees belonged to large trees (DBH ≥ 10 cm), 4567 trees belonged to understorey trees (5 ≤ DBH < 10 cm) and 2010 shrubs belonged to small stems (1 ≤ $D_{30\ \mathrm{cm}}$ < 5 cm). More than, 89 % of morphospecies were identified at the species level, 6 % at the generic level, 2 % at the family level and 3 % remained unidentified. Among the 307 species identified, some species were inventoried at the three size groups (i.e. large trees, understorey trees, and small stems). Hence, 271 species were recorded as large trees, 242 species as understorey trees and 167 species as the small stems.

Rarefaction curve of the whole 30 1 ha sample plots trees species rises more slowly, even at the outset suggesting that the forest trees species composition can be considered as satisfactorily sampled (Fig. 13). This study found that the number of species per plot varied from 109 to 131 species for the whole tree community, from 93 to 116 species for large trees, from 43 to 61 species for understorey trees and 19 to 29 species for small stems.

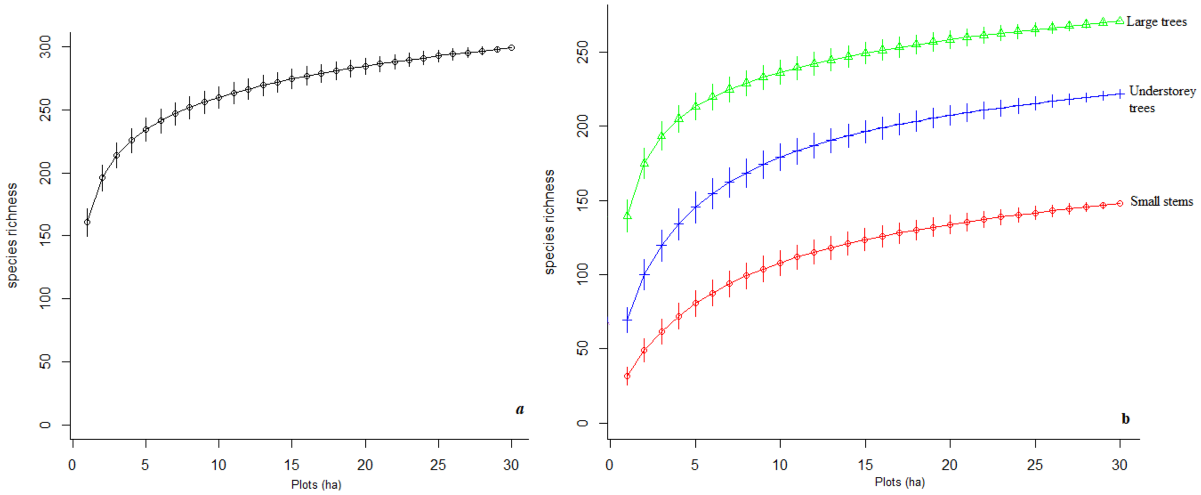

Fig. 13. Rarefaction curve of the: a) whole tree community and b) trees size classes for the 30 1 ha plots of Doume communal forest.

The Shannon-Weaver index for the whole tree community as well as the large trees did not vary too much contrary to understorey trees and small stems. The same trend was found for Simpson and Fisher-α index. However, for small stems, it was found that Simpson index value was too low with a higher variation among the plots than the other trees classes. Contrary, for Fisher-α, it was found low values and low variation among plots than the other trees classes except for the whole tree community.

Table VIII. Average value for species diversity for the whole tree community and trees size classes among the 30 1 ha plots

Estimate parameters	Whole tree community	Large trees	Understorey trees	Small stems
Species richness	121.03 ± 11.98	104.83 ± 11.96	51.63 ± 9.08	24.37 ± 4.81
Shannon-Weaver index	4.05 ± 0.15	3.99 ± 0.19	3.53 ± 0.27	2.79 ± 0.26
Simpson	0.97 ± 0.01	0.97 ± 0.01	0.94 ± 0.03	0.91 ± 0.04
Fisher-α	42.24 ± 5.30	40.38 ± 6.24	30.97 ± 9.10	17.55 ± 5.65

III.1.2.2. Conservation value and endemism

Besides, to the 307 plant species encountered in the thirty 1-ha plots, a provisional plant checklist comprising 23 species of vascular plants (only trees) found in the forest management plan, a complete check-list of 330 species. Of these species, 291 species have been identified at the specific level.

Among the 291 species whose range was known, a small proportion was comprised of widespread species found in various African phytochoria (16 %). Most species in the list are Guineo-Congolian wide (69 %) or restricted to the Upper and Lower Guinea (6 %). However, 25 species (9 %) are only known from the Lower Guinean domain. Of these species, only *Aphanocalyx hedinii* (Leguminosae-Caesalpiniaceae) and *Penianthus camerounensis* (Menispermaceae) are found in Cameroon and restricted to the southwestern and Centre Cameroon, respectively (Table IX).

A list of 50 plant species of high priority for conservation, including rare species, threatened species and Cameroon endemics, with information on their habit and chorology. These include 42 threatened species with the global as well as national level status (Table IX).

Table IX. List of species of high priority for conservation found in the Doume Communal forest.

Chorology: Lg= Lower Guinea; Gc= Guineo-Congolian; Gu = Upper and Lower Guinea; IUCN status: categories of the threat as EN = Endangered; VU= Vulnerable; LC = Least Concern and NT = Near Threatened. Habit: tr = trees and shrub;

Familly	Species	Chorology	Habit	Onana (2011)	Statut de l'IUCN (2019)	Notes
Anacardiaceae	*Antrocaryon micraster*		tr	LC	VU	Rare species with less than 0.01 trees per ha and therefore was excluded for logging
Burseraceae	*Dacryodes igaganga* Aubrév. & Pellegr.	Lg	tr,sh	VU	VU	Only known from few collections in Cameroon and Gabon
Chrysobalanaceae	*Maranthes gabunensis* (Engl.) Prance	Gc	tr	LC	LC	Rare species with less than 0.01 trees per ha, therefore, was excluded for logging in the DCF.
Clusiaceae	*Garcinia kola* Heckel	Gc	tr,sh	VU	VU	
	Garcinia mannii	Gc	tr,sh	VU	VU	
Combretaceae	*Terminalia ivorensis* A. Chev.	Gu	Tr	LC	VU	Rare species with less than 0.02 trees per ha, therefore, was excluded for logging in the DCF
Cordiaceae	*Cordia platythyrsa* Baker	Gc	tr,sh	LC	VU	
Ebenaceae	*Diospyros crassiflora* Hiern	Gc	tr,sh	NT	VU	
	Afzelia africana Pers.	Ws	tr	VU	VU	
	Afzelia bipindensis Harms	Gc	tr,sh	VU	VU	
	Afzelia pachyloba Harms	Gc	tr	VU	VU	
	Aphanocalyx hedinii (A.Chev.) Wieringa	Cam	tr,sh	EN		Rare species with reduced distribution area and know only from few collections from Mujuka in Cameroon.

Leguminosae - Caesalpinioideae	*Bikinia letestui* (Pellegr.) Wieringa	Lg	tr	LC		Rare species with less than 0.01 trees per ha and excluded from logging in the DCF.
	Brachystegia cynometroides Harms	Lg	tr	LC	LC	Rare species with less than 0.01 trees per ha and therefore was excluded from logging in the DCF and known in Cameroon only from a few collections.
	Brachystegia mildbraedii Harms	Lg	tr	LC	LC	Rare species with less than 0.01 trees per ha and therefore was excluded from logging in the DCF.
	Daniella ogea (Harms) Rolfe ex Holland	Gu	tr	LC	LC	Rare species with less than 0.01 trees per ha and therefore was excluded from logging in the DCF.
	Didelotia unifoliolata J.Léonard	Lg	tr	LC	NT	Rare species with less than 0.01 trees per ha and therefore was excluded from logging in the DCF.
	Gossweilerodendron balsamiferum (Vermoesen) Harms	Gc	tr,sh		EN	
	Gossweilerodendron joveri Aubrév.	Gc	tr		VU	
	Tetraberlinia bifoliolata (Harms) Hauman	Gc	tr	LC	LC	Rare species with less than 0.01 trees per ha and therefore was excluded from logging in the DCF.
Leguminosae - Papilionoideae	*Pericopsis elata* (Harms) Meeuwen	Gc	tr	LC	EN	Rare species with less than 0.01 trees per ha and therefore was excluded from logging in the DCF.
	Pterocarpus mildbraedii Harms	Ws	tr,sh	LC	VU	
Leguminosae-Mimosoideae	*Albizia ferruginea* (Guill. and Perr.) Benth.	Gc	tr	LC	VU	
	Bombax brevicuspe Sprague	Gc	tr	LC	VU	
	Mansonia altissima A. Chevalier	Gu	tr,sh	VU	LC	
	Nesogordonia papaverifera (A. Cheval.) Capuron	Gc	tr,sh	VU	VU	

Malvaceae	*Pterygota bequaertii* De Wild.	Gc	tr	LC	VU	
	Pterygota macrocarpa K. Schum.	Gc	tr,sh	LC	VU	
Meliaceae	*Entandrophragma angolense* (Welw.) C. DC.	Ws	tr,sh	VU	VU	
	Entandrophragma candollei Harms	Gc	tr,sh	LC	VU	
	Entandrophragma cylindricum (Sprague) Sprague	Gc	tr,sh	VU	VU	
	Entandrophragma utile (Dawe & Sprague) Sprague	Gc	tr,sh	VU	VU	
	Khaya anthotheca (Welw.) C.DC.	Gc	tr		VU	
	Khaya grandifoliola C. DC.	Ws	tr,sh		VU	
	Khaya ivorensis A. Chev.	Gc	tr	VU	VU	
	Leplaea cedrata (A.Chev.) E.J.M.Koenen & J.J.de Wilde	Gc	tr,sh	VU	VU	
	Leplaea thompsonii (Sprague & Hutch.) E.J.M.Koenen & J.J.de Wilde	Gc	tr,sh	LC	VU	
	Turraeanthus africanus (Welw. ex C. DC.) Pellegr.	Gc	tr,sh	LC	VU	
Menispermaceae	*Penianthus camerounensis* A.J.F.M. Dekker	Cam	sh	LC		Known only from few collections in Centre Cameroon.
Ochnaceae	*Lophira alata* Banks ex Gaertn. fil.	Gc	tr	VU	VU	Rare species with less than 0.01 trees per ha therefore was excluded from logging in the DCF
Ochnaceae	*Ochna calodendron* Gilg & Mildbr.	Gc	tr,sh	VU	LC	
Putranjivaceae	*Drypetes preussii* (Pax) Hutch.	Lg	tr,sh	VU	VU	
Rhizophoraceae	*Anopyxis klaineana* (Pierre) Engl.	*Gc*	tr,sh	NT	VU	
Rubiaceae	*Mitragyna ledermannii* (K.Krause) Ridsdale	Gc	tr		VU	
	Nauclea diderrichii (De Wild. & T.Durand) Merrill	Gc	tr,sh	VU	VU	
Salicaceae	*Dovyalis cameroonensis* Cheek & Ngolan	Gc	tr,sh		CR	

Sapotaceae	*Autranella congolensis* (De Wild.) A.Chev.	Gc	tr	LC	CR	
	Baillonella toxisperma Pierre	Lg	tr,sh	VU	VU	
	Chrysophyllum lacourtianum De Wild.	Gc	tr	LC		Rare species with less than 0.01 trees per ha and therefore was excluded from logging in the DCF.
	Tieghemella africana Pierre	Gc	tr	EN	EN	

III.1.3. Species associations and habitat types

III.1.3.1. Habitat types

The MRT divided the whole tree community as well as the three size classes inventoried in the Doume Communal forest plot into four habitat types (Table X). Surprisingly, it did that based on soil parameters such as pH and sodium (Na) concentration for the whole tree community, large trees and understorey trees (Figs. 14-16; Table X). The four types of habitat defined are as follows: (1) very acidic sandy loamy soil with a low concentration of nutrients ($pH \leq 6.245$ and $Na < 4.535$ cmol kg^{-1}); (2) acidic sandy soil with a low concentration of nutrients ($pH < 6.245$ and $Na < 4.535$ cmol kg^{-1}); (3) loamy sandy soil with average nutrients concentration ($4.535 \leq Na < 6.243$ cmol kg^{-1}); (4) loamy sandy soil with high nutrients concentration ($Na \geq 6.243$ cmol kg^{-1}). The soil Na contents determined the first node for habitat types (break-point = 4.535 cmol kg^{-1}) explaining 19.53% of the standardized species variance (Fig. 14). The soil pH and Na concentration determined the second (break-point = 6.245) and the third (break-point = 6.243 cmol kg^{-1}) nodes which form the four habitat types explaining 12.10 and 5.61% of the total standardized species variance respectively. Most of the inventoried plots in the DCF were covered by loamy sandy soil with high nutrients concentration habitat (50%) and acidic sandy soil with a low concentration of nutrients (30%).

Contrary to the whole tree community, large trees and understorey trees, the MRT divided the small stems class of the DCF plot into four habitats types based on soil parameters such as CEC concentration, MC and aspect of the terrain (Fig. 16; Table X).

III.1.3.2. Abundance and species richness variation among habitats

Despite the imbalance between the numbers of plots constituting each habitat within the different tree size groups, no variation regarding the number of species was found while for stems species abundance a slight difference was found. Within large trees and understorey trees group, habitat 1 ($pH \leq 6.245$; $Na < 4.535$) and habitat 4 ($Na \geq 6.243$) had high average abundance values of stems per hectare than the other habitats. Among the small stems class, the two habitats types with the highest abundances were habitat 3 and habitat 4 with approximatively 6560 and 6380 stems ha^{-1}, respectively (Table X).

Table X. Results of multivariate regression tree analyses and the number of identified indicators species for the whole trees community and the three size groups (i.e. large trees, understorey trees and small stems) in the 30 1 ha of Doume Communal Forest plots, Eastern Cameroon.

Life form	Total number of stem	Total stems in habitat	Total no species	No species per habitat	CRVE	Habitat index	Breakpoint group	No of sites	Stems per ha	Species per ha	No indi species
Whole tree community	22064	3353	307	203		1	pH ≤ 6.245, Na < 4.535	4	5547	117.50	12
		5695		169	0.786	2	pH > 6.245, Na < 4.535	9	5710	116.22	03
		1351		236		3	4.535 ≤ Na < 6.243	2	7281	130.00	09
		11665		255		4	Na ≥ 6.243	15	7248	130.93	05
Large trees	15168	2202	271	178		1	pH ≤ 6.245, Na < 4.535	4	551	95.25	11
		4078		202		2	pH > 6.245, Na < 4.535	9	453	97.00	04
		953		152	0.795	3	4.535 ≤ Na < 6.243	2	477	113.00	08
		7935		228		4	Na ≥ 6.243	15	529	110.67	05
Understorey trees	4567	654	242	117		1	pH ≤ 6.245, Na < 4.535	4	314	50.25	06
		1012		154		2	pH > 6.245, Na < 4.535	9	216	49.56	01
		254		67	0.890	3	4.535 ≤ Na < 6.243	2	244	45.50	04
		2647		199		4	Na ≥ 6.243	15	339	61.47	05
Small stems	2010	691	167	118		1	CEC < 6.49, MC < 33.64	12	4607	25.46	1
		126		44	0.925	2	CEC < 6.49, MC ≥ 33.64	2	5040	29.00	0
		328		73		3	CEC ≥ 6.49, A < (-0.82)	4	6560	26.50	0
		957		132		4	CEC ≥ 6.49, A ≥ (-0.82)	12	6380	32.36	1

III.1.3.3. Community trees habitat association and species variances

The habitat types generated for the tree size group were similar to the habitat types generated for the whole tree community described in the previous section except for the small stems class, that the MRT also generated four different habitat types (Figs. 14-17; Table X). The three nodes constituting the MRT explained 37.23, 37.45, 25.68 and 26.76 % of the total species variances for the whole tree community, large trees, understorey trees, and small stems respectively (Table XI). These species variances were associated with the CRVEs of 0.786, 0.795, 0.890 and 0.925 respectively (Figs. 14-17).

Table XI. Percentage of species variation explained from two components for the whole tree community, large tree, understorey trees, and small stems groups

Variance explained by	Whole tree community	Large trees	Understorey trees	Small stems
MRT	37.23	37.45	25.68	26.76
Unexplained by MRT	62.77	62.55	74.32	73.24

III.1.3.3.1. Whole tree community habitat associations

The MRT analysis gave a four-leaf tree with a split base only on pH and Na (Fig. 14). The three explained 37.23% of the total standardized species variance with CRVE of 0.786 (Fig. 14).

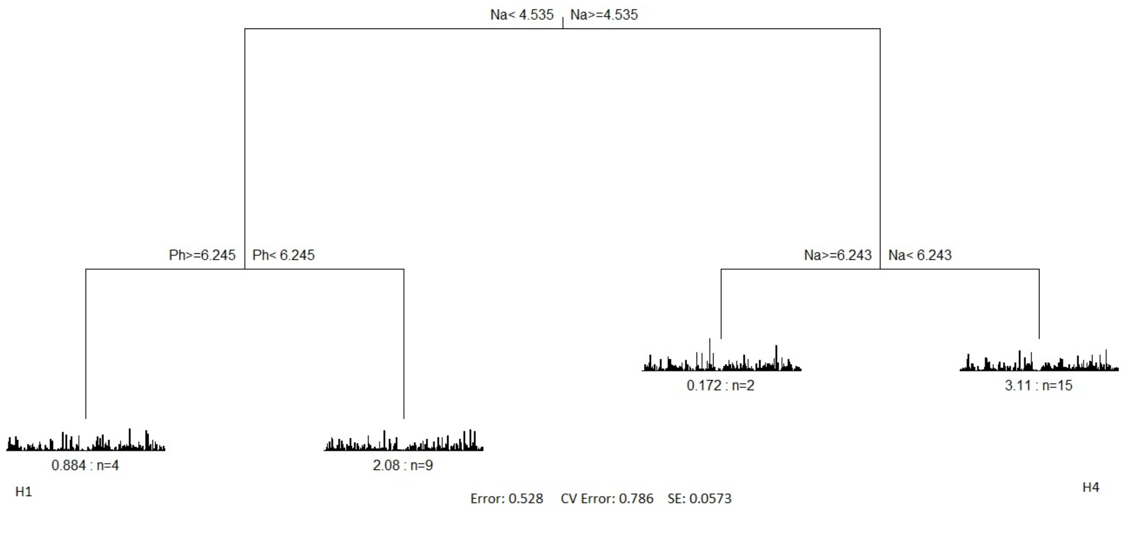

Fig. 14. Community habitat-associations of the whole tree community.
H1-H4 represents the four habitats given by the MRT; Na =sodium; pH= potential in hydrogen; SE= standard error; CV Error = Error coefficient of variation; the bar graphs show the species abundance in each habitat; n=number of plots belonging to that habitat.

However, only 17.71 of 37.23 % of the total standardized species variance was explained by the second and the third node which forms the four habitats in the DCF plots

(Table XII). Species composition varied strongly across the four groups with sites in habitats H3 and H4 (Fig. 14) having only 10 species in common (Table XII). The four associated habitats (H1-H4) are simply defined by the high level of pH (H1), low level of pH (H2), high level of Na (H3) and low-level Na (H4).

Inspection of the bar plots at each habitat showed individual species contribution to each split, and to the composition of the four final habitats. For the second node in which the split forms habitats one and two, 69.72 % of its species variance was explained by twenty-six species. Among the twenty-six species, *Anthocleista schweinfurthii* (Gentianaceae), *Elaeis guineensis* (Arecaceae), and *Margaritaria discoidea* (Phyllanthaceae) strongly determine the second split and are dominant species in habitat one (Table XII). The third node in which the split forms habitats three and four, 63 % of its species variance was explained by twelve species. The species *Grossera macrantha* (Euphorbiaceae) and *Streblus usambarensis* (Moraceae) strongly determine the third split and are dominant species in habitat 3 (Table XII)

Table XII. Variance explained by split nodes and the total tree at the whole tree community

Species	Species variance (%) explained by tree splits and the total tree						
	pH ≤ 6.245	pH > 6.245	Species node 2	Na ≥ 6.243	Na < 6.243	Species node 3	Total tree
Albizia glaberrima	0.15	0.08	1.20				0.23
Albizia zygia	0.12	0.02	2.17				0.14
Annickia chlorantha	0.03	0.15	3.25				0.18
Annona sp.				0.02	0.08	1.24	0.10
Anthocleista schweinfurthii	0.16		5.80				0.16
Anthonotha macrophylla	0.11	0.02	2.10				0.13
Aptandra zenkeri	0.04	0.10	1.77				0.14
Barteria fistulosa	0.01	0.11	2.27				0.12
Berlinia sp.				0.13	0.01	4.25	0.14
Bridelia micrantha	0.07		1.12				0.07
Celtis adolfi-friderici	0.05	0.13	1.55				0.18
Drypetes spp.				0.20	0.08	4.31	0.29
Duboscia macrocarpa	0.03	0.10	1.10				0.12
Elaeis guineensis	0.20	0.02	7.60				0.22
Ficus exasperata	0.12		3.05				0.12
Ficus mucuso	0.14	0.01	3.86				0.15
Grossera macrantha				0.36	0.08	25.02	0.44
Hylodendron gabunense				0.04	0.10	1.15	0.13
Lasiodiscus marmoratus				0.12	0.06	1.13	0.17
Macaranga hurifolia	0.15	0.06	1.92				0.29
Mallotus subulatus	0.14	0.01	3.73				0.15
Margaritaria discoidea	0.18	0.01	6.13				0.19
Milicia excelsa	0.08	0.01	1.28				0.09
Monodora tenuifolia				0.06	0.13	1.63	0.19
Myrianthus arboreus	0.04	0.12	1.55				0.16
Octolobus spectabilis				0.12	0.04	2.05	0.17
Greenwayodendron suaveolens	0.05	0.15	2.24				0.19
Pycnanthus angolensis	0.24	0.16	1.27				0.40
Rhizophora racemosa				0.08	0.01	1.65	0.09
Streblus usambarensis				0.28	0.05	16.37	0.33
Strombosia scheffleri	0.02	0.12	2.27				0.14
Terminalia superba	0.18	0.08	2.61				0.26
Thomandersia hensii	0.07	0.00	1.01	0.00	0.07	1.50	0.14
Trichilia dregeana	0.12	0.23	3.19	0.12	0.23	3.67	0.70
Uapaca guineensis	0.07	0.21	4.66				0.09
Other species	7.65		30.28	3.13		36.03	10.88
Total species variance	12.10		100	5.61		100	17.71

III.1.3.3.2. Large trees habitat association

The MRT analysis gave also four-leaf trees with the splits based on pH and Na (Fig 15). The three nodes constituting the MRT explained 37.45% of the total standardized species variance of all tree species inventoried with CRVE of 0.795. However, only 17.43 of 37.45% of the total standardized species variance was explained by the second and the third node which forms the four habitats in the DCF plots (Table XIII).

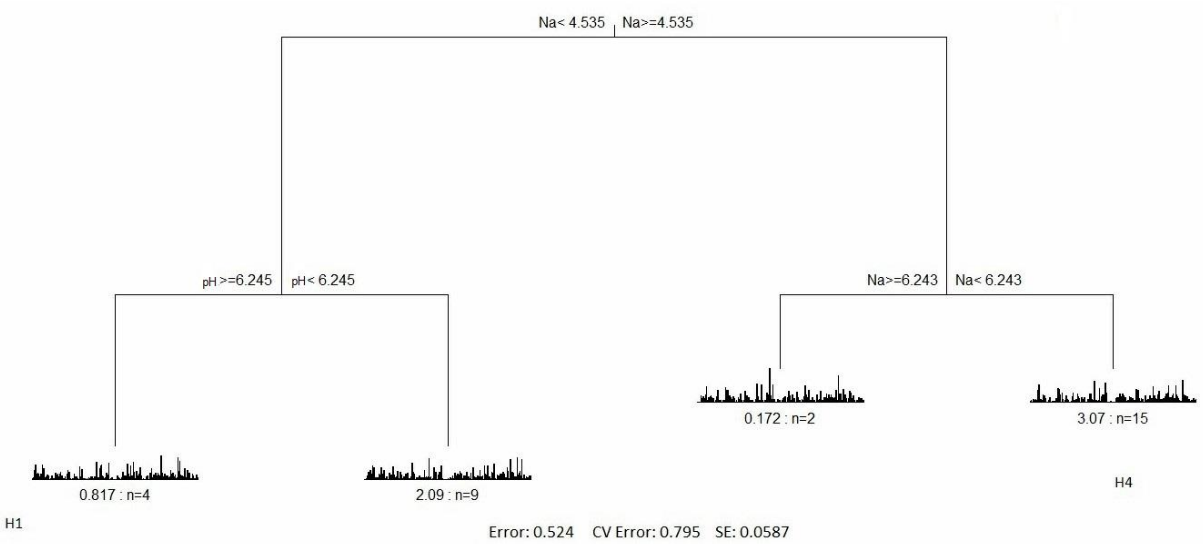

Fig. 15. Community habitat association at the large trees group.

H1-H4 represents the four habitats given by the MRT; Na =sodium; pH= potential in hydrogen; SE= standard error; CV Error = Error coefficient of variation; the bar graphs show the species abundance in each habitat; n=number of plots belonging to this habitat.

However, only 17.43 of 37.45 % of the total standardized species variance was explained by the second and the third node which forms the four habitats in the DCF plots (Table XIII). Species composition varied strongly across the four groups with sites in habitats H3 and H4 (Fig. 15) having only 5 species in common (Table XIII). The four associated habitats (H1-H4) are simply defined by the high level of pH (H1), low level of pH (H2), high level of Na (H3) and low-level Na (H4).

Inspection of the barplot at each habitat, and every four leaves, showed individual species contribution to each split, and to the composition of the four final groups (Fig. 15; Table XIII). For the first node in which the split forms habitats one and two, 41.80 % of its species variance was explained by fourteen species. Indeed, *Anthocleista schweinfurthii*, *Ficus mucuso*, *Mallotus subulatus*, *Margaritaria discoidea*, *Pycnanthus angolensis*, *Terminalia superba, and Uapaca guineensis* contributed to the second splits and are dominant species in habitats 1 (Table XIII). For the second node in which the split forms habitats one and two, 54.36 % of its species variance was explained by five species. Among the five species, *Grossera macrantha* (Euphorbiaceae) and *Streblus usambarensis* (Moraceae) strongly determined the third split and are dominant species in habitat 3 (Table XIII).

Table XIII. Variance explained by species per splits, nodes and tree of large trees

Species	Species variance (%) explained by tree splits and the total tree						
	pH ≤ 6.245	pH > 6.245	Species node 2	Na ≥ 6.243	Na < 6.243	Species node 3	Total tree
Annickia chlorantha	0.03	0.15	3.51	0.00	0.00		0.18
Anthocleista schweinfurthii	0.16	0.00	5.92	0.00	0.00		0.16
Berlinia sp.	0.00	0.00		0.13	0.01	4.47	0.14
Drypetes spp.	0.00	0.00		0.20	0.08	4.31	0.28
Ficus exasperata	0.12	0.00	3.54	0.00	0.00		0.12
Ficus mucuso	0.15	0.01	4.51	0.00	0.00		0.16
Grossera macrantha	0.00	0.00		0.36	0.08	25.20	0.44
Mallotus subulatus	0.14	0.00	4.22	0.00	0.00		0.14
Margaritaria discoidea	0.19	0.01	7.13	0.00	0.00		0.20
Pycnanthus angolensis	0.25	0.17	1.69	0.00	0.00		0.42
Streblus usambarensis	0.00	0.00		0.28	0.05	16.52	0.33
Terminalia superba	0.19	0.08	3.16	0.00	0.00		0.27
Trichilia dregeana	0.12	0.23	3.27	0.12	0.23	3.86	0.70
Uapaca guineensis	0.07	0.21	4.85	0.00	0.00		0.28
Other species	9.43		58.20	4.18		45.64	13.61
Total species variance	11.71		100	5.72		100	17.43

III.1.3.3.3. Understorey trees habitat association

The MRT analysis of understorey gave also four leaves tree with the splits based on pH and Na as well as for the whole trees community level and large trees classes (Fig 16). The three nodes constituting the MRT explained 25.68 % of the total standardized species variance of all tree species inventoried with CRVE of 0.795. However, only 13.75 of 25.68 % of the total standardized species variance was explained by the second and the third node which forms the four habitats in the DCF plots (Table XIV). Species composition varied strongly across the four groups with sites in habitats H3 and H4 (Fig. 16) having only 4 species in common (Table XIV). The four associated habitats (H1-H4) are simply defined by the high level of pH (H1), low level of pH (H2), high level of Na (H3) and low-level Na (H4).

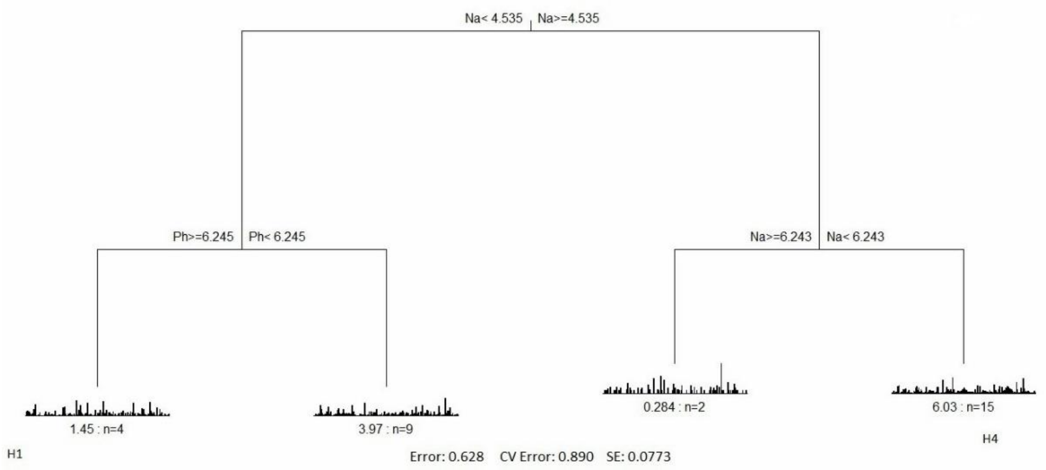

Fig. 16. Community habitat association at the understorey trees group.

H1-H4 represent the four habitats given by the MRT; Na =sodium; pH= potential in hydrogen; SE= standard error; CV Error = Error coefficient of variation; the bar graphs show the species abundance in each habitat; n=number of plots belonging to this habitat

Inspection of the barplot at each node, and every four leaves, showed individual species contribution to each split, and the composition of the four final groups. For the second node in which the split forms habitats one and two, 54.93 % of its species variance was explained by fourteen species. The species *Annickia chlorantha* (Annonaceae), *Mallotus subulatus* (Euphorbiaceae) and *Trichilia dregeana* (Meliaceae) strongly determined the second split and are dominant species in habitat one and two (Table XIV). The third node in which the splits form habitats three and four, 65.69 % of its species variance was explained by twelve species. The species *Grossera macrantha* (Euphorbiaceae) and *Streblus usambarensis* (Moraceae) strongly determined the third split and are dominant species in habitat 3 (Table XIV)

Table XIV. Variance explained by species per splits, nodes and the total tree of understorey trees inventoried

Species	Species variance (%) explained by a tree, splits, species nodes and the total tree						
	pH ≤ 6.245	pH > 6.245	Species node 2	Na ≥ 6.243	Na < 6.243	Species node 3	Total tree
Annickia chlorantha	0.02	0.18	5.85	0.00	0.12	2.42	0.32
Annona sp.	0.01	0.07	1.82	0.00	0.08	1.28	0.16
Anthocleista schweinfurthii	0.10	0.00	2.56	0.00	0.00	0.00	0.10
Anthonotha macrophylla	0.19	0.01	7.82	0.00	0.00	0.00	0.20
Aptandra zenkeri	0.05	0.14	2.16	0.00	0.00	0.00	0.19
Celtis mildbraedii	0.02	0.12	2.47	0.16	0.08	1.19	0.38
Celtis philippensis	0.00	0.00	0.00	0.00	0.12	2.52	0.12
Ficus exasperata	0.09	0.00	2.08	0.00	0.00	0.00	0.09
Funtumia elastica	0.17	0.06	2.90	0.00	0.00	0.00	0.23
Grossera macrantha	0.00	0.00	0.00	0.13	0.04	11.39	0.17
Hylodendron gabunense	0.22	0.10	3.03	0.00	0.00	0.00	0.32
Mallotus subulatus	0.24	0.02	10.52	0.00	0.00	0.00	0.26
Margaritaria discoidea	0.09	0.00	2.05	0.00	0.00	0.00	0.09
Monodora tenuifolia	0.00	0.00	0.00	0.00	0.13	3.06	0.13
Myrianthus arboreus	0.00	0.00	0.00	0.00	0.12	2.43	0.12
Greenwayodendron suaveolens	0.02	0.14	3.51	0.00	0.15	3.97	0.31
Pycnanthus angolensis	0.00	0.00	0.00	0.00	0.11	2.23	0.11
Staudtia kamerunensis	0.00	0.00	0.00	0.00	0.11	2.23	0.11
Streblus usambarensis	0.11	0.00	2.75	0.50	0.08	31.43	0.69
Trichilia dregeana	0.14	0.29	5.41	0.16	0.25	1.54	0.84
Other species	4.89		45.07	3.92		34.31	8.81
Total species variance	7.49		100	6.26		100	13.75

III.1.3.3.4. Small stem habitat associations

Contrary to the other trees level, the MRT analysis of small stems gave also four leaves tree with the splits based on CEC, MC, and aspect (Fig 17). The three nodes constituting the MRT explained 26.76 % of the total standardized species variance of all tree species inventoried with CRVE of 0.795. However, only 16.95 % of 26.76 % of the total standardized species variance was explained by the second and the third node which forms the four habitats in the DCF plots (Table XV). Species composition varied slightly across the four groups with sites in habitats H1 to H4 (Fig. 16) having 3 species in common (Table XV).

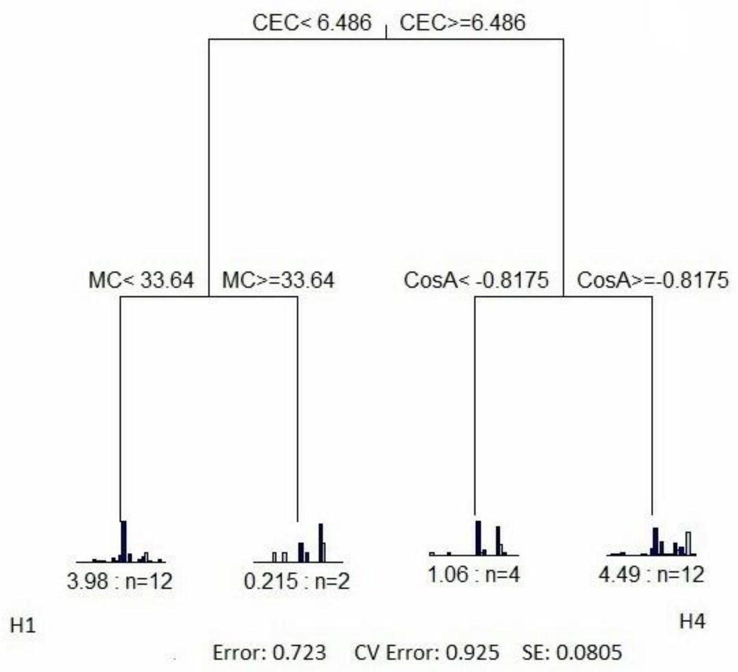

Fig. 17. Community habitat association for the small stems group.

H1-H4 represent the four habitats given by the MRT; Na =sodium; pH= potential in hydrogen; SE= standard error; CV Error = Error coefficient of variation; the bar graphs show the species abundance in each habitat; n=number of plots belonging to this habitat

Forty-three percent of the total species variance of the small stems class was explained by the species *Memecylon* sp. (Melastomataceae), *Ochna* sp. *Rinorea* sp., *Sorindeia grandifolia*, *Strychnos* spp. and *Thomandersia hensii* (Table XV). Two species contributed most to explain this variance per node.

Table XV. Variance explained by species per splits, nodes and the total tree of small stems inventoried

Species	Species variance (%) explained by a tree, splits, species nodes and the total tree						
	MC > 33.64	MC ≤ 33.64	Species node 2	A < - 0.8175	A ≥ 0.8175	Species node 3	Total tree
Memecylon sp.	0.12	0.00	2.11	0.00	0.12	3.94	0.24
Microdesmis puberula	0.76	0.37	22.81	0.63	0.51	3.44	2.27
Ochna sp.	0.00	0.00	0.00	0.09	0.26	8.38	0.35
Rinorea sp.	0.10	0.72	58.67	0.53	0.23	24.34	1.58
Sorindeia grandifolia	0.19	0.37	4.76	0.21	0.10	3.12	0.87
Strychnos spp.	0.00	0.00	0.00	0.04	0.16	3.52	0.20
Thomandersia hensii	0.00	0.00	0.00	0.00	0.43	49.02	0.43
Other species	5.97		11.65	5.03		4.24	7.81
Total species variance	8.60		100	8.34		100	13.75

III.1.3.4. Habitat indicator species

Twenty-nine species that strongly characterized the four habitat types (indicator species) within the whole tree community of the 30 1 ha sample plots were found. Within the four habitats, the index value varied between 0.33 and 0.99, with few species per habitat type with index values above 0.75. Moreover, there were some species with a low index value and strongest significance than others which had high index value (Table XVI). For the whole tree community, only *Antidesma membranaceum* (Phyllanthaceae), *Elaeis guineensis* Jacq. (Arecaceae) and *Ochthocosmus* spp. (Ixonanthaceae) species were found to be strong indicators that were not common to large and understorey trees as well as small stems group.

The number of indicators species for large trees was twenty-eight while the understorey trees class had sixteen species. For small stems, only two species were found to be strong indicators for habitats one and four. With an index value of 0.3 and $p < 0.01$, *Microdesmis puberula* (Pandaceae), was the only one strong indicator species characterizing the first habitat while *Thomandersia hensii* (Thomandersiaceae) characterized the fourth habitat with an index value of 0.75 and $p < 0.01$. Among the indicators species for the large trees class, *Anthocleista schweinfurthii* with index values of 0.98 and $p < 0.001$, were one of the best species which strongly characterized the first habitat. For habitat two, *Aptandra zenkeri* (Aptandraceae) with 0.76 and $p < 0.001$ was one of the best species indicators while for habitat four, *Khaya* (Meliaceae) with index value 0.80 and $p < 0.001$ was found. Within the third habitat, *Berlinia* sp. (Leguminosae-Caesalpinioideae) associated with R*hizophora racemosa* (Rhizophoraceae) and *Chrysophyllum perpulchrum* (Sapotaceae) were among the best species characterizing this habitat (index values > 0.89, $p < 0.001$).

Further, some strong or moderate indicator species within the large trees class changed to either non-indicator species or moderate indicator species in the understorey trees class. *Mallotus subulatus* (Euphorbiaceae) and two species of the genus *Anthonotha* (*A. macrophylla* and *A. lamprophylla*) were among the best indicators species which strongly characterized the first habitat within the understorey trees class. Within the second habitat of the understorey trees class, only *Annickia chlorantha* appeared to be the strongest species ($p < 0.001$) despite its moderate index value of 0.57 (Table XVI). For the fourth habitat, *Celtis philippensis* was the best and the strongest species indicator while four the third habitat, *Berlinia* sp., *Mansonia altissima* and *Grossera macrantha* with at least 0.80 of index values each appeared to be among the best indicator species.

Table XVI. Indicators species analysis for the whole tree community and trees size group (*p <0.05; **p <0.01; ***p <0.001)

Species	Whole tree community		Large trees		Understorey trees	
	Habitat index	Index value	Habitat index	Index value	Habitat index	Index value
Albizia adianthifolia	1	0.72**	1	0.72**	1	0.75**
Albizia glaberrima			1	0.46*		
Albizia zygia	1	0.59*	1	0.60*	1	0.42*
Annickia chlorantha	2	0.38*	2	0.38**	2	0.57***
Annona sp.	4	0.49*	4	0.49*		
Anthocleista schweinfurthii	1	0.99***	1	0.98***	1	0.50*
Anthonotha lamprophylla	3	0.52*	3	0.52*	1	0.87***
Anthonotha macrophylla	1	0.68***	1	0.68***	1	0.87***
Antidesma membranaceum	3	0.47*				
Aptandra zenkeri	2	0.77*	2	0.76*	2	0.67*
Barteria fistulosa	2	0.58***	2	0.58**		
Berlinia sp.	3	0.91***	3	0.91***	3	0.89***
Bridelia micrantha	1	0.88***	1	0.88***		
Caloncoba glauca					1	0.38*
Ceiba pentandra					1	0.50*
Celtis philippensis	4	0.61***	4	0.61***	4	0.93***
Celtis zenkeri	3	0.5**	3	0.50**		
Chrysophyllum boukokoense	4	0.48**	4	0.49**		
Chrysophyllum lacourtianum	2	0.42*	2	0.42*		
Chrysophyllum perpulchrum	3	0.89**	3	0.89**		
Cola pachycarpa	2	0.44*	2	0.44*		
Detarium macrocarpum	3	0.57*	3	0.57*		
Diospyros suaveolens	4	0.52*	4	0.52*		
Dracaena arborea	2	0.50*	2	0.50*		
Drypetes spp.	3	0.62**	3	0.70***	3	0.58**
Duboscia macrocarpa	4	0.36*	4	0.36*		
Duguetia staudtii	4	0.45*	4	0.45*		
Elaeis guineensis	1	0.69**				
Ficus exasperata	1	0.76**	1	0.76**	1	0.75**
Ficus mucuso	1	0.71**	1	0.72**		
Funtumia elastica					1	0.44*
Gossweilerodendron balsamiferum	3	0.62**	3	0.62**		
Grossera macrantha	3	0.82***	3	0.82***	3	0.88***
Homalium spp.	4	0.40*	4	0.40*	4	0.47**
Hylodendron gabunense					1	0.57**
Irvingia gabonensis					3	0.68*
Khaya anthotheca	3	0.75**	3	0.75**		
Khaya grandifoliola	4	0.8***	4	0.80***		
Klainedoxa gabonensis	4	0.39**	4	0.39**		

Lasiodiscus marmoratus	3	0.43*	3	0.42*		
Leplaea cedrata	3	0.46*	3	0.46*		
Leplaea thompsonii	4	0.35*	4	0.35*		
Macaranga hurifolia	1	0.49*	1	0.50*		
Mallotus subulatus	1	0.88***	1	0.88***	1	0.86**
Mansonia altissima	3	0.46*	3	0.45**	3	0.83**
Margaritaria discoidea	1	0.87***	1	0.87***	1	0.66*
Milicia excelsa	1	0.59*	1	0.59*		
Millettia mannii	1	0.60*	1	0.61*		
Monodora tenuifolia	4	0.45*	4	0.45*	4	0.54*
Morinda lucida	1	0.72**	1	0.73***		
Myrianthus arboreus					4	0.54**
Ochthocosmus spp.	4	0.6*				
Pachylobus trimerus	2	0.39*	2	0.38*		
Persea americana	1	0.75**	1	0.75**		
Phyllocosmus africanus	2	0.56**	2	0.56**		
Greenwayodendron suaveolens	4	0.35*	4	0.35*	4	0.45*
Polyscias fulva	1	0.57*	1	0.58*		
Pterygota macrocarpa					3	0.62*
Pycnanthus angolensis	1	0.39*	1	0.40*	1	0.44*
Rauvolfia caffra	1	0.53*				
Rauvolfia vomitoria	3	0.49*	3	0.49*		
Rhizophora racemosa	3	0.90**	3	0.90***		
Sorindeia grandifolia	4	0.36*	4	0.36*		
Staudtia kamerunensis	4	0.44**	4	0.44**	4	0.67***
Streblus usambarensis	3	0.71**	3	0.70*	3	0.73*
Strombosia pustulata	3	0.48*	3	0.48*		
Strombosia scheffleri			2	0.48*		
Synsepalum dulcificum	4	0.55*				
Terminalia superba	1	0.45**	1	0.46**		
Theobroma cacao	1	0.5*	1	0.50*		
Thomandersia hensii	1	0.49*			4	0.73**
Trichilia dregeana	2	0.33*	2	0.33*	2	0.34*
Uapaca guineensis	2	0.58**	2	0.57***		

III.1.4. Carbone stocks

III.1.4.1. Carbon pools, components and uncertainties variation

The total carbon in the main carbon components across the 30 1-ha plots of semi-deciduous sample plot forest in eastern Cameroon varied from 231.32 to 339.88 Mg C ha^{-1}, with an average and standard deviation of 285.60 ± 54.28 Mg C ha^{-1} (Table XVII). This carbon estimate includes carbon in aboveground live biomass, aboveground dead biomass, belowground biomass, and soil organic carbon.

Aboveground live carbon was the largest carbon pool and had the highest $S_{between}$ (33.59 Mg C ha^{-1}) which was higher than S_{within}. These uncertainties were mainly explained by the large tree's carbon stocks between plots (Table XVII). For all carbon pools and components, except for aboveground dead carbon and its main contributor coarse woody carbon stock, it was found that $S_{within} < S_{between}$, suggesting that the uncertainty in measuring each carbon pools and components within each plot is lower than the spatial variation of carbon among plots (Table XVII). Belowground carbon pool has the least S_{within} and the second $S_{between}$ among the main carbon pools and that these uncertainties were mainly explained by SOC carbon stock.

Table XVII. Carbon stored and uncertainty in different carbon pools and their carbon components in the 30 1 ha plots in the Doume communal forest

Carbon pool	Carbon component	S_{within}	$S_{between}$	Stotal	n	S.E.	Mean (Mg C ha^{-1})
Aboveground live carbon		18.55	33.59	38.39	30	6.14	182.62
(AGC)	Large trees (>10cm DBH)	16.18	33.47	37.18	30	6.09	177.61
	Understorey trees (5-10 cm DBH)	0.06	0.45	0.80	30	0.14	2.80
	Small stems (<5 cm DBH)	0.75	0.20	0.12	30	0.22	1.60
	Palms stems	NA	NA	NA	05	0.09	0.21
	Herbaceous vegetation	0.03	0.31	0.31	30	0.11	0.40
Aboveground dead carbon (ADC)		85.67	15.35	87.03	30	2.80	17.92
	Litter	0.09	1.09	1.10	30	0.09	2.93
	Fine woody debris	0.06	0.16	0.17	30	0.15	1.50
	Coarse woody debris	68.80	15.81	70.59	30	1.38	10.90
	Standing dead trees	0.04	2.74	2.74	30	0.50	2.59
Belowground carbon		15.86	18.65	24.48	30	2.90	85.06
	Fine Root trees	0.002	0.02	0.02	30	0.007	0.02
	Coarse Root trees	8.47	18.54	20.48	30	1.55	45.65
	Soil organic carbon	12.50	31.7	34.07	30	2.28	39.39
TOTALS							
Total aboveground carbon (TAGC)		20.54	40.90	45.80	30	7.49	200.54
Total carbon		18.03	51.19	54.28	30	9.40	285.6

Variation partitioning used to determine the contribution of different carbon pools as well as their components in explaining the variation of total carbon stocks showed that all pools well explained total carbon stocks: together they explained all variation of total carbon (Fig. 18a), mainly explained by the combined effect of aboveground and belowground carbon (61%;

Fig. 18a). The most important component explaining variation in total carbon was the interaction of AGC and BGC (60.1%, Fig. 18b).

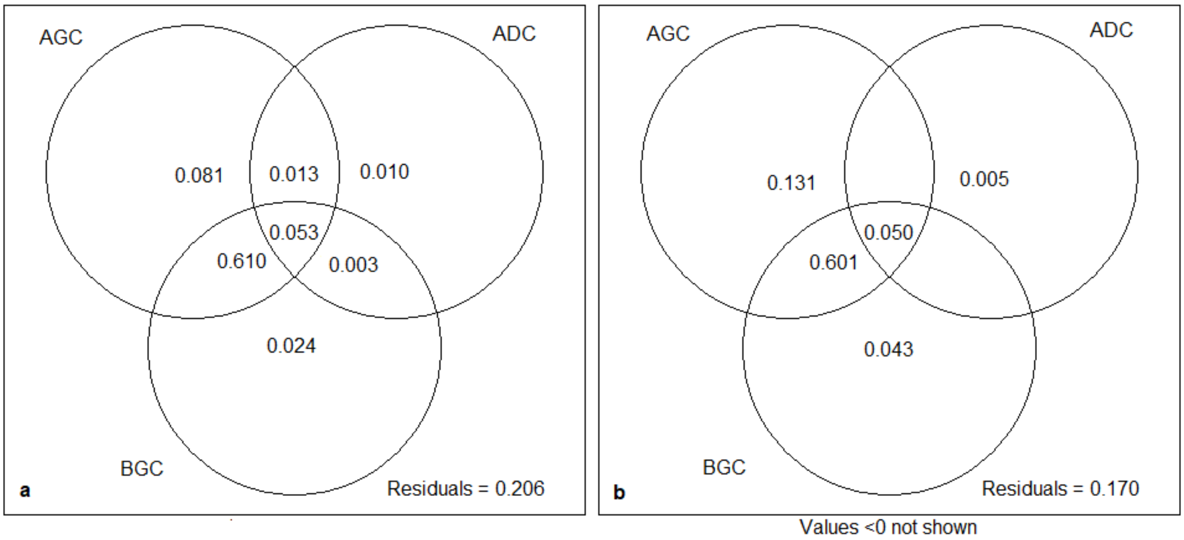

Fig. 18. Venn diagram of variation partitioning results of total carbon stock: (a) with all components (see Table XVII) of aboveground live carbon (AGC), aboveground dead carbon (ADC) and belowground carbon (BGC); (b) with the best components of each carbon pool: large trees (AGC), coarse woody debris (ADC), root and soil organic carbon (BGC). Values provided in circles represent the semi-partial correlation coefficient of a shared and pure fraction of carbon pools.

The average AGC was 182.62 ± 33.59 Mg C ha^{-1} (Table XVII). Among all AGC components, the carbon in large trees was most strongly correlated with AGC ($r = 1.00$, $p < 0.001$; Fig. 19). Carbon in large trees also explained most variation in total carbon stocks (13.1%, $p < 0.01$, Fig. 18b, Table XVIII), and represented on average 63% of total carbon stocks (Fig. 20). The relative contribution of AGC in explaining the variation of total carbon stock increased when only carbon of large trees was used (Fig. 18a vs. 18b).

The average belowground carbon (BGC) was 85.06 ± 18.65 Mg C ha^{-1}. Among all BGC components, the carbon in coarse roots was most strongly correlated with BGC ($r = 0.94$, $p = 0.001$, Fig. 19), and it represented on average 16% of total carbon stocks (Fig. 20) and significantly explained variation in total carbon stock (4.3%, $p < 0.01$, Fig. 18b, Table XVIII). As found for AGC, the relative contribution of BGC in explaining total carbon stock also increased when only coarse root carbon was included (Fig. 18a vs. 18b).

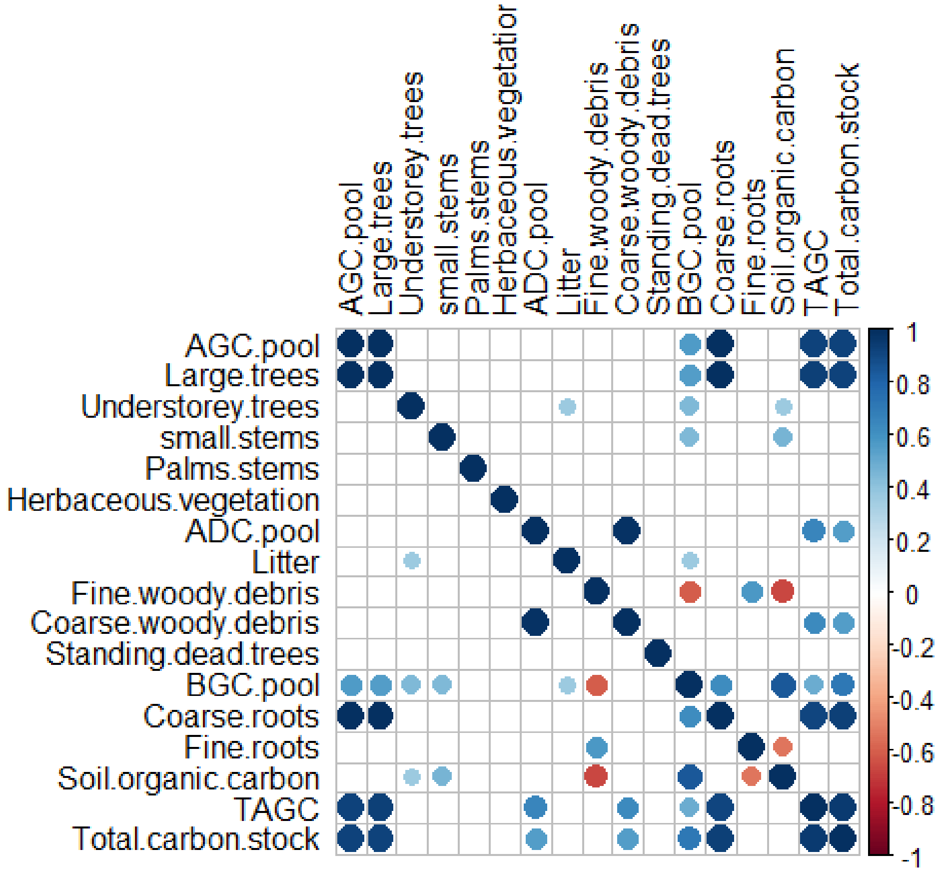

Fig. 19. Significant Pearson correlations ($p < 0.05$) between all carbon pools and components. The color intensity and the size of the circles are proportional to the correlation coefficients. AGC pool = aboveground live carbon pool, ADC pool = aboveground dead carbon pool, BGC pool = belowground carbon pool, TAGC = total aboveground carbon.

Aboveground dead carbon (ADC) was 17.92 ± 15.35 Mg C ha^{-1}. Of all dead carbon components, coarse woody debris (10.90 ± 15.81 Mg ha^{-1}) contributed most strongly to total carbon stock variation (0.10%, $p < 0.001$, Table XVIII; Fig. 18). Coarse woody debris was also the most important ADC component for total carbon stocks (4%, $r = 0.51$, $p < 0.001$, Fig. 19-20). Contrary to AGC, the relative contribution of ADC in explaining the variation of total carbon stock decreased when only carbon of coarse woody debris was used (Fig. 18a vs. 18b).

Table XVIII. Variation partition results of carbon pools and their components on total carbon stock. F-values and P-values are given only for carbon pools and significant components.

Carbon pool	Carbon component	Adjusted R^2	F-value	P-value
Aboveground live biomass (AGC)		0.79	22.23	0.001
	large trees (>10cm DBH)	0.75	87.54	0.002
	Understorey trees (5-10 cm DBH)	0.04		
	Small stems (<5 cm DBH)	0.07		
	Palms	0.01		
	Herbaceous vegetation (HV)	-0.03		
Aboveground dead Carbon (ADC)		0.04	1.23	0.324
	Litter	0.001		
	Fine woody debris (FWD)	-0.02		
	Coarse woody debris (CWD)	0.04	2.18	0.143
	Standing dead trees (SDT)	-0.02		
Belowground biomass (BGC)		0.78	67.89	0.001
	Fine Root trees (FRT)	0.01		
	Coarse Root trees (CRT)	0.77	97.60	0.002
	Soil organic carbon (SOC)	0.005		
All	All	0.10	1467	0.001

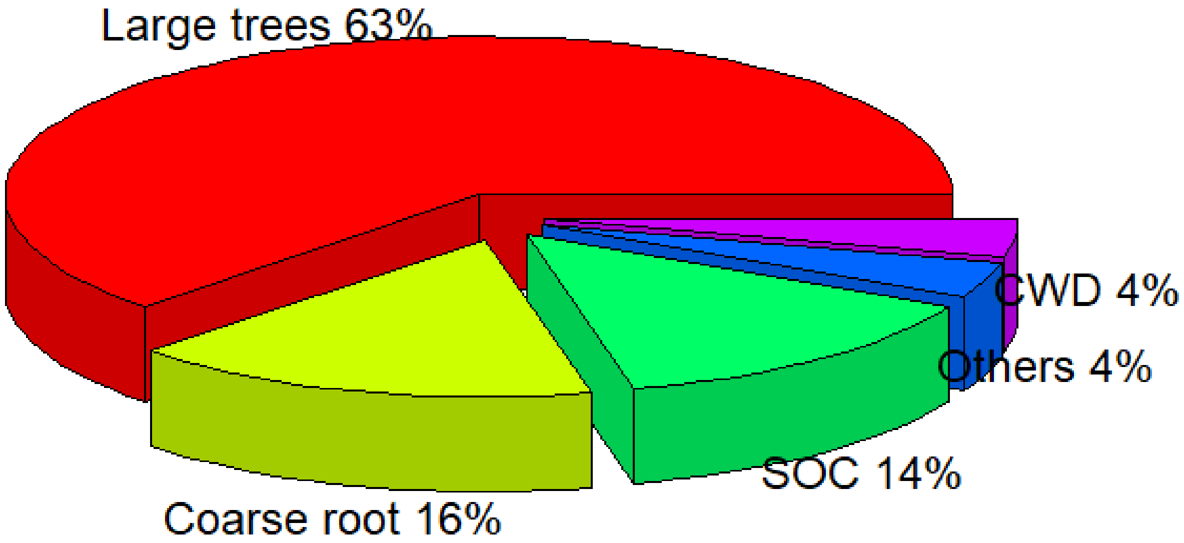

Fig. 20. Proportion of total carbon in different carbon components. SOC= soil organic carbon; CWD = coarse woody debris.

III.1.4.2. Linking aboveground live carbon with forest structure

III.1.4.2.1. Trees diameter classes carbon stocks distribution

The distribution of carbon stock per diameter class showed that most carbon is found in trees between 20 and 80 cm DBH (Fig. 21). However, despite the large variation in the diameter of individuals over 70 cm, there is also considerable variation in carbon stocks by diameter class, although their storage potential is high (Fig. 21).

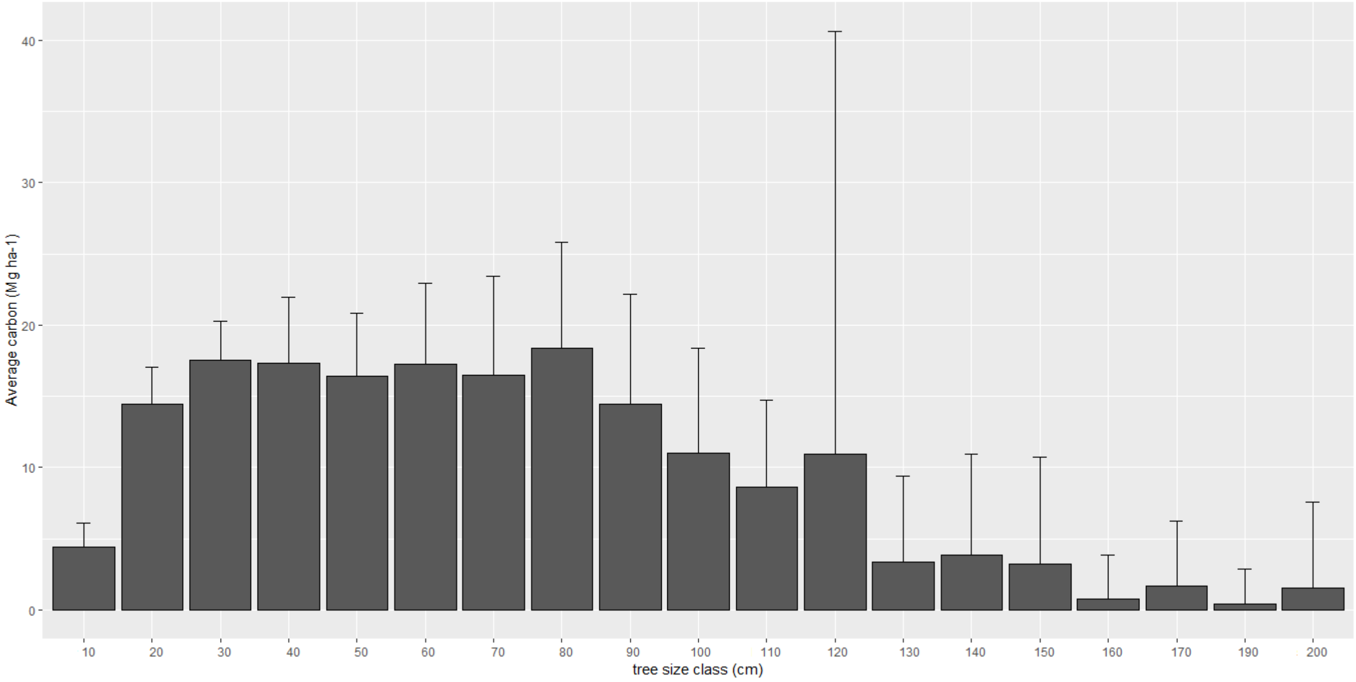

Fig. 21. Average carbon storage with standard error per tree diameter class.

III.1.4.2.2. Big-size trees relationship with carbon stocks

This study found out that, when density of big size trees increased, both total carbon stock (Fig. 22a, adj.$R^2 = 0.41$, slope = 5.57, $p<0.001$) and aboveground live carbon (Fig. 22b, adj.$R^2 = 0.38$, slope = 3.47, $p<0.001$) also increased. Although trees from 1 to 10 cm DBH accounted for 92.1% of the stems, they accounted for only 2.8% of the total aboveground carbon. Big size trees (DBH ≥70 cm), on the other hand, accounted for only 0.3 % of all stems, but 40% of aboveground live carbon and 25% of total carbon stocks.

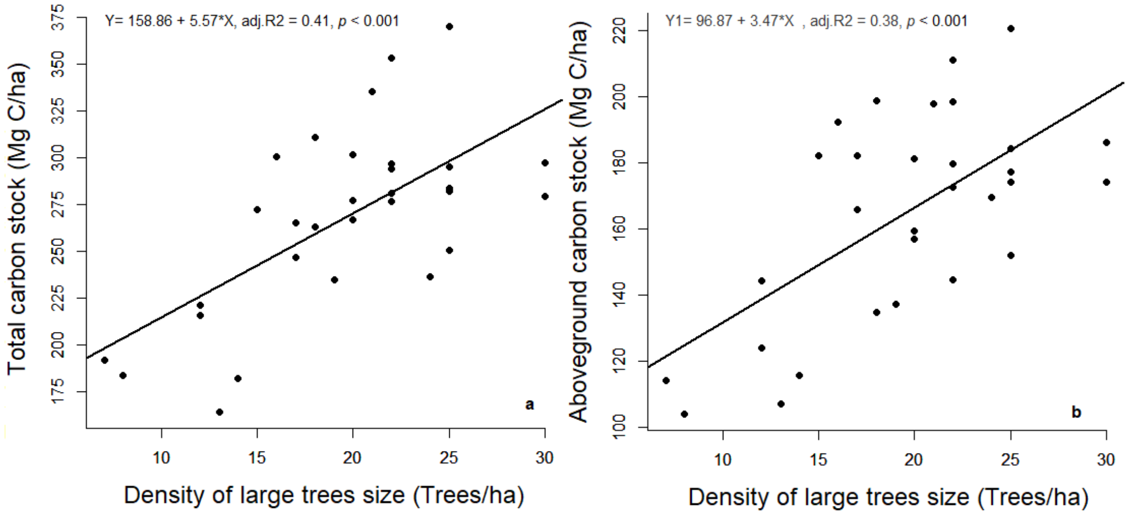

Fig. 22. Relationships of the density of big size trees (>70 cm DBH) with (a) aboveground carbon and (b) total carbon stock.

III.1.4.3. Abiotic and biotic variables influencing aboveground live carbon stocks

Different abiotic and biotic variables were selected per tree size groups and the whole tree community in the SEMs. As taxonomic diversity, the Shannon-Weaver index was selected for AGC of small stems class, rarefied species richness for AGC of understorey trees and large trees groups, and species richness for AGC of the whole tree community (Table XIX). Elevation was selected as a topographic variable influencing carbon stocks of understorey trees, and the terrain slope was selected for the two other tree size groups and the whole tree community. For soil variables, clay proportion was selected for AGC of the whole tree community and all tree size groups except for small stems where Nsoil was selected. Disturbance and structural diversity (Diversity Gini index) were included in all SEMs (Table XIX).

Table XIX. Results of all subsets regression analyses for aboveground biomass carbon for the whole tree community, large trees, understorey trees and small stems (i.e.. the response variable). The one or two soil fertility indices and trait composition indices with the highest relative variable importance (i.e. the variables in bold) were selected for further analyses using structural equation modeling (see Table XX). Standardized regression coefficient (Std. coeff), adjusted standard error (SEadj) and Imp.value= Importance value

Variable response	Predictor variables	Coeff	Adjusted SE	z value	Pr(>|z|)	Imp.value
Aboveground carbon stock of small stems	**Diversity Gini index**	**2.73**	**0.41**	**6.61**	**<0.001**	**1**
	Cation exchange capacity	**0.48**	**0.17**	**2.84**	**0.004**	**0.95**
	Disturbance	**0.04**	**0.02**	**1.85**	**0.065**	**0.62**
	Soil total Nitrogen	**1.41**	**0.81**	**1.75**	**0.080**	**0.62**
	Soil available Phosphorus	13.29	7.63	1.74	0.082	0.52
	Ration Nitrogen:Phosphorus (N:P)	-0.01	0.00	1.60	0.109	0.51
	Shannon-Weaver index	**-0.18**	**0.14**	**1.25**	**0.212**	**0.43**
	Slope	**0.03**	**0.03**	**1.25**	**0.211**	**0.40**
	Ratio Carbone:Nitrogen (C:N)	0.00	0.00	1.34	0.182	0.36
	Rarefied species richness	-0.01	0.01	0.70	0.486	0.32
	Silt proportion	<0.00	0.01	0.84	0.402	0.30
	Sand proportion	0.00	0.01	0.34	0.735	0.28
	Elevation	<0.00	0.00	0.73	0.464	0.27
	Rarefied species richness	0.12	0.14	0.88	0.379	0.27
	Moisture content	-0.01	0.01	0.96	0.337	0.24
	Curvature	-0.00	0.00	0.39	0.694	0.23
	Sine aspect	0.03	0.10	0.32	0.751	0.22
	Cosine aspect	-0.02	0.08	0.22	0.830	0.21
	Clay proportion	0.01	0.01	0.56	0.573	0.20
	pH	0.06	0.12	0.45	0.655	0.19
	Electric conductivity	0.00	0.00	0.08	0.934	0.15
Aboveground carbon stock of understorey trees	**Diversity Gini index**	**-0.11**	**3.19**	**3.64**	**<0.001**	**0.99**
	Cation exchange capacity	**0.95**	**0.55**	**1.74**	**0.082**	**0.57**
	pH	**0.49**	**0.33**	**1.50**	**0.134**	**0.46**
	Elevation	**0.01**	**0.01**	**1.36**	**0.173**	**0.44**
	Clay proportion	0.05	0.04	1.34	0.182	0.42
	Disturbance	**-0.08**	**0.07**	**1.18**	**0.240**	**0.34**
	Cosine aspect	0.18	0.21	0.89	0.373	0.29
	Rarefied species richness	**-0.02**	**0.03**	**0.80**	**0.425**	**0.28**
	Sand proportion	-0.01	0.03	0.56	0.577	0.28
	Sine aspect	-0.18	0.24	0.74	0.458	0.26
	Electric conductivity	-0.01	0.01	0.85	0.396	0.26
	Nsoil	1.88	2.19	0.86	0.391	0.26
	Curvature	<-0.00	0.01	0.60	0.549	0.25
	Shannon Weaver index	0.02	0.37	0.64	0.524	0.25
	Slope	0.04	0.06	0.57	0.571	0.24
	Psoil -	18.15	27.75	0.65	0.513	0.23

	Moisture content	-0.02	0.03	0.65	0.513	0.22
	Silt proportion	-0.01	0.03	0.26	0.797	0.21
	Ratio C:N	0.01	0.01	0.61	0.544	0.21
	Ratio N:P	-0.01	0.01	0.48	0.632	0.21
	Species richness	0.00	0.01	0.27	0.790	0.20
Aboveground carbon stock of large trees	**Diversity Gini index**	**910.47**	**207.64**	**4.39**	**<0.001**	**1**
	Slope	**4.65**	**2.54**	**1.83**	**0.067**	**0.64**
	Clay proportion	**2.76**	**1.54**	**1.80**	**0.072**	**0.60**
	Nsoil	**-115.65**	**77.82**	**1.49**	**0.137**	**0.47**
	Rarefied species richness	**0.64**	**1.20**	**0.53**	**0.598**	**0.42**
	Species richness	0.89	1.02	0.88	0.379	0.32
	Shannon-Weaver index	-57.85	45.35	1.28	0.202	0.30
	Sand proportion	-0.77	1.48	0.52	0.604	0.29
	Curvature	0.15	0.28	0.53	0.596	0.24
	Ratio N:P	-0.24	0.44	0.55	0.579	0.24
	Cosine Aspect	3.10	8.56	0.36	0.717	0.22
	Electric conductivity	-0.13	0.21	0.63	0.529	0.22
	Psoil	-691.24	1082.15	0.64	0.523	0.22
	Elevation	-0.06	0.26	0.23	0.816	0.21
	Ratio C:N	0.22	0.38	0.58	0.561	0.21
	Silt proportion	-1.09	1.71	0.61	0.539	0.21
	Sine Aspect	-1.04	10.11	0.10	0.918	0.20
	pH	-0.77	14.99	0.05	0.959	0.20
	Cation Exchange Capacity	3.97	23.30	0.17	0.865	0.18
	Disturbance	-0.30	3.01	0.10	0.920	0.18
	Moisture content	-0.36	1.18	0.30	0.761	0.18
Aboveground carbon stock of the whole tree community	**Diversity Gini index**	**0.08**	**0.03**	**3.18**	**0.001**	**0.98**
	Species richness	**1.08**	**0.60**	**1.78**	**0.075**	**0.69**
	Slope	**4.68**	**2.55**	**1.84**	**0.067**	**0.64**
	Clay proportion	**2.81**	**1.54**	**1.82**	**0.068**	**0.61**
	Nsoil	**-114.44**	**78.18**	**1.46**	**0.143**	**0.46**
	Sand proportion	-0.79	1.51	0.52	0.600	0.29
	Rarefied species richness	-0.12	1.17	0.15	0.881	0.26
	Shannon-Weaver index	-0.23	0.63	0.37	0.709	0.25
	Ratio N:P	-0.26	0.44	0.59	0.558	0.24
	Curvature	0.15	0.29	0.51	0.613	0.23
	Cosine Aspect	3.29	8.61	0.38	0.702	0.22
	Electricity conductivity	-0.13	0.21	0.63	0.526	0.22
	Psoil	-701.90	1093.19	0.64	0.521	0.22
	Elevation	-0.05	0.26	0.20	0.841	0.21
	Ratio C:N	0.23	0.38	0.61	0.544	0.21
	Silt proportion	-1.08	1.73	0.63	0.532	0.21
	Sine Aspect	-1.21	10.17	0.12	0.906	0.20
	pH	-0.18	15.08	0.01	0.990	0.20
	Disturbance	-0.32	3.03	0.11	0.916	0.18
	Cation Exchange Capacity	5.01	23.43	0.21	0.831	0.18
	Moisture content	-0.38	1.18	0.32	0.747	0.18

III.1.4.4. Abiotic and biotics factors effect on aboveground live carbon stocks

Evaluation of the direct and indirect effects of abiotic and biotic factors on carbon stocks of different tree size groups and the whole tree community using structural equation modeling (SEM) permit to have several models (Table XX). However, the SEM choose in this study have the highest R^2 (Fig. 23; Table XXI). Hence, the variation explained in carbon stocks ranged from 43 % each for AGC of large trees and the whole tree community to 72 % for understorey trees (Table XX).

Table XX. Statistics showing the model fit of structural equation models for carbon stock for the whole tree community, large trees, understorey trees and small stems. A P-value > 0.05 indicates that the model is accepted.

Response variables	Topographic variables	Taxonomic diversity variables	Soil variables	Model Chi-squared	Model P-value	R^2 of response variables
Aboveground carbon stock for the whole trees community level	Slope	Species richness	Clay proportion	2.642	0.104	0.43
			N_{Soil}	0.854	0.356	0.42
AGC of large trees	Slope	Rarefied species richness	Nsoil	0.791	0.374	0.42
			Clay proportion	0.292	0.589	0.43
AGC of understorey stems	Elevation	Rarefied species richness	Clay	5.401	0.144	0.72
			CEC	4.372	0.224	0.64
AGC for small stems	Slope	Shannon-Weaver index	Nsoil	3.653	0.056	0.54
			CEC	2.763	0.096	0.33

III.1.4.4.1. Biotic factors effects on aboveground live carbon stocks

Biotic factors had generally strong and significant effects on AGC stocks, with 5 (63%) from the eight tested relationships being significant (Fig. 23; Table XXI). The effects of taxonomic diversity were significant and positive on AGC of both large trees ($\beta = 0.29; p = 0.03$) and of the whole tree community ($\beta = 0.33; p = 0.009$) while effects of diversity Gini index being significant on all AGC stock except on AGC of understorey trees (Fig. 23a, b, and c; Table XXI).

III.1.4.4.2. Abiotic factors effects on aboveground live carbon stocks

Abiotic factors had direct and indirect effects on AGC stocks (Fig. 23; Table XXI). The terrain slope had a direct and positive effect on AGC of small stems ($\beta = 0.25$), and significant positive effect on AGC of both large trees carbon ($\beta = 0.40; p = 0.001$) and the whole tree community ($\beta = 0.36; p = 0.003$). Elevation had a direct and positive effect on AGC of understorey trees ($\beta = 0.21$). Moreover, via taxonomic diversity, it was found that AGC of the whole tree community, large trees, and small stems decreased with the increase of terrain slope while AGC of understorey trees increased with the increase of elevation (Table XXI). Contrary to taxonomic diversity via diversity Gini index, it was found out that AGC of the whole tree community and all trees size classes except for understorey trees increased with the increase of terrain slope while AGC of understorey trees decreased with the increase of elevation (Table XXI).

For soil variables, it was found out that Nsoil had a significant direct and positive effect on AGC for small stems ($\beta = 0.31; p = 0.04$). Soil texture (Clay proportion) had a direct and positive effect on AGC of the whole tree community, large and understorey trees (Fig. 23b, c, and d; Table XXI) and that effect was significant on AGC of understorey trees ($\beta = 0.38; p = 0.02$). Soil variables also had an indirect effect on AGC stocks (Fig. 23; Table XXI). Except, on AGC for small stems, via taxonomic diversity as well as diversity Gini index, it was found out that AGC stocks increased with increasing clay proportion of the soil (Fig. 23a; Table XXI). The results showed that effects of clay proportion were significant via species richness only on AGC for the whole tree community (Fig. 23d; Table XXI) and via diversity Gini on AGC of both the whole trees community and of large trees (Fig. 23c and d; Table XXI). Indeed, for the indirect effects of Nsoil on AGC for small stems, opposite patterns were observed as AGC increased when Nsoil increased via the Shannon-Weaver index while it decreased when Nsoil increased via the diversity Gini index (Fig. 23a; Table XXI).

Disturbance had a direct and indirect effect on carbon stocks. More specifically, when its intensity increased directly, it was found out that AGC stocks for understorey trees ($\beta = -0.04$), large trees ($\beta = -0.26$), and the whole tree community ($\beta = -0.22$) decreased. However, it was also found that AGC of small stems increased with increasing disturbance intensity. Moreover, except for AGC of small stems and only via Shannon-Weaver index, it was found that via taxonomic diversity as well as via diversity Gini index, AGC stocks increased with increasing disturbance intensity (Fig. 23; Table XXI) and that only via diversity Gini index, disturbance effect on AGC of the whole trees community and large trees were significant (Fig. 23c and d; Table XXI).

Table XXI. The direct, indirect standardized effects of abiotic and biotic factors on carbon stock of all tree size classes (i.e. small stems, understorey trees and large trees) and the whole tree community based on structural equation model in Fig. 23. The $p < .05$ indicated significant effects.

SEM response variable	SEM predictor variable	Coeff	Std.Coeff	z-value	*p*-value
Small stems					
Aboveground carbon stock (AGC)	Slope	0.03	0.25	1.69	0.092
	Nsoil	1.07	0.31	2.02	0.044
	Disturbance	0.03	0.18	1.20	0.232
	Shannon-Weaver index	-0.04	-0.03	-0.22	0.825
	Diversity Gini index	2.56	0.56	3.80	0.000
Shannon-Weaver index	Slope	-0.02	-0.15	-0.80	0.425
	Nsoil	0.35	0.12	0.64	0.520
	Disturbance	-0.03	-0.24	-1.38	0.167
Diversity Gini index	Slope	0.00	0.09	0.49	0.621
	Nsoil	-0.16	-0.20	-1.12	0.263
	Disturbance	0.01	0.30	1.81	0.070
R^2 AGC		0.54			
R^2 Shannon-Weaver index		0.88			
R^2 Diversity Gini index		0.83			
Understorey trees					
Aboveground carbon stock	Elevation	0.01	0.21	1.09	0.277
	Clay proportion	0.07	0.38	2.30	0.022
	Disturbance	-0.01	-0.04	-0.23	0.821
	Rarefied species richness	-0.06	-0.31	-1.96	0.050
	Diversity Gini index	4.95	0.08	0.42	0.672
Rarefied species richness	Elevation	-0.02	-0.12	-0.67	0.506
	Clay proportion	0.17	0.19	1.05	0.295
	Disturbance	0.09	0.05	0.27	0.784
Diversity Gini index	Elevation	0.00	-0.31	-1.83	0.068
	Clay proportion	0.00	0.13	0.77	0.440
	Disturbance	0.01	0.31	1.87	0.061
R^2 AGC		0.72			
R^2 Rarefied species richness		0.96			
R^2 Diversity Gini index		0.8			
Large trees					
Aboveground carbon stock	Slope	5.22	0.40	3.20	0.001
	Clay proportion	0.52	0.07	0.53	0.596
	Disturbance	-3.66	-0.26	-1.91	0.056
	Rarefied species richness	1.12	0.29	2.24	0.025
	Diversity Gini index	868.59	0.58	4.27	0.000
Rarefied species richness	Slope	-0.82	-0.25	-1.42	0.155
	Clay proportion	0.34	0.18	1.03	0.305

	Disturbance	0.77	0.21	1.21	0.227
Diversity Gini index	Slope	0.00	0.03	0.19	0.846
	Clay proportion	0.00	0.35	2.12	0.034
	Disturbance	0.00	0.35	2.11	0.035
R^2 AGC		0.43			
R^2 Rarefied species richness		0.88			
R^2 Gini		0.80			
Whole trees community					
Aboveground carbon stock	Slope	4.67	0.36	3.02	0.003
	Clay proportion	0.06	0.01	0.06	0.951
	Disturbance	-3.12	-0.22	-1.69	0.091
	Species richness	0.91	0.33	2.60	0.009
	Diversity Gini	838.00	0.56	4.23	0.000
Species richness	Slope	-0.36	-0.08	-0.44	0.657
	Clay proportion	1.05	0.39	2.29	0.022
	Disturbance	0.45	0.09	0.51	0.611
Diversity Gini index	Slope	0.00	0.03	0.19	0.846
	Clay proportion	0.00	0.35	2.12	0.034
	Disturbance	0.00	0.35	2.11	0.035
R2 AGC		0.43			
R2 Species richness		0.85			
R2 Diversity Gini index		0.80			

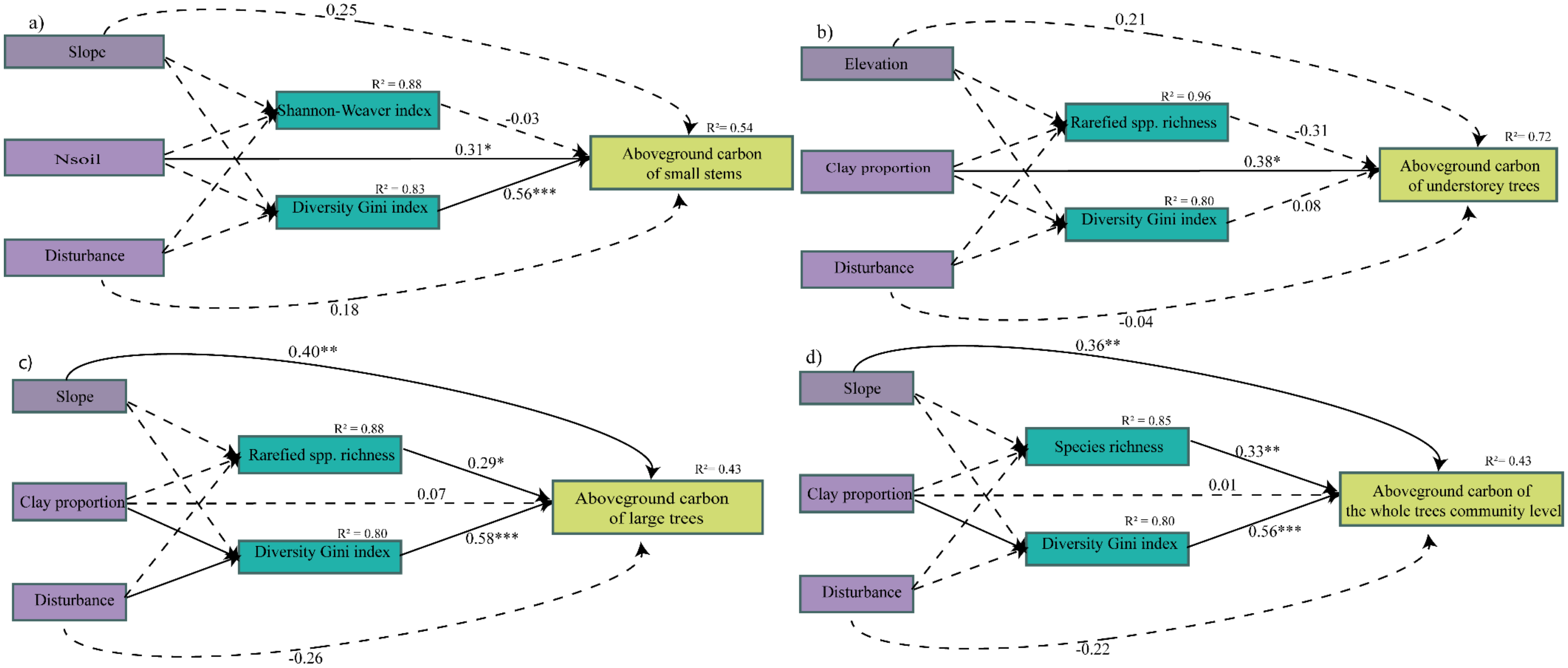

Fig. 23. Structural equation models for the effects of the abiotic variables (topography, soil properties, and disturbance) and biotic factors (Taxonomic richness and structural diversity index) on each of the four-carbon stock variables: above-ground carbon stock of a) small stems; b) understorey trees; c) large trees; d) the whole tree community.

For all significant relationships (continuous black lines), the standardized regression coefficients and significance level are given (*p <0.05; **p <0.01; ***p <0.001), and for all non-significant relations (black, dashed lines), no statistics are shown.

III.2. DISCUSSION

III.2.1. Land use and land cover dynamics

III.2.1.1. Landscape classification

The LULC types in the study area were interpreted on imagery by MLC supervised classification. With the overall accuracies and kappa statistics of the three periods LULC classification scheme all above 80% and 0.74, respectively substantiating the ability of Landsat products to accurately classify tropical dense rainforest of Cameroon. However, 80 and 83% accuracy of the 2000 and 2009 land cover maps respectively are acceptable but point towards a sub-optimal LULC classification, which may lead to a wrong interpretation of the timing of changes or even wrong trajectories.

Moreover, the lack of a clear boundary between LULC in our forest was due to the complex vegetation structure and species composition causing a major problem of relatively low accuracy for the two first-year periods, justifying thereby the misclassification between LULC (e.g. agroforestry systems land-use types such as cocoa-based agroforestry systems, banana plantations and dense forest with high tree density, dense forest with low tree density, swampy *Raphia* forest, swamp floods forest and fallow LULC types). These findings are in line with the findings of Lu *et al.* (2013) in Amazonia forests and of Zhang *et al.* (2016) in the forest of China. However, the high accuracy (89.45%) of LULC classification obtained for the 2018 year, using Landsat 8 OLI allowed us to conclude that high-resolution satellite imagery is consequential to high ability LULC classification scheme, highlighting the unavoidable availability of high-resolution satellite images for efficiently monitoring sustainable management of Congo Basin forests.

III.2.1.2. Dynamics and change trajectories of land use and land cover in Doume Communal forest

Information on detailed LULC change trajectories is often required for spatio-temporal dynamics research and is often calculated using the post-classification method at the per-pixel level as reported by several authors worldwide (Lambin, 2000; Kennedy *et al.*, 2009; Hansen & Loveland, 2012; Lu *et al.*, 2014). First of all, the post-classification method at the overall scale, allows us to analyze the status and overall forest cover changes whereby the loss and gain of LULC in the DCF was realized. This study showed that the DCF is experiencing an essentially regressive evolution which was much more significant in dense forest with high tree density LULC. Indeed, from 2000 to 2009 this LULC lost approximately 5% of its areas principally to agroforestry systems and dense forest with low tree density LULC types which gain 29 and 9% of their areas, respectively during the same periods. Several authors across Cameroon and Africa have reported a similar trend (Momo Solefack *et al.*, 2012; De Wasseige *et al.*, 2014; Meli Fokeng & Meli Meli, 2015; Momo Solefack *et al.*, 2018; Temgoua *et al.*, 2018; Toh *et al.*, 2018).

The overall-scale change detection results cannot provide the change trajectories, but the per-pixel based change detection analysis overcomes this shortcoming. Therefore, in this study, we have integrated pixel-to-pixel cross-tabulations of LULC change and our knowledge to generate a more comprehensive analysis of the main LULC change processes and trajectories in the DCF. Our findings show that most of the land cover changes between 2000 and 2018 involved degradation (~43 % of total land cover change), restoration from dense forest with low trees density to those of high trees density (26 %), conversion from forest to agroforestry systems (10 %) and deforestation to Swampy *Raphia* forest and fallow (~7 %). This high presence of forest degradation and conversion from forest to agroforestry systems may partly be related to the extensive and recurring population in the communal forest who practice agroforestry for their subsistence. Furthermore, the combined analyses showed that from 2000–2009 to 2009–2018 periods, a decreasing shift occurred from the main processes of forest degradation, deforestation but an increasing shift occurred from forest to agroforestry systems.

This study points out that agroforestry systems but not land-use types of agroforestry systems are the main causes of forest changes. These findings are in line with the findings of Lu *et al.* (2013) in the Brazilian Amazon forest. This shift does not coincide totally with the process of forest classification into a communal forest: before 2000, the DCF was facing anthropogenic pressures and illegal logging, while after 2009, access to DCF was strictly prohibited to the riparian population until the forest was approved and classified as communal forest and the management of this forest was subject to well-planned management. This finding highlights the anthropogenic influence on forests even though access was strictly prohibited, thus dismissing the question on the distribution of the benefits resulting from the management of the forest. The DCF is not the only the communal forest in Cameroon facing this phenomenon because it has also been reported in Santchou Reserve by Meli Fokeng & Meli Meli (2015), in Koupa-Matapit Gallery Forest by Momo Solefack *et al.* (2018), in Mount Bamboutos Caldera by Toh *et al.* (2018).

The results of this study show that some trajectories that are difficult to meet in nature can occur. This is the case, for example, of the abandonment and regeneration trajectory, where it would be really difficult for a fallow land in 10 years to become a dense forest with high-trees density. Such results may be due to misclassification, which may lead to a wrong interpretation of the timing of changes or even wrong trajectories.

III.2.1.3. Implications for sustainable management and conservation

This study shows that analyses of landscape trajectories can provide a more comprehensive overview on which land cover types are involved in other land cover change and forest regressions and how this land cover interacts with one another. This is particularly important for spatial planning in tropical forests where agriculture develops rapidly (Lambin, 1997; 2000; Lu *et al.*, 2013). Conversions into agroforestry systems can be identified and monitored by such trajectory analyses, and subsequently, zoning conservation and management policies can be developed to guide these changes into more sustainable directions. This is particularly important since such changes can change the socio-cultural environment of the ecosystem, impact the production of ecosystem services and therefore result in a loss of biodiversity and carbon pools and other natural resources. Therefore, it is essential and recommended that communities should be involved in the spatial planning and management process as they may play an important role in LULC change and may be affected by it. To reduce the pressures of the riparian population on the DCF, the managers could put in place some incentivized methods, for example by REDD+ or through subsidies for local food production.

III.2.2. Plant diversity, conservation and endemism

III.2.2.1. Diversity and species richness

The results of this study showed that among the thirty 1 ha of the DCF, species richness varied from 109 to 133 species ha^{-1} and that this species richness decreased with trees size classes. The species richness of large trees found in this study (104 ± 12 species ha^{-1}) was similar to the values of 119 ± 9 and 96 ± 10 species ha^{-1} found in Atlantic forest of Okoroba and Yingui respectively (Fobane, 2017), and the values of 110 species ha^{-1} found in lowlands evergreen forest of Ngovayang (Gonmadje, 2012). However, the number of 271 species found in the 30 1 ha plots of the semi-deciduous of east Cameroon was higher than the values of 207 species found in terra-firme evergreen forest in the Dja Biosphere Reserve in Cameroon (Djuikouo *et al.*, 2010) and the value of 205 species found in the same sites (Tabue *et al.*, 2016). Moreover, this result is also higher than the value of 127 species obtained in a semi-deciduous forest of east Cameroon (Chimi *et al.*, 2018). This study showed that disturbance which occurred a long time ago increased species richness, and soil conditions and topography also drove this species richness. Hence, ecological factors (i.e. rainfall, topography, disturbance and soil conditions…)

might explain the difference in species richness of the DCF plots and those studies above mentioned.

Elsewhere, this study is one of the few that evaluated species richness of understorey trees and small stems. It was found that the thirty 1 ha sample plots of the semi-deciduous forest host 242 species with an average of 52 ± 9 species ha^{-1}, and that is higher than the value of 24 species found in a semi-deciduous forest of east Cameroon (Chimi *et al.*, 2018). In addition, the 167 small stems species with on average 24 ± 5 species ha^{-1} found in the DCF was also higher than the value of 30 species obtained in 3.4 ha in a semi-deciduous forest (Chimi *et al.*, 2018). The rarefaction species accumulation curve which shows that the rate of species increase with sampling effort had yet reached an asymptote, indicating that the diversity of the DCF had been satisfactorily captured, and hence this may explain the differences found with other studies results.

A better floristic characterization of a stand is based on the interpretation of diversity indices (Mbolo *et al.*, 2016), and hence a forest is considered rich if it is characterized by a Shannon diversity index greater than or equal to 3.5 (Kent & Coker, 1992). The DCF plots, which at the whole tree community level, large trees class, and some understorey trees level had high values of Shannon diversity (H'>3.5) and Fisher-α can accordingly be considered very diverse. However, the Simpson index justifies the representativeness of the flora by some species in terms of their abundance (Sonké, 2004). McElhinny *et al.* (2005) showed that diversity indices such as Shannon, Simpson, Pielou are only elements of measurement and characterization of biodiversity.

III.2.2.2. Conservation value and endemism

Large areas are presented in the vast majority of cases as high concentrations of endemic species in contrast to small areas (Brooks *et al.*, 2002). The conservation status of the species has been done on a global scale (Onana & Cheek, 2011), and species with high priority for conservation in the Doume communal forest account for about 16% of species. This rate is higher than the 13% obtained in lowland forests of Ngovayang (Gonmadje, 2012), 11% obtained in Korup National Park where an area of 50 ha was inventoried (Kenfack *et al.*, 2007), and 9% obtained in the Atlantic forests of Yingui and Okoroba (Fobane, 2017). In addition, it should be noted that herbaceous plants have not been evaluated and therefore the increase in sampling in the Doume communal forest could be indicative of many other species with high conservation priorities or could be decreased this percentage. Moreover, it was found that some species at the global level were threatened while at the local level, they were not threatened, and hence that increased the percentage of species with high priority.

Endemic species are at high risk of extinction due to their confinement in specific habitats and their low density (Myers *et al.*, 2000; Brooks *et al.*, 2002), and therefore they are important for conservation. Hence, given the need to preserve these fragile and endangered species, it becomes essential to protect the sites that shelter them to avoid a total and irreversible erosion of this unique biodiversity.

III.2.3. Species associations and habitat types

III.2.3.1. Species associations and habitat types at the whole trees community level

In a forest ecosystem characterized by its vertical component (i.e. forest canopy) and the horizontal component (i.e. light levels, groundwater and soil properties, etc.), the coexistence of tree species can be promoted, an important aspect of spatial heterogeneity of the environment. Topo-edaphic gradients in DCF play a fundamental role in shaping plant species distributions as found in other forests elsewhere (Webb & Peart, 2000; Baldeck *et al.*, 2013a). Using MRT, it was found that species of DCF were structured into four habitats types mostly by edaphic variables and that habitats types changed with trees size classes contrary to the results of studies in other tropical and subtropical forests (Punchi-Manage *et al.*, 2013; Wang *et al.*, 2017). Among edaphic variables, soil pH and concentrations of Na were the two most important related to local species composition within the whole tree community and trees size classes except for small stems class where CEC concentration, MC and aspect were the most important topo-edaphic variables. Using similar methods, Baldeck *et al.* (2013a) divided the habitats into five types in long-term tropical forest dynamics plots of the Center for Tropical Forest Science (CTFS) network. Topography has been found as the most important abiotic factor causing spatial variation in the structure of tropical forests, since it is commonly correlated with other important environmental variables (Baldeck *et al.*, 2013a), notably the ground-water regime and the physical and chemical properties of the soils. The low topographical gradients across DCF plots may explain these differences.

The species association variance explained by topo-edaphic variables in DCF plots (37.23 %) was higher than in Sinharaja (22.73 %), and BCI (20.8%) plots obtained by Punchi-Manage *et al.* (2013). Several reasons may explain these differences. First, the sample size may contribute to the reduced unexplained variance as it has been demonstrated by several findings included in this study (Punchi-Manage *et al.*, 2013; Wang *et al.*, 2017). Second, the higher explanatory power of topo-edaphic habitats in the DCF plot may suggest stronger driving forces of soil properties for the assembly of tree communities than in these forests and hence agree with findings in tropical forest dynamics plots of the CTFS that adding soil variables to topographic variables increase species variance composition (Baldeck *et al.*, 2013a). However, the species variance obtained in this study is similar to the value of 34% obtained in a subtropical forest of China (Wang *et al.*, 2017), suggesting that the topographic gradient may play a great role.

There is still an important unmeasured environmental variation (i.e. light, drainage) that contributes to the species associations in these forests. Indeed, variables such as drainage, which exhibits spatial variation over larger spatial scales (hundreds of meters), may contribute to the variation that is spatially structured yet unexplained by our environmental variables set. Hence, the unexplained proportion of variance that is spatially structured and remains unaccounted for by either soil or topographic variables suggests an important role for dispersal-assembly alongside habitat niche processes in community structure in these forests. These results also highlight the importance of soil properties on the three associations as mentioned by previous research (John *et al.*, 2007; Baldeck *et al.*, 2013b).

III.2.3.2. Community-habitat association across trees size groups

This study showed that, during the transition from small stems and understorey trees to large, the variance explained by habitats increased and the CVRE decreased. In addition, it has been shown that seedling establishment and small stems density increase following canopy opening, gaps and often sites of high species diversity (Denslow, 1995), and hence the regeneration niche is less narrow than for the large niche. However, the explained differences in variance and CVRE were very small, which may indicate that during the transition from small stems to understorey trees and understorey trees to large trees, stochastic effects outweighed the effects of filtering and competition from the habitat or filtering and habitat competition processes counterbalanced each effect. This result was also found in the tropical forest of CTFS, and hence they argued that it is the consequence of neutral mortality rather than habitat filtering (Baldeck *et al.*, 2013b).

Across different trees size classes except for small stems, topographic and edaphic habitat types were relatively stable. This constancy in habitat types maybe because species suffer strong seed dispersal limitations that cause understorey trees to locate near large trees (Webb & Peart, 2000). In DCF, almost all indicator species for the habitats defined by large trees were also indicator species for habitats defined by understorey trees.

III.2.4. Carbon stock

III.2.4.1. Total carbon stock partitioning

This study is one of the few providing a comprehensive estimate of the main carbon pools in the moist tropical semi-deciduous rainforest of the Congo Basin. It was found that the total carbon stock of this semi-deciduous rainforest in east Cameroon was on average 285.6 ± 51.19 Mg C ha^{-1}, and mainly explained by aboveground carbon (AGC), which was on average 182.62 Mg C ha^{-1}. As found in other studies (e.g. Nascimento & Laurance, 2002; Djomo *et al.*, 2011; Kabelong *et al.*, 2018), this study found that variation in AGC was mainly determined by large trees, suggesting that carbon in large trees gives the best prediction of the total carbon stored in these forest ecosystems. This provides important implications, as carbon in large trees is relatively easy to measure for large areas. Aboveground carbon stock in this forest (182.66 Mg C ha^{-1}) was higher than the 154.9 Mg C ha^{-1} found in the tropical evergreen rainforest of southern Cameroon (Djomo *et al.*, 2011) and the value of 162.15 Mg C ha^{-1} found in a tropical semi-deciduous forest in eastern Cameroon (Chimi *et al.*, 2018). These differences may be caused by the poorer soil fertility and lower rainfall in this forest, which results in a higher abundance of dense-wooded species (van der Sande *et al.*, 2018) that accumulate high amounts of carbon. Furthermore, the floristic composition and the structural variables (basal area, height-diameter allometry, etc.) explain a large part of the spatial variation of biomass in tropical African forests (Marshall *et al.*, 2012; Shirima *et al.*, 2015): forest with high stand basal area (Day *et al.*, 2013) have generally high aboveground biomass.

Across 260 African forests, Lewis *et al.* (2013) found an average AGC (DBH ≥ 10 cm) of 185 Mg C ha^{-1}, slightly higher than the values found in our forest (177.61 Mg C ha^{-1}). Lewis *et al.* (2013) showed, however, that AGC decreases in areas with strong seasonality, such as our forest (which has also been found for Neotropical forests; Poorter *et al*., 2015). Other studies support that carbon stock is higher in humid compared to dry African forests (Day *et al.*, 2013), and in semi-deciduous compared to evergreen forests (Fayolle *et al.*, 2016). This would indicate that climate seasonality leads to lower carbon storage, whereas low soil fertility may lead to higher carbon storage.

African forests have been found to store more aboveground carbon than Amazonian forests (Malhi *et al.*, 2006; Lewis *et al.*, 2013). These differences may be associated with taller trees, higher stem density, higher wood density, and a history of lower-frequency disturbances in African forests compared to Amazonian forests (Lewis *et al.*, 2013).

It was found that belowground carbon (BGC) was the second most important pool contributing to total carbon stock and that its both components (root biomass and soil organic carbon; SOC) were important (Table 2), with a slightly more important contribution of coarse roots (Fig. 4). A root:shoot ratio was used to estimate coarse root carbon, causing a strong correlation between coarse root carbon and AGC. Since this forest had higher AGC than evergreen tropical rainforest (Djomo *et al.*, 2011) and the semi-deciduous forest in Cameroon (Chimi *et al.*, 2018), this may explain the higher coarse root carbon compared to these forests.

SOC contributed slightly more weakly to BGC than root biomass, probably because it varied more strongly among plots ($S_{between}$ = 32 Mg C ha^{-1}, compared to 19 Mg C ha^{-1} for coarse root carbon). The variation in SOC among the plots of this study may be explained by a variety of factors. The fact that this study site is poor in nutrients suggests that turnover and, hence, carbon input from litter is low. This may explain the lower SOC carbon in this forest (40 Mg ha^{-1}) compared to the evergreen rainforest in southern Cameroon (Djomo *et al.*, 2011) and multiple tropical African forests (Dixon *et al.*, 1994).

It was found that aboveground dead carbon (ADC) was the least important contributor to total carbon stocks (5 %), and was mainly determined by coarse woody debris. These results agree with deadwood mass in moist tropical Amazonian forests, which has been estimated to be less than 10% (Delaney *et al.*, 1998) of total above-ground carbon stocks. It was found that ADC and its components varied widely among the plots and that this variation was due mostly to environmental factors (Zekeng *et al.*, 2020). Interestingly, disturbance did not affect ADC, in contrast to earlier studies (Pfeifer *et al.*, 2015; Rozak *et al.*, 2018), probably because disturbance was relatively low and occurred 20 years ago (Weedon *et al.*, 2009; Garbarino *et al.*, 2015; Osone *et al.*, 2016). Differences in decomposition rates among species (Harmon *et al.*, 1995; Barbosa *et al.*, 2017) and structural forest traits (Pfeifer *et al.*, 2015) may also explain the large heterogeneity in ADC among our plots.

III.2.4.2. Carbon partitioning among forest carbon components

It was found that carbon in large trees was the main component of total carbon stock, followed by root carbon, soil organic carbon, and coarse woody debris. Furthermore, most of the carbon in large trees came from the big size trees in the forest (>70 cm DBH; Fig. 5). Therefore, in this semi-deciduous forest, the carbon stored by big-size trees could be used as a useful proxy for total carbon stock. The role of big size trees in driving forest carbon stocks is well recognized (Slik *et al.*, 2013; Bastin *et al.*, 2018; Lutz *et al.*, 2018) and the amount of biomass in big size trees has been quantified recently across the tropics (Stegen *et al.*, 2011; Slik *et al.*, 2013; Bastin *et al.*, 2015; Poorter *et al.*, 2015; Bastin *et al.*, 2018; Lutz *et al.*, 2018). A Pantropical analysis for 120 lowland tropical forests showed that 70% of the site variation in aboveground biomass was determined by the density of big-size trees (DBH > 70 cm) (Lewis *et al.*, 2013). Furthermore, the authors showed that African forests are dominated by relatively low-frequency disturbance regimes, allowing trees time to grow large and stands to self-thin, and therefore reaching higher carbon stocks than forests in South America and Asia. Because of their importance for aboveground biomass, big size trees play an important role in ecosystem functioning, such as primary productivity (Stephenson *et al.*, 2014).

Even though small and medium-sized trees (10-40 and 40-70 cm DBH) occur in higher density, they cannot provide carbon storage equivalent to the few large canopy and emergent trees. In order to maintain high carbon stocks in the long term, trees should be allowed to reach these large sizes. Therefore, the diversity and abundances of trees with DBH < 10 cm should be safeguarded so that forests will maintain high carbon storage also in the future (Memiaghe *et al.*, 2016).

It was found very low carbon storage by understorey vegetation. Although the forest understorey trees were often quite dense with many small stems, the herb layer was much smaller than in many other forests (e.g. Nascimento & Laurance, 2002; Djomo *et al.*, 2011; Kabelong *et al.*, 2018). This difference is probably due to the poor soils and the disturbance history of the forest. In this study, the carbon stored by understorey and small trees (DBH < 10 cm; 4.40 Mg C ha^{-1}) was similar to that in old secondary evergreen forest in Deng Deng (region of east Cameroon; Kabelong et *al.*, 2018) and higher than in evergreen managed forest in southern Cameroon (Djomo et *al*. 2011).

Carbon stored in coarse woody debris (10.90 Mg C ha^{-1}) in this forest was lower compared to values of 16.1 Mg C ha^{-1} found in a moist lowland tropical forest in Central Panama (Gora *et al.*, 2019). Coarse woody debris is determined by the input of deadwood and output through decomposition. In old-growth, lowland tropical forests growing on very nutrient-poor soils, or in very dry sites, coarse woody debris is often low due to low rates of CWD input (Baker *et al.*, 2007). In our forest on poor soils, the input of woody debris may also be low, causing slow accumulation and low carbon stocks in coarse woody debris.

Standing deadwood contributed 16% to aboveground dead carbon, and 1% to total carbon. Carbon in dead biomass from our site was higher than in old secondary forest in eastern Cameroon (Kabelong *et al.*, 2018), possibly because this forest has higher tree density and total biomass, which could lead to a higher input of dead biomass. Even though standing deadwood is only a small part of total carbon, it's carbon storage across large areas can be substantial. Estimates of standing deadwood are therefore important for validating carbon cycling models

(Chambers *et al.*, 2000). However, these data, as well as carbon estimates of woody debris, trees with diameter ≤ 5 cm and litter, are available only for few tropical forest sites.

III.2.4.3. Correlations among carbon components

It was expected that total carbon stock would be positively correlated with its underlying carbon pools and components. Furthermore, all carbon components would be positively correlated, as a forest with higher total biomass and tree density would have more biomass and carbon in all components. It was indeed found strong positive correlations between total carbon stock and aboveground carbon pool, and aboveground dead carbon pool and belowground carbon pool.

As this is a managed forest, it is expected that carbon stored in large trees would be negatively correlated with woody debris and standing dead trees, because plots with higher disturbance would have fewer large trees and more debris. Furthermore, forests with high carbon stocks in large trees would be denser with less light reaching the understory and, hence, have a more open forest understorey. Interestingly, it was found that carbon in large trees was strongly positively correlated with root carbon, but not with any of the other carbon components. Aboveground carbon stocks depend on the long-term buildup of carbon and are balanced by mortality and decomposition. For that reason, the amount of carbon present in different components, of which the buildup and removal are driven by different factors, may be unrelated.

It was found that a positive correlation existed between litter and carbon in understorey trees, probably because the high density of understorey trees can increase the amount of litter produced. Moreover, it was found that only a weak correlation existed between carbon in live components and carbon in dead trees, probably because most dead carbon is derived from large trees that die, but mortality of these large trees is largely a stochastic process (van der Sande *et al.*, 2017a).

Variation partitioning results showed that ADC and coarse woody debris were positively correlated with total carbon stock, though more weakly than the two other carbon pools. A negative correlation between soil organic carbon and fine woody debris was also found. This is striking, as a higher input of fine woody debris would automatically lead to a higher input of carbon to the soil, which would suggest a positive correlation between the two. Perhaps the input of fine woody debris is limited, and decomposition would reduce carbon in fine woody debris while increase soil organic carbon.

III.2.4.4. Abiotic and biotic effect on carbon stock

III.2.4.4.1. Species diversity increases carbon stocks

It was expected that taxonomic diversity (i.e. rarefied species richness, Shannon-Weaver index and species richness) would have a positive effect on AGC stock through niche complementary, the selection effect, and/or facilitation. However, it was found that taxonomic diversity strongly drives carbon stock for only large trees and the whole tree community. The benefits of plant-plant interactions such as facilitation, and hence some species could enhance soil fertility for the productivity of other species may also explain these results. But it might also be well possible that increasing species richness increases the chances of inclusion of highly productive favored dominant species (Ruiz-Benito *et al.*, 2014). To our knowledge, this is the first local scale study analyzing the relationship between carbon stocks across tree size groups and the whole tree community of Cameroon tropical rainforest and its multiple underlying drivers. Most empirical studies that have examined the effects of diversity on forest carbon or productivity have ignored the effect of forest structure and environment (but see Day *et al.*, 2013). The significant positive effects of rarefied species richness and species richness on aboveground carbon stocks of the large trees and the whole tree community found in this study have also been reported in several local and global tropical forest ecosystems (Con *et al.*, 2013; Day *et al.*, 2013; Cavanaugh *et al.*, 2014; Poorter *et al.*, 2017; van der Sande *et al.*, 2018).

III.2.4.4.2. Structural diversity increased aboveground carbon stocks

It was found a significant positive effect of structural diversity (Gini index) on aboveground carbon stocks of the whole tree community, large trees and understory trees. When structural diversity is high, there is strong layering within the canopy which can more efficiently fit high amounts of biomass in the same area. Also, high structural diversity may indicate the presence of some very large trees that contribute disproportionally to forest biomass and carbon. This is confirmed by an earlier study in this forest, which showed that aboveground carbon at the whole tree community and at the large trees group are strongly driven by big-diameter trees (Zekeng *et al.*, 2020).

III.2.4.4.3. Topography, soil conditions and disturbance shape aboveground carbon stocks

It was expected that topographic variables could strongly affect carbon stocks. However, we found that topography (i.e. terrain slope) only affected AGB of large trees and of the whole tree community, while fertile soils only increased AGC of small stems (through Nsoil) and of understorey stems (through clay content). The positive effect of slope on AGC of large trees and the whole tree community, showed evidence that differences in AGC stocks can result from topological constraints, particularly difference in terrain slope (Chave *et al.*, 2003; de Castilho *et al.*, 2006; Mensah *et al.*, 2016; Salinas-Melgoza *et al.*, 2018). It is important to note that dominant terrain slopes in our rainforest varied from 3 to 15 %, and hence are considered as steep slopes (Zare Chahouki *et al.*, 2012). Normally, one would expect that AGC decreases in steep slopes because it has shallow soils (Gong *et al.*, 2008), and are richer in the sand but poorer in silt content (Pachepsky *et al.*, 2001), and hence are more vulnerable to erosion. Surprisingly, it was found out that the slope increased AGC.

Soils of the semi-deciduous communal forest of Doume are leached, and hence may be nutrient-poor habitats. It was therefore expected that increasing soil resources would strongly determine carbon storage. Soil nitrogen indeed significantly increased aboveground carbon stocks of small stems, and higher soil clay content – which is generally correlated with higher fertility – increased AGC of understory trees and structural diversity. It has been recognized as we found that soil textural properties are the most important characteristics of the soil, influencing, directly and indirectly, cascades of relations between soil nutrients, ions and soil drainage (Silver *et al.*, 2000), and hence expected to have strong effects on AGC stocks. These results are in line with other studies (Zarin *et al.*, 2001; Lewis *et al.*, 2013; van der Sande *et al.*, 2018), and demonstrate the importance of small-scale variation in soil conditions for the forest's capacity to store carbon.

This study did not detect any significant effects of logging disturbance on carbon stock of all tree size groups and the whole tree community, maybe because it depends on the distribution of commercial species and that they didn't strongly vary between plots. Contrary to our expectation, logging as a continuous variable didn't reduce carbon stocks of the whole tree community and all three size groups. These results may be due to the small disturbance variation and that the disturbance has appeared a too long time ago. Therefore, carbon stocks can rapidly recover. Contrary, disturbance increase significantly carbon stocks of large trees and the whole tree community through the diversity Gini index. It has been shown in the Amazonian forest that disturbance resulted in a decrease in AGB, but with time, it increases the recruitment of small trees (Holm *et al.*, 2014) and hence this phenomenon could explain the results observed in our study. Our results, in conjunction with recent studies across Neotropical forest (Poorter *et al.*, 2017; van der Sande *et al.*, 2018) indicates that disturbance is an important process, by increasing the availability of light and others resources, hence promote the recruitment of small trees in the lower forest strata.

III.2.4.5. Implications for carbon and REDD+

To best of our knowledge, this is the first empirical study that has shown that aboveground carbon stocks are related to the abiotic factors as well as to taxonomic and structural diversity at all tree size groups and at the whole tree community within a Cameroonian tropical rainforest. The results showed that structural diversity has significant effects on aboveground carbon stocks of the whole tree community, large trees, and understory trees, which means that it is important to maintain a layered structure and also tall trees in the forest. It was also found that aboveground carbon increased with increasing species richness and hence conserving biodiversity is not just an objective in itself. This result showed implication for REDD + that forests with high diversity also tend to have high carbon stocks, indicating that forests with high carbon storage potential also have high conservation potential. Species richness could also help protect ecosystem productivity from environmental change (Isbell *et al.*, 2011) and enhance the resilience of these ecosystems to disturbance (Díaz *et al.*, 2009). Therefore, as diversity co-determines the functioning of the forest, many authors recommended that biodiversity conservation should not be seen as a simple simultaneous benefit of REDD+, but as integral and crucial components of all its activities (Díaz *et al.*, 2009). Hence, due to his essential role in the forest functioning, biodiversity conservation is a win-win strategy for programs such as REDD+ and those under the Convention of Biological Diversity.

This study has a second implication for REDD+. Indeed, the results obtained for carbon stocks, their representativeness as well as their uncertainties can be associated with remote sensing tools, and used to validate carbon maps of tropical semi-deciduous forests at the country level, for instance.

CHAPTER IV. CONCLUSION AND PERSPECTIVES

IV.1. CONCLUSION

The existence and persistence of important ecosystem processes in tropical forests are dependent on abiotic and biotic conditions. Therefore, human actions and decisions are crucial for both practical and scientific goals. The present study evaluated the LULC change during the last two decades, and how abiotic factors in the terra-firme forest type identified drive species assemblages, and carbon stocks in the Doume Communal forest. The conclusions of this study are arranged according to the hypothesis and research questions mentioned in the introduction.

This study showed that LULC of about half of the study area changed in the period 2000-2009. Based on our quantitative and spatial analyses, forest degradation, restoration, conversion of forest and fallow to agroforestry systems and deforestation to swampy *Raphia* forest and fallow were found to be the dominant LULC change processes causing reduction of forest cover. Also, the post-classification based on per-pixel scale showed that the different types of LULC changes in the study area increased and involved a more diverse set of characteristic trajectories in the period 2009-2018, compared to the period 2000-2009. It was found that deforestation to fallow decreased between 2000 and 2018 and entailed a total land area of ~1377 ha in 2000-2009 and ~1191 ha in 2009-2018 which is about 6.76 and 6.84 %, respectively of the total land cover change area in these periods. However, degradation increased from 38.8 % of the total LULC change in the period 2000-2009 to 44.54 % in 2009-2018. Conversion from the forest and fallow to agroforestry systems increased from 3.60 % in 2000-2009 to 11 % in 2009-2018.

The species inventory of terra-firme forest has shown the importance of the Doume communal forest for the conservation of tree diversity. It has been shown here that, in terms of alpha diversity, Doume communal forest is a rich and diverse forest.

This study provides indications of the relative importance of topographic and habitat factors in structuring local species. Across trees size groups except for the small stems group and the whole tree community, this study revealed that forest plots constituting each habitat that drives species associations were the same. This study also found that 37 % of the species variance was due to topographic and edaphic habitat association and that species variance decreased down to 26 % with tree size classes. The unaccounted edaphic variables could contribute to the unexplained species variance found in this study, and hence suggest that stochastic effects and spatially structured processes such as dispersal limitation may also have a substantial contribution and that both neutral and niche processes may jointly shape local species associations in the DCF.

This study found that aboveground live carbon was the main pool contributing to explain the variation in total carbon stock, followed by belowground carbon pool. Large trees were the main forest component contributor to aboveground live carbon stocks and total carbon stocks, while carbon in coarse roots was the main contributor to belowground carbon stocks and total carbon stock. Belowground and aboveground live carbon stocks were significantly correlated with total carbon stock. Hence, it was shown that most carbon is stored by aboveground biomass in large trees, indicating that variation among the terra-firme semi-deciduous forest in aboveground biomass is a good predictor for variation in total carbon storage. However, aboveground carbon and belowground carbon and their interactions explained most of the variation in total carbon stock, indicating that a whole-ecosystem approach is necessary for a full understanding of the carbon cycle.

This study highlights that large canopy and emergent trees play an important role in forest community structure and ecosystem carbon storage and can be used as a predictor for total carbon stocks, but not as a predictor for the carbon stored in individual carbon pools. Preserving large trees, as well as leaving dead biomass in the forest, could, therefore, enhance and maintain forest carbon stocks. Furthermore, protecting small stems and understorey trees would secure maximum long-term carbon storage. These measures would contribute to the effectiveness and efficiency of the REDD+ mechanism, as well as the sustainable management of the Congo Basin forests. Moreover, this study showed that, across treesize groups and the whole tree community, aboveground carbon stocks were driven by different abiotic factors with different magnitudes and strengths. The results showed that both biotic and abiotic factors drive carbon stock, but biotic factors were the best predictors of carbon stocks across tree size classes and the whole tree community in the rainforest. It also found that aboveground carbon increased with the increase of species richness, and hence conserving biodiversity is not just an objective in itself.

IV.2. PERSPECTIVES

This work has brought new insights into the knowledge of plant diversity, species conservation, and carbon storage potential with a focus on biodiversity conservation and sustainable forest management in the Communal forest. However, future research would deepen and help to clearly understand several phenomena such as:

This study showed that LULC and trajectories were most diverse and mostly included trajectories which involved degradation with a high rate than was expected. Therefore, further studies should determine the drivers of these processes and changes to simulate its influence on LULC, and hence make previsions in what could happen to that forest in the short run.

To have a real view on biodiversity potentialities of the forest, most efforts in terms of sampling area and other land covers of the forest need to be done.

Given the relevance of tropical forests to human wellbeing and nature, future research efforts should aim to clarify how mechanisms underlying ecosystem processes depend on the spatial and temporal scale and site conditions. This should be done at local levels to improve local forest management and safeguard sustainable ecosystems and livelihoods, and at the global level to influence national and international policies that tackle global problems and provide a framework for local-level sustainability.

Further studies should assess the contributions of topography and soil conditions in the variation of diversity and carbon storage.

This study was limited to assess how abiotic factors drive aboveground live carbon only, and hence further studies could mostly focus on other carbon pools.

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APPENDICES

Appendix 1. Publications issues from the thesis

Appendix 2. Land cover change matrix (in ha) 2000–2009 for the Doume Communal forest. These matrices indicate the number of pixels (and thus the hectares) change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period (LULC types – AgrL, DFHTD, DFLTD, RphSF, SwFF and GrlD represent Agroforestry systems Land, dense forest with high tree density, dense forest with low tree density, swampy *Raphia* forest, swampy flooded forest and grassland respectively).

	AgrL	DFHTD	DFLTD	RphSF	SwFF	GrlD	Total 2000
AgrL	423	75	318		33	33	882
DFHTD	452	14 364	7 759	842	364	153	23 934
DFLTD	127	7 372	4 228	320	124	62	12 233
RphSF	85	615	640	623	45		2 008
SwFF	41	369	289	112	358		1 169
GrlD	29	38	69			19	155
Total 2009	1 158	22 833	13 304	1 897	924	267	40 382

Appendix 3. Land cover change matrix (in ha) 2009–2018 for the Doume Communal forest. These matrices indicate the number of pixels (and thus the hectares) change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period (LULC types – AgrL, DFHTD, DFLTD, RphSF, SwFF and GrlD represent Agroforestry systems Land, dense forest with high density, dense forest with low density, swampy *Raphia* forest, swampy flooded forest and grassland respectively).

	AgrL	DFHTD	DFLTD	RphSF	SwFF	GrlD	Total 2018
AgrL	675	86	325		9	43	1 137
DFHTD	724	13 637	7 646	497	179	150	22 833
DFLTD	1 026	4 283	7 336	391	114	153	13 303
RphSF	86	722	253	766	106		1 933
SwFF	47	236	82	68	467		900
GrlD	33	8	150			85	276
Total 2009	2 590	18 972	15 793	1 722	875	430	40 382

Appendix 4. Land cover change matrix (in ha) 2000–2018 for the Doume Communal forest. These matrices indicate the number of pixels (and thus the hectares) change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period (LULC types – AgrL, DFHTD, DFLTD, RphSF, SwFF and GrlD represent Agroforestry systems land, dense forest with high density, dense forest with low density, swampy Raphia forest, swampy flooded forest and grassland respectively).

	AgrL	DFHTD	DFLTD	RphSF	SwFF	GrlD	Total 2018
AgrL	428	63	300		40	50	882
DFHTD	1 224	12 191	9 240	726	303	250	23 934
DFLTD	665	5 645	5 250	393	167	112	12 233
RphSF	148	613	661	481	106		2 008
SwFF	81	423	290	84	286		1 163
GrlD	46	36	51			28	161
Total 2000	2593	18971	15792	1683	902	441	40382

Appendix 5. Land cover change matrix (in %) 2000–2009 for the Doume Communal forest. These matrices indicate the number of pixels change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period (LULC types – AgrL, DFHTD, DFLTD, RphSF, SwFF and GrlD represent Agroforestry systems land, dense forest with high tree density, dense forest with low tree density, swampy Raphia forest, swampy flooded forest and wooded savanna respectively).

	AgrL	DFHTD	DFLTD	RphSF	SwFF	GrlD	Total 2000
AgrL	1.05	0.19	0.79	0.00	0.08	0.08	2.19
DFHTD	1.12	35.57	19.22	2.08	0.90	0.38	59.27
DFLTD	0.31	18.25	10.47	0.79	0.31	0.15	30.29
RphSF	0.21	1.52	1.59	1.54	0.11	0.00	4.97
SwFF	0.10	0.91	0.72	0.28	0.89	0.00	2.89
GrlD	0.07	0.09	0.17	0.00	0.00	0.05	0.38
Total 2009	2.87	56.54	32.94	4.70	2.29	0.66	100.00

Appendix 6. Land cover change matrix (in %) 2009–2018 for the Doume Communal forest. These matrices indicate the number of pixels change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period (LULC types – AgrL, DFHTD, DFLTD, RphSF, SwFF and GrlD represent Agroforestry systems land, dense forest with high tree density, dense forest with low tree density, swampy Raphia forest, swampy flooded forest and wooded savanna respectively).

	AgrL	DFHTD	DFLTD	RphSF	SwFF	GrlD	Total 2000
AgrL	1.67	0.21	0.80	0.00	0.02	0.11	2.82
DFHTD	1.79	33.77	18.94	1.23	0.44	0.37	56.54
DFLTD	2.54	10.61	18.17	0.97	0.28	0.38	32.94
RphSF	0.21	1.79	0.63	1.90	0.26	0.00	4.79
SwFF	0.12	0.58	0.20	0.17	1.16	0.00	2.23
GrlD	0.08	0.02	0.37	0.00	0.00	0.21	0.68
Total 2009	6.41	46.98	39.11	4.26	2.17	1.06	100.00

Appendix 7. Land cover change matrix (in %) 2000–2018 for the Doume Communal forest. These matrices indicate the number of pixels change from one land cover type (vertical axis) to another (horizontal axis) within the selected time period (LULC types – AgrL, DFHTD, DFLTD, RphSF, SwFF and GrlD represent Agroforestry systems land, dense forest with high tree density, dense forest with low tree density, swampy Raphia forest, swamp floods forest and grassland respectively).

	AgrL	DFHTD	DFLTD	RphSF	SwFF	GrlD	Total 2000
AgrL	1.06	0.16	0.74	0.00	0.10	0.12	2.18
DFHTD	3.03	30.19	22.88	1.80	0.75	0.62	59.27
DFLTD	1.65	13.98	13.00	0.97	0.41	0.28	30.29
RphSF	0.37	1.52	1.64	1.19	0.26	0.00	4.97
SwFF	0.20	1.05	0.72	0.21	0.71	0.00	2.88
GrlD	0.11	0.09	0.13	0.00	0.00	0.07	0.40
Total 2009	6.42	46.98	39.11	4.17	2.23	1.09	100.00

Appendix 8. List of species found in the 30 1-ha plots of the Doume Communal Forest with their habit (tr=trees and sh=shrubt) and the IUCN status (categories of the threat as EN = Endangered; VU = Vulnerable; LC to Least Concern and NT = Near Threatened).

Famille	Noms scientifiques authorifié	*Chorology*	*Onana (2011)*	Statut de l'IUCN
Achariaceae	*Caloncoba glauca* (P. Beauv.) Gilg	Gc	LC	
Achariaceae	*Camptostylus mannii* (Oliv.) Gilg	Gc	*LC*	LC
Achariaceae	*Scottellia klaineana* Pierre	Gc	LC	LC
Achariaceae	*Caloncoba gilgiana* (Sprague) Gilg	*Gc*	LC	LC
Anacardiaceae	*Antrocaryon klaineanum* Pierre	Lg	LC	
Anacardiaceae	*Sorindeia grandifolia* Engl.	Gc	LC	LC
Anacardiaceae	*Trichoscypha acuminata* Engl.	Gc	LC	LC
Anacardiaceae	*Lannea welwitschii* (Hiern) Engl.	Gc	LC	
Anisophylleaceae	*Poga oleosa* Pierre	Lg	DD	
Annonaceae	*Annickia affinis* (Exell) Versteegh & Sosef	Gc		
Annonaceae	*Annickia chlorantha* (Oliv.) Setten & Maas	Gc	LC	
Annonaceae	*Anonidium mannii* (Oliv.) Engl. & Diels	Lg	LC	LC
Annonaceae	*Cleistopholis glauca* Pierre ex Engl. & Diels	Gc	LC	LC
Annonaceae	*Greenwayodendron suaveolens (Engl. & Diels) Verdc.*	Gc	LC	LC
Annonaceae	*Xylopia aurantiiodora* De Wild. & T. Durand	Gc	NT	LC
Annonaceae	*Xylopia hypolampra* Mildbr. & Diels	Gc	LC	LC
Annonaceae	*Xylopia quintasii* Engl. & Diels	Gu	LC	
Annonaceae	*Xylopia staudtii* Engl. & Diels	Gc	LC	
Annonaceae	*Duguetia staudtii* (Engl. & Diels) Chatrou	Gc	LC	
Annonaceae	*Xylopia parviflora* (A. Rich.) Benth.	Gc	LC	
Annonaceae	*Cleistopholis patens* (Benth.) Engl. & Diels	Gc	LC	
Annonaceae	*Hexalobus crispiflorus* A. Rich.	Gc	LC	
Annonaceae	*Isolona hexaloba* Pierre ex Engl. & Diels	Gc	LC	
Annonaceae	*Monodora tenuifolia* Benth.	Gc	LC	
Annonaceae	*Xylopia aethiopica* (Dunal) A. Rich.	Gc	LC	LC
Apocynaceae	*Hunteria umbellata* (K.Schum.) Hall. fil.	Gc	LC	
Apocynaceae	*Picralima nitida* (Stapf) Th. & H. Durand	Gc	LC	LC
Apocynaceae	*Tabernaemontana crassa* Benth.	Gc	LC	LC
Apocynaceae	*Funtumia elastica* (Preuss) Stapf	Tra	LC	LC
Apocynaceae	*Alstonia boonei* De Wild.	Tra	LC	LC
Apocynaceae	*Rauvolfia caffra* Sond.	Tra	LC	LC

Apocynaceae	*Rauvolfia vomitoria* Afzel.	Tra	LC	LC
Apocynaceae	*Tabernaemontana pachysiphon* Stapf	Tra	LC	LC
Apocynaceae	*Voacanga africana* Stapf ex Scott-Elliot	Tra	LC	LC
Aptandraceae	*Aptandra zenkeri* Engl.	Gc	LC	LC
Aptandraceae	*Ongokea gore* (Hua) Pierre	Gc	LC	LC
Araliaceae	*Polyscias fulva* (Hiern) Harms	Tra	NT	LC
Arecaceae	*Elaeis guineensis* Jacq.	In		LC
Asparagaceae	*Dracaena arborea* (Willd.) Link	Gc		LC
Asteraceae	*Vernonia conferta* Sch. Bip. ex Baker	Tra		
Asteraceae	*Dichrocephala integrifolia*	Tra	LC	LC
Bignoniaceae	*Fernandoa adolfi-friderici* (Gilg & Mildbr.) Heine	Gc	LC	LC
Bignoniaceae	*Markhamia lutea* (Benth.) K.Schum.	Gc	LC	LC
Bignoniaceae	*Markhamia tomentosa* (Benth.) K.Schum. ex Engl.	Gc	LC	LC
Bignoniaceae	*Stereospermum acuminatissimum* K. Schum	Gu	LC	LC
Bignoniaceae	*Kigelia africana* (Lam.) Benth.	Tra	LC	LC
Bignoniaceae	*Spathodea campanulata* Beauv.	Gc	LC	LC
Burseraceae	*Dacryodes edulis* (G. Don) H. J. Lam.	Gc	LC	
Burseraceae	*Dacryodes macrophylla* (Oliv.) H. J. Lam.	Lg	LC	LC
Burseraceae	*Dacryodes igaganga* Aubrév. & Pellegr.	Lg	VU	VU
Burseraceae	*Pachylobus trimerus* Guillaum.	Gc	LC	LC
Burseraceae	*Dacryodes klaineana* (Pierre) H. J. Lam.	Gc	LC	LC
Burseraceae	*Canarium schweinfurthii* Engl.	Tra	LC	LC
Calophyllaceae	*Mammea africana* G. Don	Gc	LC	
Cannabaceae	*Celtis mildbraedii* Engl.	Gc	LC	LC
Cannabaceae	*Celtis tessmannii* Rendle	Gc	LC	LC
Cannabaceae	*Celtis adolfi-friderici* Engl.	Gu	LC	LC
Cannabaceae	*Trema orientalis* (L.) Blume	PAL	LC	
Cannabaceae	*Celtis philippensis* Blanco	Tra	LC	LC
Cannabaceae	*Celtis zenkeri* Engl.	Tra	LC	LC
Chrysobalanaceae	*Parinari hypochrysea* Mildbraed ex R. Letouzey & F. White	Lg	LC	
Chrysobalanaceae	*Maranthes gabunensis* (Engl.) Prance	Gc	LC	LC
Chrysobalanaceae	*Magnistipula zenkeri* Engl.	Gu	LC	
Chrysobalanaceae	*Parinari excelsa* Sabine	Gc	LC	LC
Chrysobalanaceae	*Maranthes aubrevillei* (Pellegr.) Prance ex F.White	Gc	LC	LC
Clusiaceae	*Allanblackia kisonghi* Vermoesen	Gc		
Clusiaceae	*Garcinia lucida* Vesque	Gu	LC	LC
Clusiaceae	*Garcinia mannii* Oliv.	Gu	LC	LC

Clusiaceae	*Garcinia kola* Heckel	Gc	VU	VU
Clusiaceae	*Pentadesma butyracea* Sabine	*Lg*		LC
Clusiaceae	*Symphonia globulifera* L. fil.	Pan		LC
Combretaceae	*Terminalia ivorensis* A. Chev.	Gu	LC	VU
Combretaceae	*Terminalia superba* Engl. & Diels	Gc	LC	LC
Combretaceae	*Terminalia hylodendron* (Mildbr.) Gere & Boatwr.	Gc		
Ebenaceae	*Diospyros bipindensis* Gürke	Gc	LC	LC
Ebenaceae	*Diospyros crassiflora* Hiern	Gc	NT	VU
Ebenaceae	*Diospyros iturensis* (Gürke) Letouzey & F.White	Gc	LC	LC
Ebenaceae	*Diospyros sanza-minika* A.Chev.	Lg	LC	LC
Ebenaceae	*Diospyros suaveolens* Gürke	Lg	LC	LC
Ebenaceae	*Diospyros canaliculata* De Wild.	Gc	LC	LC
Cordiaceae	*Cordia platythyrsa* Baker	*Gc*	LC	VU
Cordiaceae	*Cordia aurantiaca* Baker	*Lg*	LC	LC
Euphorbiaceae	*Alchornea floribunda* Müll.Arg.	Gc	LC	LC
Euphorbiaceae	*Croton oligandrus* Pierre ex Hutch.	Gc	LC	LC
Euphorbiaceae	*Dichostemma glaucescens* Pierre	Gc	LC	LC
Euphorbiaceae	*Erythrococca atrovirens* (Pax) Prain	Gc	LC	LC
Euphorbiaceae	*Grossera macrantha* Pax	Gc	NT	
Euphorbiaceae	*Macaranga assas* Amougou	Gc	LC	
Euphorbiaceae	*Macaranga staudtii* Pax	Gc	LC	
Euphorbiaceae	*Mallotus subulatus* Müll.Arg.	Gc	LC	
Euphorbiaceae	*Mareyopsis longifolia* (Pax) Pax & K.Hoffm.	Gc	LC	
Euphorbiaceae	*Tetrorchidium didymostemon* (Baill.) Pax & K.Hoffm.	Gc	LC	LC
Euphorbiaceae	*Macaranga alnifolia* Baker	Malgaches (Mal)		LC
Euphorbiaceae	*Mallotus oppositifolius* (Geiseler) Müll.Arg.	Tra	LC	LC
Euphorbiaceae	*Shirakiopsis elliptica* (Hochst.) Esser	Tra		
Euphorbiaceae	*Discoglypremna caloneura* (Pax) Prain	Gc	LC	LC
Euphorbiaceae	*Croton macrostachyus* Hochst. ex Delile	Tra	LC	LC ver 3.1
Euphorbiaceae	*Ricinodendron heudelotii* (Baill.) Heckel	Tra	LC	LC
Euphorbiaceae	*Macaranga hurifolia* Beille	Gc		
Gentianaceae	*Anthocleista schweinfurthii* Gilg	Tra	LC	
Irvingiaceae	*Irvingia gabonensis* Baill. ex Lanen.	Gc	LC	LC
Irvingiaceae	*Irvingia grandifolia* (Engl.) Engl.	Gc	LC	LC
Irvingiaceae	*Irvingia robur* Mildbraed	Gu	LC	LC
Irvingiaceae	*Desbordesia glaucescens* (Engl.) Tiegh.	Lg	LC	
Irvingiaceae	*Klainedoxa gabonensis* Pierre	Gc	LC	

Ixonanthaceae	*Phyllocosmus africanus* Klotzsch	Gc	LC	
Ixonanthaceae	*Phyllocosmus calothyrsus* Mildbr.	Gc	LC	
Lamiaceae	*Vitex grandifolia* Gürke	Gc	LC	LC
Lamiaceae	*Vitex rivularis* Gürke	Gc	LC	LC
Lauraceae	*Beilschmiedia obscura* Engl. ex Stapf	Gc	LC	
Lauraceae	*Persea americana* Mill.	In	LC	LC ver 3.1
Lecythidaceae	*Petersianthus macrocarpus* (P.Beauv.) Liben	Gc	LC	LC
Leguminosae - Caesalpinioideae	*Bikinia letestui* (Pellegr.) Wieringa	Lg	LC	
Leguminosae - Caesalpinioideae	*Brachystegia cynometroides Harms*	Lg	LC	LC
Leguminosae - Caesalpinioideae	*Brachystegia mildbraedii Harms*	Lg	LC	LC
Leguminosae - Caesalpinioideae	*Didelotia unifoliolata* J.Léonard	Lg	LC	NT
Leguminosae - Caesalpinioideae	*Microberlinia bisulcata A.Chev.*	Gc	VU	CR
Leguminosae - Caesalpinioideae	*Tetraberlinia bifoliolata* (Harms)Hauman	Gc	LC	LC
Leguminosae - Caesalpinioideae	*Guibourtia demeusei* (Harms)J.Leonard	Gc	LC	LC
Leguminosae - Caesalpinioideae	*Afzelia africana* Pers.	Pan	VU	VU
Leguminosae - Caesalpinioideae	*Aphanocalyx microphyllus (Harms) Wieringa*	Gc	LC	LC
Leguminosae - Caesalpinioideae	*Guibourtia ehie* (A.Chev.)J.Leonard	Gc	LC	LC
Leguminosae - Caesalpinioideae	*Daniella ogea (Harms) Rolfe ex Holland*	Gu	LC	LC
Leguminosae - Papilionoideae	*Gossweilerodendron joveri* Aubrév.	Gc		VU
Leguminosae - Papilionoideae	*Bobgunnia fistuloides* (Harms)J.H.Kirkbr. & Wiersema	Gc		LC
Leguminosae - Papilionoideae	Millettia barteri (Benth.) Dunn	Gc	LC	LC
Leguminosae - Papilionoideae	*Pericopsis elata* (Harms)Meeuwen	Gc	LC	EN
Leguminosae-Caesalpinioideae	*Aphanocalyx hedinii* (A.Chev.)Wieringa	Cam	EN	CR
Leguminosae-Caesalpinioideae	*Anthonotha lamprophylla* (Harms)J.Leonard	Gc	LC	
Leguminosae-Caesalpinioideae	*Anthonotha macrophylla* P.Beauv.	Gc	LC	LC
Leguminosae-Caesalpinioideae	*Detarium macrocarpum* Harms	Lg	LC	
Leguminosae-Caesalpinioideae	*Dialium bipindense* Harms	Lg	LC	NT

Leguminosae-Caesalpinioideae	*Hylodendron gabunense* Taub.	Gc	LC	LC
Leguminosae-Caesalpinioideae	*Pachyelasma tessmannii* (Harms)Harms	Gc	LC	
Leguminosae-Caesalpinioideae	*Tessmannia africana* Harms	Gc	LC	LC
Leguminosae-Caesalpinioideae	*Afzelia pachyloba* Harms	Gc	VU	VU
Leguminosae-Caesalpinioideae	*Anthonotha fragrans* (Baker f.)Exell & Hillc.	Gc	LC	LC
Leguminosae-Caesalpinioideae	*Distemonanthus benthamianus* Baill.	Gu	LC	LC
Leguminosae-Caesalpinioideae	*Erythrophleum ivorense* A.Chev.	Gu	LC	
Leguminosae-Caesalpinioideae	*Gossweilerodendron balsamiferum* (Vermoesen)Harms	Gc		EN
Leguminosae-Caesalpinioideae	*Oxystigma oxyphyllum* (Harms)Leonard	Gc		
Leguminosae-Caesalpinioideae	*Afzelia bipindensis* Harms	Gc	VU	VU
Leguminosae-Caesalpinioideae	*Erythrophleum suaveolens* (Guill. & Perr.)Brenan	Tra	LC	LC
Leguminosae-Mimosoideae	*Albizia ferruginea* (Guill. and Perr.) Benth.	Gc	LC	VU
Leguminosae-Mimosoideae	*Pentaclethra eetveldeana* De Wild. & T.Durand	Gc	LC	LC
Leguminosae-Mimosoideae	*Albizia zygia* (DC.)J.F.Macbr.	Tra	LC	
Leguminosae-Mimosoideae	*Aubrevillea platycarpa* Pellegr.	Gu	LC	
Leguminosae-Mimosoideae	*Parkia bicolor* A.Chev.	Gc	LC	
Leguminosae-Mimosoideae	*Cylicodiscus gabunensis* Harms	Gc	LC	LC
Leguminosae-Mimosoideae	*Pentaclethra macrophylla* Benth.	Gc	LC	LC
Leguminosae-Mimosoideae	*Piptadeniastrum africanum* (Hook.f.)Brenan	Gc	LC	
Leguminosae-Mimosoideae	*Tetrapleura tetraptera* (Schum. & Thonn.)Taub.	Tra	LC	LC
Leguminosae-Mimosoideae	*Albizia adianthifolia* (K. Schum.) W. Wight	Gc	LC	
Leguminosae-Mimosoideae	*Albizia glaberrima* (Schum. & Thonn.)Benth.	Gc	LC	LC
Leguminosae-*Papilionoideae*	*Millettia mannii* Baker	Lg	LC	LC
Leguminosae-*Papilionoideae*	*Baphia leptobotrys* Harms	Lg	VU	LC

Leguminosae-*Papilionoideae*	*Pterocarpus soyauxii* Taub.	Gc	LC	
Leguminosae-*Papilionoideae*	*Ormocarpum muricatum* Chiov.	Gc	LC	
Leguminosae-*Papilionoideae*	*Amphimas pterocarpoides* Harms	Gc	LC	LC
Leguminosae-*Papilionoideae*	*Millettia sanagana* Harms	Gu	LC	LC
Leguminosae-*Papilionoideae*	*Pterocarpus mildbraedii* Harms	Tra	LC	VU
Leguminosae-*Papilionoideae*	*Andira inermis* (Wright)DC.	Tra	LC	LC
Lepidobotryaceae	*Lepidobotrys staudtii* Engl.	Gc	LC	LC
Loganiaceae	*Strychnos ternata* Gilg	Gc	NT	
Malvaceae	*Cola altissima* Engl.	Gc	LC	LC
Malvaceae	*Cola lepidota* K. Schum.	Lg	LC	LC
Malvaceae	*Cola pachycarpa* K. Schum.	Lg	LC	LC
Malvaceae	*Duboscia macrocarpa* Bocq.	Gc	LC	LC
Malvaceae	*Bombax brevicuspe* Sprague	Gc	LC	VU
Malvaceae	*Theobroma cacao*	In		LC
Malvaceae	*Cola lateritia* K. Schum.	Gc	LC	LC
Malvaceae	*Octolobus spectabilis* Welw.	Gc	LC	LC
Malvaceae	*Pterygota macrocarpa* K. Schum.	Gc	LC	VU
Malvaceae	*Cola acuminata* (P. Beauv.) Schott & Endl.	Gc	LC	LC
Malvaceae	*Christiana africana* DC.	Pa	LC	LC
Malvaceae	Desplatsia dewevrei (De Wild. & Th. Lur.) Burret	Gc	LC	LC
Malvaceae	*Triplochiton scleroxylon* K. Schum.	Gc	LC	LC
Malvaceae	*Bombax buonopozense* Beauv.	Tra	LC	LC
Malvaceae	*Ceiba pentandra* (L.) Gaertn.	Pa	LC	LC
Malvaceae	*Sterculia tragacantha* Lindl.	Tra	LC	LC
Malvaceae	*Eribroma oblongum* (Mast.) Pierre ex A. Chev.	Gc		
Malvaceae	*Mansonia altissima* A. Chevalier	Gu	VU	VU
Malvaceae	*Nesogordonia papaverifera* (A. Cheval.) Capuron	Gc	VU	VU
Malvaceae	*Pterygota bequaertii* De Wild.	Gc	LC	VU
Malvaceae	*Sterculia rhinopetala* K. Schum.	Gc	LC	LC
Malvaceae	*Cola caricaefolia* (G. Don) K. Schum.	Gc		
Meliaceae	*Trichilia rubescens* Oliver	Gc	LC	LC
Meliaceae	*Trichilia welwitschii* C. DC.	Gc	LC	
Meliaceae	*Turraeanthus africanus* (Welw. ex C. DC.) Pellegr.	Gc	LC	VU
Meliaceae	*Entandrophragma candollei* Harms	Gc	LC	VU

Meliaceae	*Leplaea cedrata* (A.Chev.) E.J.M.Koenen & J.J.de Wilde	Gc	VU	VU
Meliaceae	*Leplaea thompsonii* (Sprague & Hutch.) E.J.M.Koenen & J.J.de Wilde	Gc	LC	VU
Meliaceae	*Trichilia tessmannii* Harms	Gc	LC	LC
Meliaceae	*Entandrophragma angolense* (Welw.) C. DC.	Tra	VU	VU
Meliaceae	*Entandrophragma cylindricum* (Sprague) Sprague	Gc	VU	VU
Meliaceae	*Entandrophragma utile* (Dawe & Sprague) Sprague	Gc	VU	VU
Meliaceae	*Lovoa trichilioides* Harms	Gc	VU	LC
Meliaceae	*Khaya anthotheca* (Welw.) C.DC.	Gc		VU
Meliaceae	*Khaya grandifoliola* C. DC.	Tra		VU
Meliaceae	*Trichilia dregeana* Harv. & Sond.	Tra	LC	LC
Meliaceae	*Khaya ivorensis* A. Chev.	Gc	VU	VU
Menispermaceae	*Penianthus camerounensis* A.J.F.M. Dekker	Cam	LC	
Moraceae	*Treculia africana* Decne. ex Trec.	Tra	LC	LC
Moraceae	*Ficus asperifolia* Miq.	Gc	LC	LC
Moraceae	*Ficus kamerunensis* Warb. ex Mildbr. & Burret	Gc	LC	
Moraceae	*Treculia obovoidea* N. E. Br.	Gc	LC	LC
Moraceae	*Ficus mucuso* Welw. ex Ficalho	Gc	LC	LC
Moraceae	*Ficus exasperata* Vahl	Tra	LC	LC
Moraceae	*Milicia excelsa* (Welw.) C.C. Berg	Tra	LC	NT
Moraceae	*Morus mesozygia* Stapf	Tra	LC	
Moraceae	*Streblus usambarensis* (Engl.) Berg	Tra		LC
Moraceae	*Trilepisium madagascariense* DC.	Tra	LC	
Moraceae	*Antiaris toxicaria* subsp. *welwitschii* (Engl.) C. C. Berg	Gc	LC	LC
Moraceae	*Ficus elastica* Roxb.	Gc	LC	
Myristicaceae	*Coelocaryon preussii* Warb.	Gc	LC	LC
Myristicaceae	*Staudtia kamerunensis* Warb.	Gc	LC	
Myristicaceae	*Pycnanthus angolensis* (Welw.) Exell	Gc	LC	LC
Myrtaceae	*Syzygium rowlandii* Sprague	Gc	LC	
Myrtaceae	*Psidium guajava* L.	Pa	LC	
Ochnaceae	*Ochna calodendron* Gilg & Mildbr.	Gc	VU	LC
Ochnaceae	*Lophira alata* Banks ex Gaertn. fil.	Gc	VU	VU
Pandaceae	*Microdesmis puberula* Hook.f. ex Planch.	Gc	LC	LC
Passifloraceae	*Barteria fistulosa* Mast.	Gc	LC	LC
Phyllanthaceae	*Antidesma laciniatum* Müll.Arg.	Gc	LC	
Phyllanthaceae	*Bridelia micrantha* (Hochst.) Baill.	Gc	LC	LC
Phyllanthaceae	*Margaritaria discoidea* (Baill.) G.L.Webster	Pa	LC	LC
Phyllanthaceae	*Uapaca guineensis* Müll.Arg.	Gc	LC	DD

Phyllanthaceae	*Antidesma membranaceum* Müll.Arg.	Tra	LC	
Phyllanthaceae	*Keayodendron bridelioides* Leandri	Gu	LC	
Phyllanthaceae	*Spondianthus preussii* Engl.	Gc	LC	
Phyllanthaceae	*Hymenocardia heudelotii* Müll. Arg.			
Putranjivaceae	*Drypetes gossweileri* S.Moore	Gc		
Putranjivaceae	*Drypetes preussii* (Pax) Hutch.	Lg	VU	VU
Rhamnaceae	Maesopsis eminii Engl.	Tra	LC	LC
Rhamnaceae	*Lasiodiscus marmoratus* C. H. Wright	Gc	DD	
Rhizophoraceae	*Anopyxis klaineana* (Pierre) Engl.	*Gc*	*NT*	VU
Rhizophoraceae	*Rhizophora racemosa* G.F.W. Meyer	*Pa*	*LC*	LC
Rubiaceae	*Aoranthe cladantha* (K.Schum.) Somers	Gc	LC	LC
Rubiaceae	*Brenania brieyi* (De Wild.) E.M.A.Petit	Gc	LC	LC
Rubiaceae	*Coffea canephora* Pierre ex A.Froehner	Gc	LC	LC
Rubiaceae	*Heinsia crinita* (Wennberg) G.Taylor	Gc	LC	LC
Rubiaceae	*Rothmannia lujae* (De Wild.) Keay	Gc	LC	LC
Rubiaceae	*Schumanniophyton magnificum* (K.Schum.) Harms	Gc	LC	LC
Rubiaceae	*Nauclea diderrichii* (De Wild. & T.Durand) Merrill	Gc	VU	VU
Rubiaceae	*Corynanthe pachyceras* K.Schum.	Gc	LC	LC
Rubiaceae	*Morinda lucida* Benth.	Gc	LC	VU
Rubiaceae	*Corynanthe macroceras* K.Schum.	Gc		LC
Rubiaceae	*Psydrax arnoldiana* (De Wild. & T.Durand) Bridson	Gc	LC	LC
Rubiaceae	*Mitragyna ledermannii* (K.Krause) Ridsdale	Gc		VU
Rutaceae	*Vepris louisii* Gilbert	Gc	LC	LC
Rutaceae	*Zanthoxylum gilletii* (de Wildeman) Waterman	Gc	LC	
Rutaceae	*Zanthoxylum heitzii* (Aubrev. & Pellegr.) Waterman	Gc	LC	
Rutaceae	*Zanthoxylum leprieurii* Guill. & Perr.	Gc	LC	LC
Rutaceae	*Afraegle paniculata* (Schum.) Engl.	Gu	LC	
Rutaceae	*Citrus grandis* (L.) Osbeck	Gc	LC	
Rutaceae	*Zanthoxylum tragodes* (L.) DC.	Gc		
Salicaceae	*Homalium letestui* Pellegr.	Gc		
Salicaceae	*Dovyalis cameroonensis* Cheek & Ngolan	Gc		CR
Sapindaceae	*Eriocoelum macrocarpum* Gilg ex Radlk.	Lg	LC	LC
Sapindaceae	*Blighia welwitschii* (Hiern) Radlk.	Gc	LC	
Sapotaceae	*Baillonella toxisperma* Pierre	Lg	VU	VU

Sapotaceae	*Chrysophyllum boukokoense* (Aubrév. & Pellegr.) L.Gaut.	Gc	LC	VU
Sapotaceae	*Chrysophyllum lacourtianum* De Wild.	Gc	LC	
Sapotaceae	*Letestua durissima* (A.Chev.) Lecomte	Gc	LC	
Sapotaceae	*Omphalocarpum elatum* Miers	Gc	LC	LC
Sapotaceae	*Synsepalum stipulatum* (Radlk.) Engl.	Gc	LC	LC
Sapotaceae	*Chrysophyllum africanum* A.DC.	Gc	LC	
Sapotaceae	*Tieghemella africana* Pierre	Gc	EN	EN
Sapotaceae	*Synsepalum dulcificum* (Schumach. & Thonn.) Daniell	Gc	LC	LC
Sapotaceae	*Omphalocarpum procerum* P.Beauv.	Gc	LC	LC
Sapotaceae	*Chrysophyllum perpulchrum* Mildbr. ex Hutch. & Dalziel	Gc	LC	
Sapotaceae	*Pouteria alnifolia* (Baker) Roberty	Gc	LC	
Sapotaceae	*Pouteria altissima* (A.Chev.) Baehni	Gc		CD
Sapotaceae	*Breviea sericea* Aubrév. & Pellegr.	Gc	LC	NT
Sapotaceae	*Chrysophyllum beguei* Aubrév. & Pellegr.	Gc	LC	
Sapotaceae	*Chrysophyllum giganteum* A.Chev.	Gc	LC	
Sapotaceae	*Donella pruniformis* (Engl.) Pierre ex Engl.	Gc		
Sapotaceae	*Donella ubangiensis* (De Wild.) Aubrév.	Gc		
Sapotaceae	*Pouteria pierrei* (A.Chev.) Baehni	Gc	LC	LC
Sapotaceae	*Autranella congolensis* (De Wild.) A.Chev.	Gc	LC	CR
Simaroubaceae	*Quassia undulata* (Guill. & Perr.) D. Dietr.	Gc		LC ver 3.1
Strombosiaceae	*Strombosia grandifolia* Hook.fil. ex Benth.	Gc		
Strombosiaceae	*Strombosia pustulata* Oliver	Gc		LC
Strombosiaceae	*Strombosia scheffleri* Engl.	Gc		
Strombosiaceae	*Strombosiopsis tetrandra* Engl.	Gc		LC
Thomandersiaceae	*Thomandersia hensii* De Wild. & T.Durand	Gc		LC
Ulmaceae	*Holoptelea grandis* (Hutch.) Mildbr.	Gc	LC	LC
Urticaceae	*Musanga cecropioides* R. Br. apud Tedlie	Gc	LC	LC
Urticaceae	*Myrianthus arboreus* Beauv.	Gc	LC	LC
Zygophyllaceae	*Balanites aegyptiaca* (L.) Delile	Gc		LC

Appendix 9. Partition table of the variation partitioning results for aboveground biomass carbon (AGC=X1), above dead biomass carbon (ADC=X2) and belowground carbon (BGC=X3). R.square, Adjusted R.square of variation partitioning, and F and pvalue of ANOVA results are provided only for a fraction of interest.

All carbon pools with their components					Only significant carbon pools components			
Fractions	Df	R.square	Adj.R.square	Testable	Df	R.square	Adj.R.square	Testable
[a+d+f+g] = X1	5	0.82239	0.78539	TRUE	1	0.75765	0.74900	TRUE
[b+d+e+g] = X2	4	0.16448	0.03079	TRUE	1	0.07213	0.03900	TRUE
[c+e+f+g] = X3	3	0.80042	0.77739	TRUE	1	0.77707	0.76911	TRUE
[a+b+d+e+f+g] = X1+X2	9	0.82767	0.75012	TRUE	2	0.75800	0.74008	TRUE
[a+c+d+e+f+g] = X1+X3	8	0.84933	0.79194	TRUE	2	0.80342	0.78886	TRUE
[b+c+d+e+f+g] = X2+X3	7	0.80814	0.74709	TRUE	2	0.77753	0.76106	TRUE
[a+b+c+d+e+f+g] = All	12	0.85283	0.74895	TRUE	3	0.80524	0.78276	TRUE
Individual fractions					Individual fractions			
[a] = X1 | X2+X3	5		0.00186	TRUE	1		0.02171	TRUE
[b] = X2 | X1+X3	4		-0.04299	TRUE	1		-0.00610	TRUE
[c] = X3 | X1+X2	3		-0.00117	TRUE	1		0.04269	TRUE
[d]	0		0.01269	FALSE	0		-0.00196	FALSE
[e]	0		0.00772	FALSE	0		-0.00283	FALSE
[f]	0		0.71747	FALSE	0		0.67937	FALSE
[g]	0		0.05337	FALSE	0		0.04988	FALSE
[h] = Residuals			0.25105	FALSE	[h] = Residuals		0.21724	FALSE
Controlling 1 table X						Controlling 1 table X		
[a+d] = X1 | X3	5		0.01455	TRUE	1		0.01975	TRUE
[a+f] = X1 | X2	5		0.71933	TRUE	1		0.70108	TRUE
[b+d] = X2 | X3	4		-0.03030	TRUE	1		-0.00806	TRUE
[b+e] = X2 | X1	4		-0.03527	TRUE	1		-0.00892	TRUE
[c+e] = X3 | X1	3		0.00654	TRUE	1		0.03986	TRUE
[c+f] = X3 | X2	3		0.71630	TRUE	1		0.72206	TRUE

Appendix 10: Pearson's correlations matrix between carbon stock components of the forest (Aboveground live carbon (AGC) pool, Aboveground dead carbon (ADC) pool, BelowGround Carbon (BGC) pool, Total aboveground carbon (TAGC)) *** $p < 0.001$, ** $p < 0.01$ and *$p < 0.05$.

	AGC pool	large trees	understorey trees	Small stems	Palms	Herbaceous vegetation	ADC pool	Litter	Fine woody debris	Coarse woody debris	Standing dead trees	BGC pool	Coarse roots	Fine roots	Soil organic carbon	TAGC	Total carbo stock
AGC pool	1.00																
Large trees	1.00***	1.00															
Understorey trees	0.27	0.24	1.00														
Samll stems	0.15	0.11	0.30	1.00													
Palms	-0.25	-0.25	0.13	-0.20	1.00												
Herbaceous vegetation	-0.12	-0.14	0.31	-0.10	0.15	1.00											
ADC pool	0.30	0.30	-0.10	0.02	-0.18	-0.35	1.00										
Litter	0.18	0.17	0.36*	0.19	0.22	0.12	-0.07	1.00									
Fine woody debris	-0.16	-0.14	-0.33	-0.30	0.15	0.02	0.18	-0.24	1.00								
Coarse woody debris	0.28	0.29	-0.11	-0.01	-0.17	-0.36	0.98***	-0.07	0.14	1.00							
Standing dead trees	0.13	0.12	0.10	0.22	-0.19	-0.01	0.15	-0.14	0.02	-0.03	1.00						
BGC pool	0.62***	0.60***	0.41*	0.45*	-0.22	0.01	0.10	0.37*	-0,61***	0.12	-0.01	1.00					
Coarse roots	1.00***	1.00***	0.27	0.16	-0.25	-0.13	0.30	0.18	-0.16	0.28	0.14	0.62***	1.00				
Fine roots	0.19	0.21	-0.23	-0.32	-0.07	-0.16	0.27	-0.27	0.57***	0.29	-0.21	-0.32	0.19	1.00			
Soil organic carbon	0.11	0.08	0.34	0.46*	-0.10	0.10	-0.08	0.34	-0.66***	-0.04	-0.10	0.85***	0.11	-0.54**	1.00		
TAGC	0.93***	0.94***	0.19	0.13	-0.27	-0.23	0.62***	0.12	-0.06	0.60***	0.17	0.55**	0.93***	0.26	0.06	1.00	
Total carbon stock	0.94***	0.93***	0.27	0.24	-0.28	-0.18	0.52**	0.21	-0.24	0.51***	0.13	0.74***	0.94***	0.10	0.31	0.97***	1.00