APFNet PROJECT

To Demonstrate the Development and Application of Standing-Tree Carbon Equations to Improve the Accuracy of Forest-Cover Carbon Stock Estimates in Thailand
[Project ID: 2015P6-THA]

TECHNICAL REPORT NO. 1

DEVELOPMENT OF STANDING-TREE CARBON EQUATIONS

Kasetsart University Faculty of Forestry, Thailand

AND

Asia-Pacific Network for Sustainable Forest Management and Rehabilitation

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ABOUT THE PROJECT

Project title	To demonstrate the development and application of standing-tree carbon equations to improve the accuracy of forest-cover carbon stock estimates in Thailand [2015P6-THA]
Supervisory agency	Royal Forest Department, Bangkok, Thailand
Executing agency	Kasetsart University Faculty of Forestry, Bangkok, Thailand
Project Director: Dr. Khwanchai Duangsathaporn **Tel**: (+66 2) 5790174 ext. 21 **Email:** fforkcd@ku.ac.th **Fax:** (+66 2) 9428108	
Target area: Mae Huad sector, Ngao Demonstration Forest, Lampang Province, Thailand	
Project implementation duration: 1/2017 to 12/2018 (24 months)	

ACRONYMS

GOT	Government of Thailand
MONRE	Ministry of Environment and Natural Resources of Thailand
PD	Project Director
PSC	Project Steering Committee
RFD	Royal Forest Department of Thailand
SFM	Sustainable Forest Management

PROJECT TECHNICAL STAFF

National Experts

Project Director	Dr. Khwanchai Duangsathaporn
Project Assistants	Mr. Narapong Sangram

1. Tree species ID expert: Dr. Kritsadapan Palakit, Lecturer, Department of Forest Management, KUFF (National consultant)
2. Biometrician: Dr. Patsi Prasomsin, Associate Professor, Department of Forest Management, KUFF (National consultant)
3. Remote Sensing Expert: Mr. Prasong Saguantam, Associate Professor, Department of Forest Management, KUFF (National consultant)
4. Data Analysts: (1) Mr. Pichit Lumyai, Lecturer, Department of Forest Management, KUFF (National consultant);
   (2) Mr. Purin Sikareepaisarn, Laboratroy of Tropical Dendrochronology, KUFF (Project staff)
5. Technical Assistant: (1) Mr. Narapong Sangram, Laboratory of Tropical Dendrochronology, KUFF (Project staff);
   (2) Miss Sunisa Amnatpook, Laboratory of Tropical Dendrochronology, KUFF (Project staff)
6. Crew Chief: Miss Chokdee Khantawan, Laboratory of Tropical Dendrochronology, KUFF (Project staff) (Project staff)

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PART I: INTRODUCTION

BACKGROUND AND RATIONALE

This project originates from the Kasetsart University Faculty of Forestry (KUFF), Bangkok, Thailand. The rationale for this project is that there is uncertainty in the accuracy of national estimates of Thailand's forest-cover carbon stocks, incomplete reporting of carbon stocks and limited knowledge of the methods of carbon stocks assessment among the stakeholders. This, in turn, affects the national planning and other policy decisions that rely on information on national carbon stocks.

The carbon stock estimates are inaccurate because the commonly used equations to estimate tree volume are biased (over- or under-estimate tree volume). The bias occurs because (1) the sample trees used to develop the equations was small (because of the need to minimize destructive sampling of trees and lack of instruments to accurately measure standing tree upper stem diameters) and, in some cases, not representative of the economy; 2) some of the equations were local volume equations, which used only DBH as the independent variable and did not include tree height; (3) the past equations were focused on areas to be logged (mainly big trees), yet, since the national logging ban, the interested has shifted to protected areas that include smaller trees; and (4) the species grouping was too broad (e.g., volume equations by tree family). The commonly used existing equations are the local tree volume equations developed by Pochai and Nanakorn (1992). These equations developed by the RFD based on upper stem diameter measurements of standing trees using a Spiegel Relascope. However, these equations were developed for one local area in northern Thailand using a small sample of trees. Yet, they are commonly applied nationally. As well, the specific gravity coefficients used to convert volume to biomass were developed based on a small sample of trees. Finally, the generally assumed carbon/biomass fraction of 0.47 (IPCC 2006), for converting biomass to carbon, is too general. The IPCC indicates that "… higher tier methods may allow for variation with different species, different components of a tree or a stand (stem, roots and leaves) and age of the stand …" (IPCC 2003, page 3.25).

A new and novel approach has been developed at KUFF to estimate standing tree carbon content as a function of standing tree attributes (total height and DBH), using sample tree increment cores. Some research has been successfully done by Kasetsart University Faculty of Forestry (KUFF) on ways to directly estimate carbon content on standing trees using wood samples (increment cores) (Duangsathaporn et al. 2011). Other studies have used wood samples to determine carbon content (e.g., Kraenzel, et al. 2003; Wutzler, et al. 2006). Through this project, Thailand sought financial assistance and limited technical support from APFNet to demonstrate this new approach that could be used to develop new national standing-tree carbon equations. These equations could be used to estimate carbon stocks in Thailand's natural forests. This project is to demonstrate this process in Mae Huad sector, Ngao Demonstration Forest in Lampang province.

PART II:FIELD SAMPLE TREE DATA COLLECTION

1. Inventory Data

The inventory data were collected in the following stpes.

1.1 Reviewed existing secondary data, including maps, reports, forest types and land use patterns, about the Mae Huad Sector of the Ngao Demonstration Forest, which was the Project demonstration area.

1.2 Determined the field sample plan, which included systematic sampling with a random start, and point sample plots laid out on a uniform fixed 3 x 3 km grid (Figure 1) . The Crew Leader prepared tally sheets and field measurement instruments, including Spiegel relascope and Suunto.

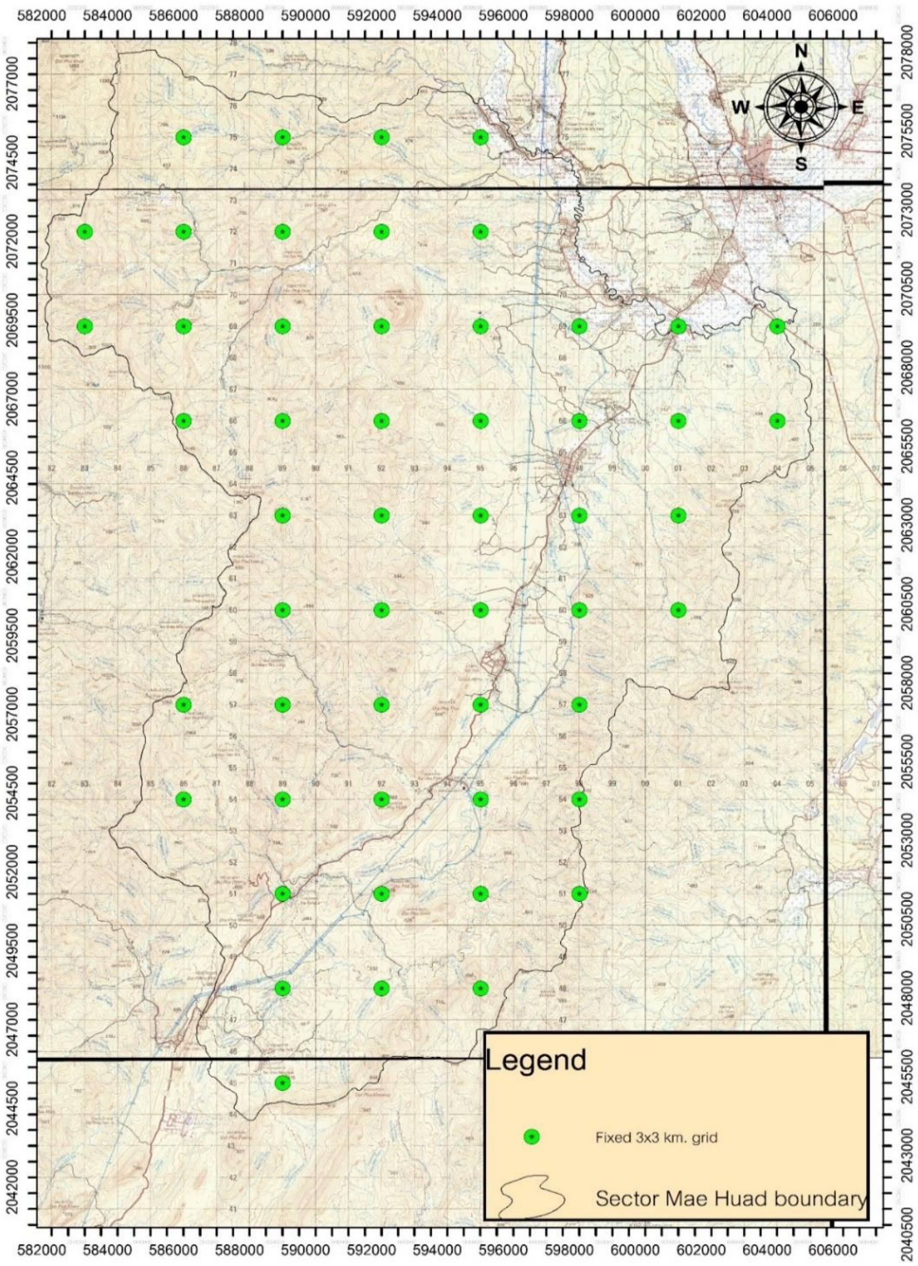

Figure 1 Map of Mae Huad Sector of NDF showing sample plot istributions

1.3 Using two, 4-person crews, established 54 point sample plots and recorded tree measurement and other field data, including tree species, DBH, height, number, and topography.

1.4 Summarized the field data to obtain per-hectare plot statistics, including basal area, number of species, wood density by specie, and IVI (Importance Value Index). See Table 1 for basal area per hectare and number of tree per hectare, Table 2 for number of species, and Tables 3, 4, and 5 for IVI of the 3 forest types including the mixed deciduous forest (MDF), the dry evergreen forest (DEF) and the dry dipterocarp forest (DDF), while the agricultural field (AF) was eliminated from the study.

Table 1 Basal area per hectare and number of tree per hectare

No. of sampling point	Basal area (m^2/ha)	Tree number (No./ha)	Forest Type
1	33.69	407.86	MDF
2	21.88	256.65	DEF
3	27.56	1,454.44	MDF
4	-	-	AF
5	7.81	71.17	DEF
6	42.88	599.07	DDF
7	33.69	308.70	DDF
8	-	-	AF
9	30.63	1,659.10	MDF
10	-	-	AF
11	10.94	106.32	DEF
12	24.50	6,924.34	MDF
13	21.44	152.54	MDF
14	18.38	928.98	MDF
15	24.50	235.79	MDF
16	-	-	AF
17	-	-	AF
18	18.38	1,991.65	MDF
19	10.94	16.75	DEF
20	21.44	200.52	MDF
21	33.69	1,101.04	DDF
22	9.19	402.62	MDF
23	-	-	AF
24	-	-	AF
25	21.44	851.84	MDF
26	12.25	68.06	MDF
27	39.81	1,023.93	DDF
28	6.13	398.65	MDF
29	18.38	372.36	MDF
30	24.50	532.67	MDF

No. of sampling point	Basal area (m²/ha)	Tree number (No./ha)	Forest Type
31	30.63	635.10	DDF
32	15.31	137.26	MDF
33	15.31	78.23	MDF
34	24.50	368.03	MDF
35	21.44	273.27	MDF
36	15.63	14.67	DEF
37	36.75	544.14	DDF
38	12.50	16.13	DEF
39	21.44	138.66	MDF
40	9.19	545.13	MDF
41	23.44	188.40	DEF
42	24.50	46.49	MDF
43	27.56	1048.98	MDF
44	0.00	0.00	AF
45	36.75	1,263.64	DDF
46	-	-	AF
47	18.38	552.07	MDF
48	30.63	280.33	MDF
49	27.56	1,223.44	MDF
50	33.69	440.49	DDF
51	21.44	580.68	MDF
52	15.31	76.06	MDF
53	-	-	AF
54	17.19	28.07	DEF
SUM	993.13	28,544.33	
AVERAGE	18.39	538.57	

Table 2 Number of species by forest type

NO.	Forest Type	Number of Species
1	MDF	46
2	DDF	18
3	DEF	32

Table 3 Tree species important value index (IVI) in the Mixed Deciduous Forest

NO.	SCIENTIFIC NAME	IVI VALUE	RANK
1	*Pterocarpus macrocarpus* Kurz	23.26	3
2	*Xylia xylocarpa* Taub.	32.80	1
3	*Tectona grandis* Linn .f.	27.41	2
4	*Millettia brandisiana* Kurz	16.93	7
5	*Lagerstroemia duperreana* Pierre	16.23	8
6	*Albizia odoratissima* Benth.	20.01	5

NO.	SCIENTIFIC NAME	IVI VALUE	RANK
7	*Irvingia malayana* Oliv .ex A .Benn.	3.30	23
8	*Terminalia alata* Heyne ex Roth	8.88	10
9	*Terminalia corticosa* Pierre ex Laness.	4.90	17
10	*Lannea coromandelica* Merr.	5.76	13
11	*Cleidion spiciflorum* Merr.	4.45	19
12	*Quercus kerrii* Craib	3.57	22
13	*Grewia elastica* Royle	20.61	4
14	*Schleichera oleosa* Merr.	4.40	20
15	*Terminalia nigrovenulosa* Pierre ex Laness.	4.72	18
16	*Vitex canescens* Kurz	4.96	16
17	*Anogeissus acuminata* Wall.	6.07	11
18	*Sterculia pexa* Pierre	5.83	12
19	*Dillenia obovata* (Blume) Hoogland	3.19	25
20	*Buchanania latifolia* Roxb.	3.77	21
21	*Mallotus macrostachyus* Muell .Arg.	4.96	15
22	*Diospyros ehretioides* Wall.	2.70	26
23	*Butea monosperma* Ktze.	1.81	32
24	*Litsea glutinosa* C.B .Robinson	1.52	36
25	*Stereospermum neuranthum* Kurz	1.37	40
26	*Madhuca thorelii* (Pierre ex Dubard) H.J.Lam	2.00	31
27	*Chukrasia velutina* Wight & Arn.	1.35	41
28	*Diospyros mollis* Griff.	1.31	42
29	*Canarium subulatum* Guill.	1.30	44
30	*Radermachera pierrei* P .Dop	1.53	35
31	*Spondias bipinnata* Airy Shaw & Forman	3.27	24
32	*Dipterocarpus turbinatus* Gaertn .f.	2.21	30
33	*Dalbergia oliveri* Gamble.	1.44	38
34	*Tetrameles nudiflora* R .Br.	1.30	45
35	*Eugenia cumini* Druce	1.30	43
36	*Ailanthus triphysa* Alston	2.61	27
37	*Bombax insulare* Ridl.	5.43	14
38	*Miliusa velutina* Hook .f .& Th.	2.32	29
39	*Cananga latifolia* Finet & Gagnep.	1.47	37
40	*Terminalia bellerica* Roxb.	10.02	9
41	*Ficus var.pubescens* Corner	19.24	6
42	*Vitex peduncularis* Wall .ex Schauer	1.42	39
43	*Terminalia nigrovenulosa* Pierre ex Laness.	2.43	28
44	*Dipterocarpus costatus* Gaerta .f.	1.26	46
45	*Lagerstroemia macrocarpa* Wall.	1.74	33
46	*Elaeocarpus stipularis* Bl.	1.61	34

Table 4 Species important value index (IVI) in the Dry Dipterocarp Forest

NO.	SCIENTIFIC NAME	IVI VALUE	RANK
1	*Shorea siamensis* Miq.	120.04	1
2	*Shorea obtusa* Wall.	66.18	2
3	*Terminalia corticosa* Pierre ex Laness.	10.34	5
4	*Dipterocarpus obtusifolius* Teijsm .ex Miq.	10.65	4
5	*Pterocarpus macrocarpus* Kurz	12.63	3
6	*Mitragyna brunonis* Craib	9.73	6
7	*Bridelia pierrei* Gagnep.	7.09	9
8	*Xylia xylocarpa* Taub.	4.87	20
9	*Dalbergia assamica* Benth.	4.87	19
10	*Terminalia alata* Heyne ex Roth	6.06	13
11	*Irvingia malayana* Oliv.ex A .Benn.	6.36	12
12	*Quercus SP.*	4.88	18
13	*Buchanania latifolia* Roxb.	5.85	14
14	*Quercus kerrii* Craib	5.03	15
15	*Haldina cordifolia*) Roxb (.Ridsdale.	4.99	16
16	*Gardenia sootepensis* Hutch.	8.75	7
17	*Millettia brandisiana* Kurz	4.96	17
18	*Dalbergia oliveri* Gamble ex Prain.	6.73	10

Table 5 Species important value index (IVI) in the Dry Evergreen Forest

NO.	SCIENTIFIC NAME	IVI VALUE	RANK
1	*Croton roxburghii* N.P.Balakr.	53.12	1
2	*Hopea odorata* Roxb.	29.77	2
3	*Anogeissus acuminata* Wall.	13.08	5
4	*Dipterocarpus costatus* Gaerta .f.	14.49	4
5	*Quercus kerrii* Craib	10.04	7
6	*Schima wallichii* Korth.	9.41	9
7	*Eugenia aequea* Burm .f.	8.91	12
8	*Duabanga grandiflora* Walp.	20.16	3
9	*Careya sphaerica* Roxb.	6.14	16
10	*Castanopsis acuminatissima* Rehd.	5.99	18
11	*Lithocarpus annamensis* A .Camus	6.13	17
12	*Terminalia corticosa* Pierre ex Laness.	8.30	13
13	*Quercus* SP.	9.00	11
14	*Pterocarpus macrocarpu*s Kurz	9.11	10
15	*Artocarpus lakoocha* Roxb.	9.72	8
16	*Dalbergia cultrata* Graham ex Benth.	5.06	21
17	*Tetrameles nudiflora* R .Br.	6.71	14
18	*Parkia leiophylla* Kurz	4.45	23
19	*Bischofia javanica* Bl.	4.19	28
20	*Lagerstroemia tomentosa* Presl	5.29	20
21	*Dalbergia oliveri* Gamble ex Prain.	4.35	25
22	*Terminalia nigrovenulosa* Pierre ex Laness.	4.02	31
23	*Xylia xylocarpa* Taub.	11.12	6

NO.	SCIENTIFIC NAME	IVI VALUE	RANK
24	*Terminalia nigrovenulosa* Pierre ex Laness.	4.14	29
25	*Quercus lamellosa* Smith	6.33	15
26	*Terminalia alata* Heyne ex Roth	4.78	22
27	*Podocarpus neriifolius* D .Don.	3.99	32
28	*Adenanthera pavonina* Linn.	4.21	26
29	*Harpullia arborea*) Blanco (Radlk.	4.07	30
30	*Cratoxylum formosum*)Jack (Dyer.	4.40	24
31	*Dillenia obovata*) Blume (Hoogland	5.34	19
32	*Cleidion spiciflorum* Merr.	4.20	27

2. Tree Wood Density Classification

Tree wood density was obtained from published data and classified in the following steps.2.1 Grouped the sample trees into wood density classes by forest type and species i. e., 10 groups for each of 3 forest types, for a total of 30 groups. See Tables 6-8 which show the groups of species by wood density classand forest type.

Table 6 Groups of species and wood density of trees in the Mixed Deciduous Forest

Class No.	Range of wood density (kg/m^2)	Scientific name	Wood density (kg/m^2)
1	282-385	*Ficus var.pubescens* Corner	282
		Cananga latifolia Finet & Gagnep.	292
		Bombax insulare Ridl.	313
2	386-488	*Tetrameles nudiflora* R .Br.	390
		Elaeocarpus stipularis Bl.	403
		Croton roxburghii N.P.Balakr.	426
		Sterculia pexa Pierre	460
		Litsea glutinosa C.B .Robinson	460
		Grewia elastica Royle	462
		Ailanthus triphysa Alston	470
3	489-591	*Cleidion spiciflorum* Merr.	495
		Lannea coromandelica Merr.	497
		Canarium subulatum Guill.	510
		Miliusa velutina Hook .f .& Th.	540
4	592-694	*Radermachera pierrei* P .Dop	640
		Tectona grandis Linn .f.	642
		Lagerstroemia duperreana Pierre	680
		Terminalia nigrovenulosa Pierre ex Laness.	680
5	695-797	*Buchanania latifolia* Roxb.	700
		Spondias bipinnata Airy Shaw & Forman	700
		Dipterocarpus turbinatus Gaertn .f.	700
		Dipterocarpus costatus Gaerta .f.	700
		Albizia odoratissima Benth.	730
		Terminalia bellerica Roxb.	740
		Lagerstroemia macrocarpa Wall.	770
		Dillenia obovata)Blume (Hoogland	780

Class No.	Range of wood density (kg/m²)	Scientific name	Wood density (kg/m²)
6	798-900	*Stereospermum neuranthum* Kurz	800
		Anogeissus acuminata Wall.	860
		Terminalia nigrovenulosa Pierre ex Laness.	890
		Vitex canescens Kurz	900
		Chukrasia velutina Wight & Arn.	900
		Eugenia cumini Druce	900
		Vitex peduncularis Wall .ex Schauer	900
7	901-1003	*Pterocarpus macrocarpus* Kurz	920
		Madhuca thorelii)Pierre ex Dubard (H.J.Lam	920
		Diospyros ehretioides Wall.	990
8	1004-1106	*Xylia xylocarpa* Taub.	1010
		Millettia brandisiana Kurz	1020
		Irvingia malayana Oliv .ex A .Benn.	1040
		Terminalia alata Heyne ex Roth	1040
		Schleichera oleosa Merr.	1080
9	1107-1209	*Butea monosperma* Ktze.	1130
		Dalbergia oliveri Gamble.	1143
10	1210-1312	*Quercus kerrii* Craib	1210
		Terminalia corticosa Pierre ex Laness.	1250
		Diospyros mollis Griff.	1310

Table 7 Groups of species and wood density of trees in the Dry Dipterocarp Forest

Class No.	Range of wood density (kg/m²)	Scientific name	Wood density (kg/m²)
1	400-485	*Mitragyna brunonis* Craib	400
2	486-570	*Bridelia pierrei* Gagnep.	499
3	571-655	*Gardenia sootepensis* Hutch.	621
4	656-740	*Haldina cordifolia*) Roxb (.Ridsdale.	690
		Buchanania latifolia Roxb.	700
5	741-825	*Dipterocarpus obtusifolius* Teijsm .ex Miq.	900
6	826-910		
7	911-995	*Dalbergia assamica* Benth.	960
		Pterocarpus macrocarpus Kurz	995
8	996-1080	*Shorea siamensis* Miq.	1000
		Millettia brandisiana Kurz	1020
		Shorea obtusa Wall.	1040
		Terminalia alata Heyne ex Roth	1040
		Irvingia malayana Oliv .ex A .Benn.	1040
		Quercus kerrii Craib	1040
9	1081-1165	*Xylia xylocarpa* Taub.	1095
		Dalbergia oliveri Gamble ex Prain.	1143

Class No.	Range of wood density (kg/m^2)	Scientific name	Wood density (kg/m^2)
10	1166-1250	*Quercus SP.*	1210
		Terminalia corticosa Pierre ex Laness.	1250

Table 8 Groups of species and wood density of trees in the Dry Evergreen Forest

Class No.	Range of wood density (kg/m^2)	Scientific name	Wood density (kg/m^2)
1	387-474	*Parkia leiophylla* Kurz	387
		Tetrameles nudiflora R .Br.	390
		Duabanga grandiflora Walp.	410
2	475-561	*Adenanthera pavonina* Linn.	495
		Cleidion spiciflorum Merr.	495
		Croton roxburghii N.P.Balakr.	525
		Podocarpus neriifolius D .Don.	532
		Bischofia javanica Bl.	551
3	562-648	*Lithocarpus annamensis* A .Camus	580
		Castanopsis acuminatissima Rehd.	623
		Harpullia arborea (Blanco) Radlk.	623
		Careya sphaerica Roxb.	644
4	649-735	*Artocarpus lakoocha* Roxb.	660
		Terminalia nigrovenulosa Pierre ex Laness.	680
		Dipterocarpus costatus Gaerta .f.	700
		Eugenia aequea Burm .f.	720
		Lagerstroemia tomentosa Presl	720
5	736-822	*Dillenia obovata*) Blume (Hoogland	780
		Cratoxylum formosum)Jack (Dyer.	800
		Hopea odorata Roxb.	808
		Schima wallichii Korth.	810
6	823-909	*Anogeissus acuminata* Wall.	870
7	910-996	*Pterocarpus macrocarpus* Kurz	970
8	997-1083	*Terminalia alata* Heyne ex Roth	1040
9	1084-1170	*Xylia xylocarpa* Taub.	1095
		Dalbergia cultrata Graham ex Benth.	1110
		Dalbergia oliveri Gamble ex Prain.	1143
		Terminalia nigrovenulosa Pierre ex Laness.	1143
10	1171-1257	*Quercus* SP.	1210
		Quercus lamellosa Smith	1210
		Quercus kerrii Craib	1210
		Terminalia corticosa Pierre ex Laness.	1250

2.2 A total of 30 major tree species were selected from the three forest types. This was done in the following two steps : 1) Within each forest type, the values of wood density were used to classify tree species into 10 wood density classes (groups) from the lowest to the higest density classes; and 2) from each wood density class, only one species with the highest importance value index (IVI) was selected as a major species to be sampled (See Table 9-11).

Table 9 Selected major species by density class in the Mixed Deciduous Forest

Class No.	Range of wood density (kg/m^2)	Major species (Scientific name)
1	282-385	*Cananga latifolia. Finet & Gagnep.*
2	386-488	*Litsea glutinosa C.B .Robinson*
3	489-591	*Lannea coromandelica* Merr.
4	592-694	*Tectona grandis* Linn .f.
5	695-797	*Albizia odoratissima* Benth.
6	798-900	*Terminalia nigrovenulosa* Pierre ex Laness.
7	901-1003	*Pterocarpus macrocarpus* Kurz
8	1004-1106	*Xylia xylocarpa* Taub.
9	1107-1209	*Dalbergia oliveri Gamble.*
10	1210-1312	*Terminalia corticosa* Pierre ex Laness.

Table 10 Selected major species by density class in the Dry Dipterocarp Forest

Class No.	Range of wood density (kg/m^2)	Major species (Scientific name)
1	400-485	*Mitragyna brunonis* Craib
2	486-570	*Bridelia pierrei* Gagnep.
3	571-655	*Gardenia sootepensis* Hutch.
4	656-740	*Haldina cordifolia* (Roxb.) Ridsdale.
5	741-825	*Dipterocarpus obtusifolius* Teijsm .ex Miq.
6	826-910	NA
7	911-995	*Pterocarpus macrocarpus* Kurz
8	996-1080	*Shorea siamensis* Miq.
9	1081-1165	*Dalbergia oliveri* Gamble ex Prain.
10	1166-1250	*Terminalia corticosa* Pierre ex Laness.

Table 11 Selected major species by density class in the Dry Evergreen Forest

Class No.	Range of wood density (kg/m^2)	Major species (Scientific name)
1	387-474	*Duabanga grandiflora* Walp.
2	475-561	*Croton roxburghii* N.P.Balakr.
3	562-648	*Careya sphaerica* Roxb.
4	649-735	*Artocarpus lakoocha Roxb.*
5	736-822	*Cratoxylum formosum (Jack) Dyer.*
6	823-909	*Anogeissus acuminata* Wall.
7	910-996	*Pterocarpus macrocarpu*s Kurz
8	997-1083	*Terminalia alata* Heyne ex Roth
9	1084-1170	*Xylia xylocarpa* Taub.
10	1171-1257	*Quercus kerrii* Craib

2.3 The ranges of tree diameter classes in each tree species were equally defined based on the minimum and maximum values of DBH specified by the Data Analysts (small, medium and large DBH classes), and then the major species trees were selected following the criterion of these 3 diameter classes. See Tables 12-14 that show the ranges of the diameter classes of the major species trees in the three forest types.

Table 12 Range of the diameter classes of the major species in the Mixed Deciduous Forest

No.	Major species (Scientific name)	Ranges of the diameter classes (DBH, cm)		
		Small	Medium	Large
1	*Cananga latifolia Finet & Gagnep.*	4.5-39.71	39.72-74.78	74.79-109.92
2	*Litsea glutinosa C.B.Robinson*	4.5-29.61	29.62-54.71	54.72-79.8
3	*Lannea coromandelica* Merr.	4.5-20.21	20.22-35.91	35.92-51.6
4	*Tectona grandis* Linn.f.	4.5-30.91	30.92-57.31	57.32-83.7
5	*Albizia odoratissima* Benth.	4.5-54.17	54.18-103.84	103.85-153.51
6	*Terminalia nigrovenulosa* Pierre ex Laness.	4.5-23.43	24.44-42.36	42.37-61.29
7	*Pterocarpus macrocarpus* Kurz	4.5-24.23	24.24-43.96	43.97-63.69
8	*Xylia xylocarpa* Taub.	4.5-36.33	36.33-68.16	68.16-99.99
9	*Dalbergia oliveri Gamble.*	4.5-14.27	14.27-24.04	24.04-33.81
10	*Terminalia corticosa* Pierre ex Laness.	4.5-21.06	21.06-37.62	37.62-54.18

Table 13 Range of the diameter classes of the major species trees in the Dry Dipterocarp forest

No.	Major species (Scientific name)	Ranges of the diameter classes (DBH, cm)		
		Small	Medium	Large
1	*Mitragyna brunonis* Craib	4.5-9.11	9.12-13.71	13.72-18.3
2	*Bridelia pierrei* Gagnep.	4.5-14.33	14.34-24.16	24.17-33.99
3	*Gardenia sootepensis* Hutch.	4.5-14.33	14.34-24.16	24.17-33.99
4	*Haldina cordifolia (Roxb.) Ridsdale.*	4.5-11.31	11.32-18.16	18.17-24.99
5	*Dipterocarpus obtusifolius* Teijsm.ex Miq.	4.5-20.17	20.18-35.84	35.85-51.51
6		NA		
7	*Pterocarpus macrocarpus* Kurz	4.5-14.47	14.48-24.44	24.45-34.41
8	*Shorea siamensis* Miq.	4.5-38.01	38.02-71.51	71.52-105
9	*Dalbergia oliveri* Gamble ex Prain.	4.5-13.01	13.02-21.51	21.52-30
10	*Terminalia corticosa* Pierre ex Laness.	4.5-15.43	15.44-26.36	26.37-37.29

Table 14 Rang of the diameter classes of the major species trees in Dry Evergreen Forest

No.	Major species (Scientific name)	Ranges of the diameter classes (DBH, cm)		
		Small	Medium	Large
1	*Duabanga grandiflora* Walp.	4.5-49.67	49.68-94.84	94.85-140.01
2	*Croton roxburghii N.P.Balakr.*	4.5-18.43	18.44-32.36	32.37-46.29
3	*Careya sphaerica* Roxb.	4.5-20.56	20.57-36.62	36.63-52.68
4	*Artocarpus lakoocha Roxb.*	4.5-30.67	30.68-56.84	56.85-83.01

No.	Major species (Scientific name)	Ranges of the diameter classes (DBH, cm)		
		Small	Medium	Large
5	*Cratoxylum formosum (Jack) Dyer.*	4.5-42.33	42.34-80.16	80.17-117.99
6	*Anogeissus acuminata* Wall.	4.5-10.91	10.92-17.31	17.32-23.7
7	*Pterocarpus macrocarpu*s Kurz	4.5-24.23	24.24-43.96	43.97-63.69
8	*Terminalia alata* Heyne ex Roth	4.5-22.43	22.44-40.36	40.37-58.29
9	*Xylia xylocarpa* Taub.	4.5-43.73	43.74-82.96	82.97-122.19
10	*Quercus kerrii* Craib	4.5-29.53	29.54-54.56	54.57-79.59

3. Selection of Sample Trees for Tree Volume and Wood Carbon Fraction Calculation

Sample trees and wood samples for carbon content determination were selected in the following steps.

3.1 Selected a total of 450 sample trees for collecting wood samples, using purposive stratified sampling . It involved 30 major species, 3 diameter classes per major spcies, and 5 sample trees per diameter class per major species (i.e., 30 x 3 x 5 = 450 trees in total).

3.2 Recorded tree DBH, total height, merchantable height and bark thickness of the selected trees. Measured each sample tree bole upper-stem diameters measured with Wheeler Pentaprism Caliper by 2-metre sections up to the first major branch. The upper stem diameter measurements were used to calculate the tree whole-bole wet volume.

3.3 Collected a total of 724 wood samples from 64 sample trees from 24 major species and two wood samples per tree by using an increment borer. The original plan was to select 900 wood samples but the duplicates of similar major species among forest types were not sampled. Upper stem diameters of the sample trees were also taken in order to calculate tree whole-bole wet volume. The whole-bole wet volume is converted to whole-bole carbon content based on the wood sample ratio of carbon content to wet volume (see Part IV, equation 3).

PART III: DETERMINATION OF WOOD SAMPLES CARBON CONTENT

Wood Carbon Fraction Analysis

Each wood sample was weighted, dried, re-weighed and pulverized to analyze the carbon content in the laboratory using the C/N analyzer. Carbon contents of sample trees in each forest type are shown in Tables 15-17.

Table 15 Carbon contents of sample trees in the Mixed Deciduous Forest

Range of wood density (kg/m^2)	Major Species (Scientific name)	No. of sample trees	Cabon content (%)
282-385	*Cananga latifolia.* Finet & Gagnep.	15	47.75
386-488	*Litsea glutinosa* C.B. Robinson	15	46.86
489-591	*Lannea coromandelica* Merr.	16	45.75
592-694	*Tectona grandis* Linn. f.	16	49.66
695-797	*Albizia odoratissima* Benth.	15	46.84
798-900	*Terminalia nigrovenulosa* Pierre ex Laness.	16	47.13
901-1003	*Pterocarpus macrocarpus* Kurz	15	48.41
1004-1106	*Xylia xylocarpa* Taub.	15	48.03
1107-1209	*Dalbergia oliveri* Gamble.	17	47.13
1210-1312	*Terminalia corticosa* Pierre ex Laness.	15	48.55

Table 16 Carbon contents of sample trees in the Dry Dipterocarp Forest

Range of wood density (kg/m^2)	Major Species (Scientific name)	No. of sample trees	Cabon content (%)
400-485	*Mitragyna brunonis* Craib	15	47.57
486-570	*Bridelia pierrei* Gagnep.	12	47.16
571-655	*Gardenia sootepensis* Hutch.	15	46.06
656-740	*Haldina cordifolia* (Roxb.) Ridsdale.	15	48.262
741-825	*Dipterocarpus obtusifolius* Teijsm. ex Miq.	15	47.62
826-910	NA		
911-995	*Pterocarpus macrocarpus* Kurz	15	48.41
996-1080	*Shorea siamensis* Miq.	15	46.76
1081-1165	*Dalbergia oliveri* Gamble ex Prain.	17	47.13
1166-1250	*Terminalia corticosa* Pierre ex Laness.	15	48.55

Table 17 Carbon contents of sample trees in the Dry Evergreen Forest

Range of wood density (kg/m^2)	Major Species (Scientific name)	No. of sample trees	Cabon content (%)
387-474	*Duabanga grandiflora* Walp.	15	46.92
475-561	*Croton roxburghii* N.P.Balakr.	15	47.77
562-648	*Careya sphaerica* Roxb.	15	47.47
649-735	*Artocarpus lakoocha* Roxb.	15	48.31
736-822	*Cratoxylum formosum* (Jack) Dyer.	15	46.83
823-909	*Anogeissus acuminata* Wall.	15	46.81
910-996	*Pterocarpus macrocarpu*s Kurz	15	48.41
997-1083	*Terminalia nigrovenulosa* Pierre ex Laness.	15	45.75
1084-1170	*Xylia xylocarpa* Taub.	15	48.03
1171-1257	*Quercus kerrii* Craib	15	45.43

PART IV: SAMPLE TREE CARBON SEQUESTRATION DATA

Wet volume (V_t) of the bole of each of the 724 sample trees was calculated using Smalian's formula (Equation 1), and carbon sequestration in each wood sample core (C_c) was then calculated using equation 2 (Duangsathaporn *et al.*, 2011). The whole-bole carbon sequestration, C_t, of each sample tree was then calculated using equation 3.

$$V_t = \sum_{i=1}^{n} \frac{L}{2} (Ab_i + Au_i) \qquad (1)$$

where Ab_i is cross-sectional area at base of stem segment i
Au_i is cross-sectional area at upper of stem segment i
L is length of stem segment i (m)

$$C_c = W_d \times C_w \qquad (2)$$

where C_c is weight of carbon in a wood sample core (kg)
W_d is dry weight of a wood sample core (kg)
C_w is carbon content in a sample core (%)

$$C_t = \frac{C_c}{V_w} \times V_t \qquad (3)$$

where C_t is weight of carbon in a standing sample tree bole (kg)
C_c is weight of carbon in a wood sample core (kg)
V_w is wet volume of wood sample core
V_t is wet volume of standing tree bole

Following the above equations, for example, teak (*Tectona grandis* Linn. f.) sample tree was cored and the data derived from this sample core is 1) dry weight of wood sample (W_d) = 0.00151 kg, 2) carbon content of teak tree sample (C_w) = 47.43%, 3) volume of sample core (V_w) = 2.6637×10^{-6} m^3 and 4)Volume of standing tree bole (V_t) = 0.04618 m^3. Using the equations 1, 2 and 3 to calculated carbon storage in a standing tree bole, carbon storage in this teak tree was 12.418 kg. The summation of weights of carbon in a standing sample tree bole (C_t) of each tree species in all diameter classes (small, medium, and large) divided by the number of trees of the species were then calculated to obtain the average carbon storage in each sample species. The summary of average and range of carbon storage in all selected trees are shown in Tables 18 – 20. Note that there are some cases of very large ranges of carbon storage, e.g., *Terminalia corticosa* with a range of 16.45-1,600.00 kg/tree. This is due to a mix of very small and very large trees.

Table 18 Carbon Storage of sample trees in the Mixed Deciduous Forest

NO.	Major species (Scientific name)	No. of sample trees	Range of Carbon Storage (kg/tree)	Average Cabon Storage (kg/tree)
1	*Cananga latifolia. Finet & Gagnep.*	15	16.73-344.12	121.81
2	*Litsea glutinosa C.B. Robinson*	15	27.45-887.61	368.88
3	*Lannea coromandelica* Merr.	16	6.53-1,117.40	341.51
4	*Tectona grandis* Linn. f.	16	6.60-949.87	407.20
5	*Albizia odoratissima* Benth.	15	9.52-380.83	145.33

NO.	Major species (Scientific name)	No. of sample trees	Range of Carbon Storage (kg/tree)	Average Cabon Storage (kg/tree)
6	*Terminalia nigrovenulosa* Pierre ex Laness.	16	29.49-692.41	278.52
7	*Pterocarpus macrocarpus* Kurz	15	14.71-1,143.32	334.48
8	*Xylia xylocarpa* Taub.	15	21.39-976.19	369.92
9	*Dalbergia oliveri Gamble.*	17	12.85-617.10	216.17
10	*Terminalia corticosa* Pierre ex Laness.	15	16.45-1,600.00	445.84

Table 19 Carbon Storage of sample trees in the Dry Dipterocarp Forest

NO.	Major species (Scientific name)	No. of sample trees	Range of Carbon Storage (kg/tree)	Average Cabon Storage (kg/tree)
1	*Mitragyna brunonis* Craib	15	10.31-356.11	140.70
2	*Bridelia pierrei* Gagnep.	12	4.72-139.95	50.78
3	*Gardenia sootepensis* Hutch.	15	18.23-618.14	154.86
4	*Haldina cordifolia (Roxb.) Ridsdale.*	15	5.58-457.70	127.66
5	*Dipterocarpus obtusifolius* Teijsm. ex Miq.	15	5.96-398.94	112.30
6	NA			
7	*Pterocarpus macrocarpus* Kurz	15	14.71-1,143.32	334.48
8	*Shorea siamensis* Miq.	15	9.17-854.63	329.44
9	*Dalbergia oliveri* Gamble ex Prain.	17	12.85-617.10	216.17
10	*Terminalia corticosa* Pierre ex Laness.	15	16.45-1,600.00	445.84

Table 20 Carbon Storage of sample trees in Dry Evergreen Forest

NO.	Major species (Scientific name)	No. of sample trees	Range of Carbon Storage (kg/tree)	Average Cabon Storage (kg/tree)
1	*Duabanga grandiflora* Walp.	15	38.32-4011.84	1368.52
2	*Croton roxburghii* N.P.Balakr.	15	4.66-233.52	82.04
3	*Careya sphaerica* Roxb.	15	7.45-159.91	65.91
4	*Artocarpus lakoocha Roxb.*	15	5.64-631.99	175.74
5	*Cratoxylum formosum (Jack) Dyer.*	15	5.55-85.51	26.53
6	*Anogeissus acuminata* Wall.	15	30.32-1,369.03	455.46
7	*Pterocarpus macrocarpu*s Kurz	15	14.71-1,143.32	334.48
8	*Terminalia nigrovenulosa Pierre ex Laness.*	15	16.45-1,600.00	445.84
9	*Xylia xylocarpa* Taub.	15	21.39-976.19	369.92
10	*Quercus kerrii* Craib	15	7.21-369.94	133.86

PART V: FITTING STANDING TREE CARBON REGRESSION EQUATIONS

Regression equations relating above-ground bole tree carbon to standing tree attributes includingtotal height and DBH were fitted. Note that estimation of carbon stocks below ground, in the forest litter, and in tree branches and leaves were not considered because the pilot-tested methodology was not suitable for the estimation of these carbon stock components.

The Biometrician developed the standing tree carbon equations to predict tree carbon content from standing tree data of total height and DBH by fitting the equations of the form: C = f(Total Height, DBH) in each forest type and tree wood density range (group).

A total of 36 tree carbon equations were constructed: the mixed deciduous forest 11 equations, the Dry Dipterocarp Forest 7 equations and the dry evergreen forest 9 equations.

1. Tree Carbon Equations in the Mixed Deciduous Forest

Ten tree carbon equations derived from the Mixed Deciduous Forest were constructed based on wood density that ranged between 282-1,312 kg/m^3. A general equation which was used for all wood density groups in the Mixed Deciduous Forest was also constructed. These 11 equations are shown in Table 21.

In oder to select the optimal tree carbon equation in each range of wood density, the coefficiant of determination (R^2), Standard error of estimate (SE), F-value and Significant Value (p-value) were considerated. The general (overall) tree carbon equation in the Mixed Deciduous Forest is as follows:

$$C= 0.018155\, D^{2.2204}\, H^{0.490} \quad \ldots\ldots(4)$$

where; C = Carbon storage in stem bole, kg/tree
D = Diameter at breast height of tree, cm
H = Total height of tree, m

The value of the standard error of estimate was 0.13 with the F-value for 1274.61 (Table 21). The residual which was the difference between the carbon estimated and actual and diameter at breast height of tree (cm) are shown in the Figure 2.

2. Tree Carbon Equations in the Dry Dipterocarp Forest

Nine tree carbon equations the Dry Dipterocarp Forest were constructed based on wood density that ranged between 400-1,250 kg/m^3. A general equation which was used for all tree species in the Dry Dipterocarp Forest was also constructed. These 10 equations are shown in Table 22.

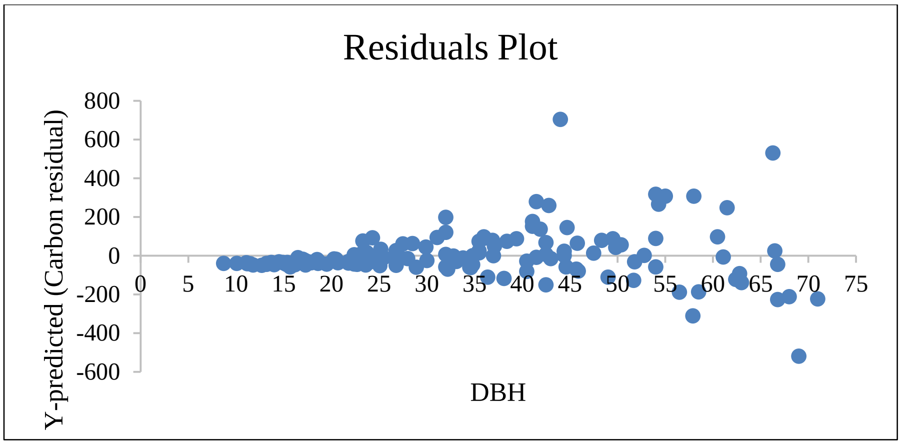

Figure 2 Residual (difference between observed and predicted) carbon content (kg/tree) in stem bole of selected trees in the Mixed Deciduous Forest.

In oder to select the optimal tree carbon equation in each range of wood density, the coefficiant of determination (R^2), Standard error of estimate (SE), F-value and Significant Value (p-value) were considerated. The general tree carbon equation in the Dry Dipterocarp Forest is as followed:

$$C = 0.009462\ D^{2.328}\ H^{0.602} \quad \text{.............................(5)}$$

where; C = Carbon storage in stem bole, kg/tree
D = Diameter at breathn height of tree, cm
H = Total height of tree, m

The value of the standard error of estimate was 0.20 with the F-value for 293.13 (Table 22). The residual between the atual and estimated carbon in various diameter at breast height of tree shown in the Figure 3.

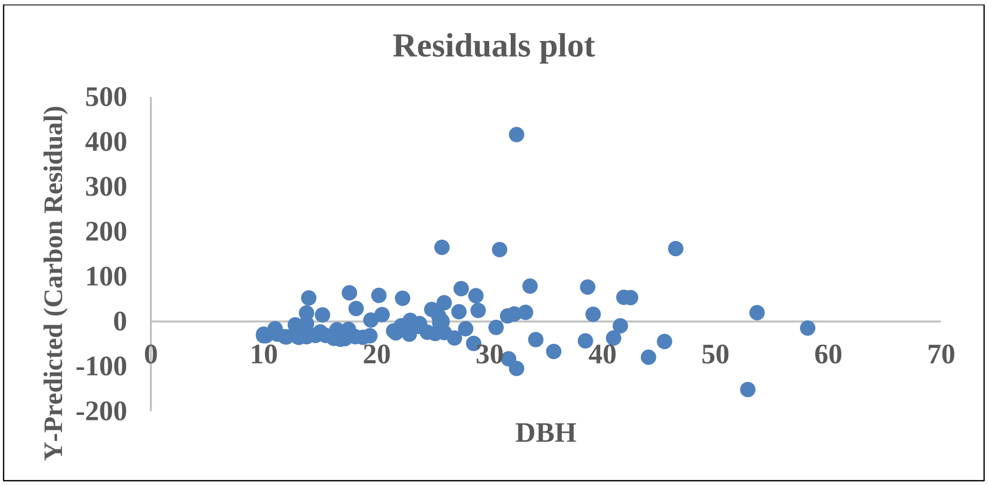

Figure 3 Residual (difference between observed and predicted)) carbon content (kg/tree) in stem bole of selected trees in in the Dry Dipterocarp Forest

Table 21 Summary of carbon equation classified by wood density of tree in the mixed deciduous forest

No.	Range of Wood Density (kg/m2)	Sample Species*	Carbon Equation	Sample Tree No.	DBH Range (cm)	R^2	P-Value	SE	F	Remark
1	282-385	*Ficus var.pubescens* Corner *Cananga latifolia* Finet & Gagnep. *Bombax insulare* Ridl.	$C = 0.008730\ D^{2.335}\ H^{0.570}$	15	13.2-43	97.14	0.00	0.08	203.46	
2	386-488	*Tetrameles nudiflora* R. Br. *Elaeocarpus stipularis* . Bl. *Croton roxburghii* N.P.Balakr. *Grewia elastica* Royle *Litsea glutinosa* C.B. Robinson *Sterculia pexa* Pierre *Ailanthus triphysa* Alston	$C = 0.019454\ D^{2.335}\ H^{0.338}$	15	16.2-63	97.29	0.00	0.09	215.37	
3	489-591	*Cleidion spiciflorum* Merr. *Lannea coromandelica* Merr. *Canarium subulatum* Guill. *Miliusa velutina* Hook. f. & Th.	$C = 0.001538\ D^{3.014}\ H^{0.475}$	16	11.8-58	94.22	0.00	0.20	105.91	
4	592-694	*Radermachera pierrei* P. Dop *Tectona grandis* Linn. f. *Lagerstroemia duperreana* Pierre *Terminalia nigrovenulosa* Pierre ex Laness.	$C = 0.018836\ D^{1.833}\ H^{0.848}$	16	8.7-71	99.02	0.00	0.07	653.91	
5	695-797	*Buchanania latifolia* Roxb. *Spondias bipinnata* Airy Shaw & Forman *Dipterocarpus turbinatus* Gaertn. f. *Dipterocarpus costatus* Gaerta. f. *Albizia odoratissima* Benth. *Terminalia bellerica* Roxb. *Lagerstroemia macrocarpa* Wall. *Dillenia obovata* (Blume) Hoogland	$C = 0.011350\ D^{2.043}\ H^{0.853}$	15	11.0-29	94.69	0.00	0.11	106.94	
6	798-900	*Stereospermum neuranthum* Kurz *Anogeissus acuminata* Wall. *Terminalia nigrovenulosa* Pierre ex Laness. *Vitex canescens* Kurz *Chukrasia velutina* Wight & Arn. *Eugenia cumini* Druce *Vitex peduncularis* Wall. ex Schauer	$C = 0.067764\ D^{2.011}\ H^{0.277}$	16	15-69	93.87	0.00	0.11	99.47	

No.	Range of Wood Density (kg/m2)	Sample Species*	Carbon Equation	Sample Tree No.	DBH Range (cm)	R^2	P-Value	SE	F	Remark
7	901-1003	*Pterocarpus macrocarpus* Kurz *Madhuca thorelii* (Pierre ex Dubard) H.J.Lam *Diospyros ehretioides* Wall.	$C = 0.014093\ D^{2.068}\ H^{0.723}$	15	11.5-61.5	97.75	0.00	0.09	260.96	The same equation with DDF (910-995) and DEF (909-1083)
8	1004-1106	*Xylia xylocarpa* Taub. *Millettia brandisiana* Kurz *Irvingia malayana* Oliv. ex A. Benn. *Terminalia alata* Heyne ex Roth *Schleichera oleosa* Merr.	$C = 0.011967\ D^{2.067}\ H^{0.791}$	15	13.2-68.8	97.69	0.00	0.09	253.67	
9	1107-1209	*Butea monosperma* Ktze. *Dalbergia oliveri* Gamble.	$C = 0.017539\ D^{2.276}\ H^{0.547}$	17	11.1-42.8	97.14	0.00	0.08	237.51	The same equation with DDF(1080-1165)
10	1210-1312	*Quercus kerrii* Craib *Terminalia corticosa* Pierre ex Laness. *Diospyros mollis* Griff.	$C = 0.005957\ D^{2.206}\ H^{0.819}$	15	13.2-66.5	98.26	0.00	0.09	338.31	The same equation with DDF (1080-1165)
11		General Equation for all species/wood density groups	$C = 0.018155\ D^{2.2204}\ H^{0.490}$	155	8.7-71	94.37	0.00	0.13	1274.61	

* List of tree species in the wood density range in the Mixed Deciduous Forest

Table 22 Summary of carbon equation classified by wood density of tree in the Dry Dipterocarp Forest

No.	Range of Wood Density (kg/m2)	Sample Species*	Carbon Equation	Sample Tree No.	DBH Range (cm)	R^2	P-Value	SE	F	Remark
1	400-485	*Mitragyna brunonis* Craib	$C = 0.006353\ D^{2.227}\ H^{0.802}$	15	13-44.1	95.76	0.00	0.11	135.37	
2	486-570	*Bridelia pierrei* Gagnep.	$C = 0.004887\ D^{2.618}\ H^{0.438}$	12	10-28.6	97.84	0.00	0.09	203.58	
3	571-655	*Gardenia sootepensis* Hutch	$C = 0.020417\ D^{2.237}\ H^{0.696}$	15	11-2.4	88.12	0.00	0.16	44.50	
4	656-740	*Haldina cordifolia* (Roxb.) Ridsdale *Buchanania latifolia* . Roxb.	$C = 0.001928\ D^{2.664}\ H^{0.679}$	15	10.2-41.9	96.09	0.00	0.13	147.46	
5	741-825	*Dipterocarpus obtusifolius* Teijsm. ex Miq.	$C = 0.000975\ D^{2.389}\ H^{1.277}$	15	13.1-42.5	97.56	0.00	0.09	239.52	
6	826-910		NA							
7	911-995	*Dalbergia assamica* Benth. *Pterocarpus macrocarpus* Kurz	$C = 0.014093\ D^{2.068}\ H^{0.723}$	15	11.5-61.5	97.75	0.00	0.09	260.96	The same equation with MDF (900-1003)
8	996-1080	*Shorea siamensis* Miq. *Millettia brandisiana* Kurz *Shorea obtusa* Wall. *Terminalia alata* Heyne ex Roth *Irvingia malayana* Oliv. ex A. Benn. *Quercus kerrii* Craib	$C = 0.022751\ D^{2.209}\ H^{0.458}$	15	11.2-58.2	95.71	0.00	0.12	133.79	
9	1081-1165	*Xylia xylocarpa* Taub. *Dalbergia oliveri* Gamble ex Prain	$C = 0.017539\ D^{2.276}\ H^{0.547}$	17	13.2-66.8	97.14	0.00	0.08	237.51	The same equation with MDF (1106-1209)
10	116-1250	*Quercus SP.* *Terminalia corticosa* Pierre ex Laness.	$C = 0.005957\ D^{2.206}\ H^{0.819}$	15	13.2-66.5	98.26	0.00	0.09	338.31	The same equation with MDF (1209-1312)
11		General Equation for all species/ wood density groups	$C = 0.009462\ D^{2.328}\ H^{0.602}$	134	10-66.8	87.47	0.00	0.20	293.13	

* List of tree species in the wood density range in the Dry Dipterocarp Forest

3. Tree Carbon Equations in the Dry Evergreen Forest

Ten tree carbon equation the Dry Evergreen Forest were constructed based on wood density, ranged between 387-1,257 kg/m^3. A general equation which was used for all tree species in the dry evergreen forest was also constructed. These 11 equations were shown in Table 23.

In oder to select the optimal tree carbon equation in each range of wood density, the coefficiant of determination (R^2), Standard error of estimate (SE), F-value and Significant Value (p-value) were respectively considerated. The general tree carbon equation in the dry evergreen forest is as followed:

$$C = 0.011803\ D^{2.1844}\ H^{0.617} \quad \text{.................................(6)}$$

Where; C = Carbon storage in stem bole, kg/tree
D = Diameter at breathn height of tree, cm
H = Total height of tree, m

The value of the standard error of estimate was 0.18 with the F-value for 890.93 (Table 23). The residual between the atual and estimated carbon in various diameter at breast height of tree shown in the Figure 4

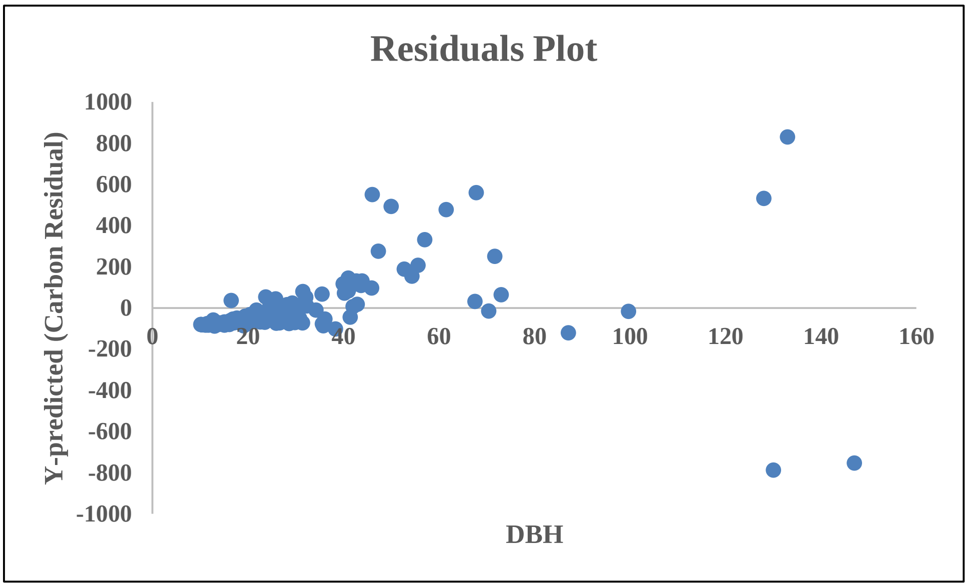

Figure 4 Residual (difference between observed and predicted) carbon content (kg/tree) in stem bole of selected trees in the Dry Evergreen Forest

Table 23 Summary of carbon equation classified by wood density of tree in Dry Evergreen Forest

No.	Range of Wood density (kg/m2)	Sample Species*	Carbon Equation	Sample Tree No.	DBH Range (cm)	R^2	P-Value	SE	F	Remark
1	387-474	*Parkia leiophylla* Kurz *Tetrameles nudiflora* R. Br. *Duabanga grandiflora* Walp.	$C = 0.049317\ D^{1.997}\ H^{0.357}$	15	18-147	96.33	0.00	0.12	157.70	
2	475-561	*Adenanthera pavonina* Linn. *Cleidion spiciflorum* Merr. *Croton roxburghii* N.P.Balakr. *Podocarpus neriifolius* D. Don. *Bischofia javanica* Bl	$C = 0.019498\ D^{2.300}\ H^{0.300}$	15	12.5-42	72.69	0.00	0.27	15.97	
3	562-648	*Lithocarpus annamensis* A. Camus *Castanopsis acuminatissima* Rehd. *Harpullia arborea* (Blanco) Radlk. *Careya sphaerica* Roxb	$C = 0.012134\ D^{2.056}\ H^{0.668}$	15	12.0-3830	93.18	0.00	0.11	81.97	
4	649-735	*Artocarpus lakoocha* Roxb. *Terminalia nigrovenulosa* Pierre ex Laness. *Dipterocarpus costatus* Gaerta. f. *Eugenia aequea* Burm. f. *Lagerstroemia tomentosa* Presl	$C = 0.001549\ D^{2.608}\ H^{0.854}$	15	11.10-47.30	95.01	0.00	0.15	114.16	
5	736-822	*Dillenia obovata* (Blume) Hoogland *Cratoxylum formosum* (Jack) Dyer. *Hopea odorata* Roxb. *Schima wallichii* Korth.	$C = 0.003192\ D^{2.374}\ H^{0.876}$	15	9.7-26.2	89.69	0.00	0.14	52.20	
6	823-909	*Anogeissus acuminata* Wall.	$C = 0.015560\ D^{2.109}\ H^{0.625}$	15	18.6-71.7	94.40	0.00	0.14	101.12	
7	910-996	*Pterocarpus macrocarpus* Kurz	$C = 0.014093\ D^{2.068}\ H^{0.723}$	15	11.5-61.5	97.75	0.00	0.09	260.96	The same equation with MDF (900-1003)
8	997-1083	*Terminalia alata* Heyne ex Roth	$C = 0.002624\ D^{2.263}\ H^{1.086}$	15	12.8-52.7	96.02	0.00	0.12	144.90	
9	1084-1170	*Xylia xylocarpa* Taub. *Dalbergia cultrata* Graham ex Benth. *Dalbergia oliveri* Gamble ex Prain. *Terminalia nigrovenulosa* Pierre ex Laness.	$C = 0.049317\ D^{1.997}\ H^{0.357}$	15	13.2-66.8	97.69	0.00	0.09	253.67	
10	1171-1257	*Quercus* SP. *Quercus lamellosa* Smith *Quercus kerrii* Craib *Terminalia corticosa* Pierre ex Laness.	$C = 0.006353\ D^{2.482}\ H^{0.609}$	15	10.9-43.7	97.96	0.00	0.08	288.39	The same equation with MDF (1209-1312)
11		General Equation for all species/ wood density groups	$C = 0.011803\ D^{2.1844}\ H^{0.617}$	150	9.7-147	93.84	0.00	0.17	890.93	

* List of tree species in the wood density range in the Dry Dipterocarp Forest

4. Tree Carbon Equation of Mae Huad Sector, Ngao Demonstration Forest

In oder to select the optimal tree carbon equation in all species of the Mae Huad Sector of the Ngao Demonstration Forest, Lampang Province the coefficiant of determination (R^2), Standard error of estimate (SE), F-value and Significant Value (p-value) were consideratedly. The general tree carbon equation in the Mae Huad Sector is as follows:

$$C = 0.012348\ D^{2.1676}\ H^{0.6539} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(7)$$

Where; C = Carbon storage in stem bole, kg/tree
D = Diameter at breathn height of tree, cm
H = Total height of tree, m

The value of the standard error of estimate was 0.17 with the F-value for 2270.36. The residual between the atual and estimated carbon in various diameter at breast height of tree shown in the Figure 5.

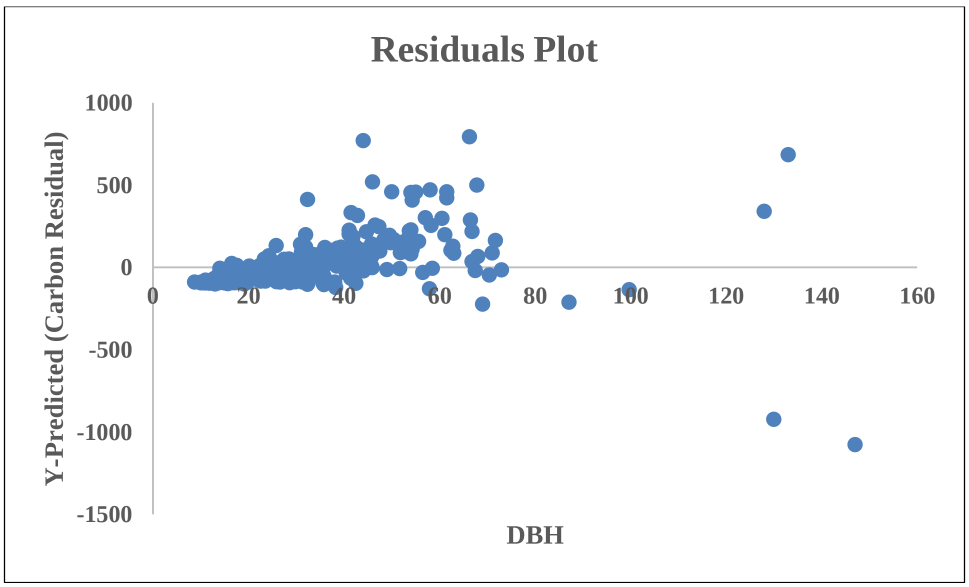

Figure 5 Residual (difference between observed and predicted) carbon content (kg/tree) in stem bole and DBH of each tree in the Mae Huad sector, Ngao Demonstration Forest

PART VI COMPARISON OF THE NEW EQUATIONS WITH THE EXISTING EQUATIONS

The new equations (from this Project) were compared with the existing equations by calculating the differences between the new and existing equations, to assess the level of magnitude of the differences in the carbon estimates from the two equation types. Sixty sample tree data from the first inventory were randomly selected to test the difference between the new and existing equations. The tree samples were classified by forest type (Mixed Deciduous Forest, Dry Dipterocarp Forest and Dry Evergreen Forest) and 20 sample trees were used for each forest type. The tree DBH and total height were used to estimate tree carbon storage. The existing biomass equations (Table 24) were multipled by the carbon fraction of 0.47 (IPCC, 2006) to estimate carbon content value. The tree carbon contents per tree are shown in Tables 25-27.

Table 24 The existing equation to estimate biomass and convert to carbon storage on stem - bole by multiply with carbon fraction of 0.47

NO.	Biomass Equation	Forest Type/ Species	Location	Sample Tree No.	DBH range (cm)	Source
1	$Ws = 0.00509DBH^2H^{0.919}$	Dry evergreen forest and Hill evergreen forest	Namphom Pitsanulok Thailand	6	4.5-84.5	*Tsutsumi et al.*, 1983
2	$Ws =0.01334DBH^2H^{1.027} x\ 0.45$	Dry evergreen forest	Nakonratchasema Thailand	NA	NA	*Issare, 1982*
3	$Ws = 189\ ((DBH/100)^2\ x\ H)^{0.902}$	Dry Dipterocarp Forest	Nakonratchasema Thailand	16	2.0-23.0	*Ogino et al,1967*
4	$Ws = 0.0396\ (DBH^2H^{0.9326}$	Dry Dipterocarp Forest	Nakonratchasema Thailand	16	>4.5	*Ogawa et al,1965*
5	$Ws = 0.02903\ DBH^2H^{0.9813}$	Mixed deciduous forest	Nakonratchasema Thailand	74	>4.5	*Ogawa et al,1965*
6	$Ws = 0.2141\ DBH^2H^{0.9814}$	Pine forest / *Pinus merkusii*	Chiangmai Thailand	NA	NA	*Kajornsrichon, 1988*
7	$Ws = 0.02698\ DBH^2H\ ^{0.9846}$	Pine forest / *Pinus kesiya*	NA	NA	NA	*Sahunalu, 1981*

The carbon storages of the tree samples in the Mixed Deciduous Forest were estimated using the exiting equation of Ogawa *et al.* (1965) (Table 24), and the new equation of this project. The carbon contents from the exting equation were similar to the new equation. The relative difference of these 2-carbon equation was 3.65-36.82%. The carbon storages of the tree samples in the Dry Dipterocarp Forest were estimated from the exting equation of Ogawa *et al.* (1965) (Table 24). The carbon content from the exting equation was similar to the new equation. The relative difference of these 2-carbon equations was 1.28-33.5%. The carbon storages of the tree samples in the Dry Evergreen Forest were estimated from the exting equation of Tsusumi *et al.* (1983) (Table 24). The carbon content from the exting equation was different from the new equation by 9.8-39.50%. The relative difference of carbon content were shown in Tables 25-27.

Table 25 The comparison of tree carbon storage using new quation and existing equation in the Mixed Deciduous Forest

NO. of sample tree	DBH (cm)	Total Height (m)	Carbon content using new equation (kg)	Carbon content using existing equation with carbon factor (kg)	Relative difference (%)
1	40.20	24.90	320.01	450.29	30.04
2	9.20	9.50	7.55	9.68	25.51
3	7.50	6.90	4.10	4.74	17.81
4	35.20	18.20	204.35	255.09	35.14
5	53.90	24.90	613.70	800.67	31.62
6	21.80	17.60	69.38	96.39	36.82
7	94.00	38.10	2598.88	3620.49	24.86
8	19.30	11.20	42.42	48.71	13.83
9	22.80	16.20	73.59	97.03	28.44
10	12.80	14.80	19.54	28.60	28.39
11	41.90	14.30	267.35	283.42	21.92
12	36.50	26.80	267.73	400.43	35.46
13	11.30	14.80	14.81	22.39	19.37
14	109.70	26.00	3036.77	3369.52	3.65
15	71.70	28.50	1235.57	1600.39	17.51
16	69.60	24.40	1071.89	1296.27	25.63
17	95.00	38.10	2660.67	3696.47	29.42
18	38.00	22.00	265.79	357.07	28.79
19	32.50	19.00	174.81	227.51	26.11
20	46.00	24.40	427.37	575.07	28.78

The existing equations firstly used as an indirect method to estimate tree biomass multiplied by a carbon fraction to obtain carbon storage of the standing tree. The commonly used existing equations to estimate tree biomass might be biased (over- or under-estimated tree biomass). The bias occurs due to (1) the sample trees used to develop the equations was small (because of the need to minimize destructive sample trees and lack of instruments to accurately measure standing-tree upper stem diameters); and (2) the existing equations were focused on estimation in the logged area (mainly big trees). After the national logging ban occured, the interest has shifted to protected areas that include smaller trees.

Table 26 The comparison of tree carbon storage by using new quation and existing equation in the Dry Dipterocarp Forest

NO. of sample tree	**DBH (cm)**	**Total Height (m)**	**Carbon content using new equation (kg)**	**Carbon content using existing equation with carbon factor (kg)**	**Relative difference (%)**
1	105.80	31.00	3861.91	2733.43	11.15
2	81.50	21.00	1663.99	1168.38	2.09
3	55.10	24.20	728.55	642.59	13.38
4	27.00	16.30	109.13	117.51	7.13
5	36.60	19.20	244.53	241.44	1.28
6	69.00	14.70	911.10	614.12	4.48
7	38.50	12.20	209.38	173.83	20.45
8	32.40	18.10	177.69	182.04	2.39
9	13.40	16.60	21.60	32.36	33.25
10	17.80	17.40	43.03	57.41	25.05
11	19.80	16.80	53.98	67.77	20.34
12	28.60	24.40	159.08	190.58	16.53
13	30.10	19.00	154.14	166.03	7.16
14	25.70	23.60	121.57	151.35	19.68
15	23.10	13.00	66.23	71.13	6.89
16	34.00	21.70	221.73	235.88	6.00
17	33.80	20.50	211.35	221.24	4.47
18	11.60	9.60	11.10	14.83	25.17
19	33.00	15.00	165.62	158.11	4.75
20	26.80	19.00	117.63	133.70	12.02

The new equations from this project are preferable to the existing equations because the new established equations use the direct method for estimating tree carbon storage. There was no destructive sampling of trees because of use of the recently developed technology. The new equations were also established using many tree species from three forest types of the Mixed deciduous, Dry dipterocarp and Dry evergreen forests. Other advantages of the new equations were (1) the large sample sizes used to develop the new equations were 362 trees, (2) the various sizes of trees (DBH between 8.7-147 cm), and (3) many tree species in the three forest types grouped by wood density. All these new equations are shown in Tables 21-23.

Table 27 The comparison of tree carbon storage using new quation and existing equation in the Dry Evergreen Forest

NO. of sample tree	DBH (cm)	Total Height (m)	Carbon content using new equation (kg)	Carbon content by usingexisting equation with carbon factor (kg)	Relative difference (%)
1	13.90	11.90	17.08	29.38	27.60
2	15.60	5.10	13.03	16.67	21.87
3	40.90	21.00	256.13	359.98	28.85
4	10.60	6.70	6.63	10.53	37.07
5	15.20	8.40	16.75	25.15	33.40
6	24.60	14.30	66.56	99.34	33.00
7	62.40	24.30	705.21	894.82	21.19
8	48.60	25.10	416.76	582.31	28.43
9	67.00	27.70	893.07	1150.22	22.36
10	45.70	28.50	394.06	584.45	32.58
11	122.20	33.60	3738.95	4145.32	9.80
12	24.20	12.80	59.97	87.06	31.11
13	15.00	11.40	19.64	32.49	39.55
14	14.80	13.10	20.78	36.02	25.14
15	18.60	9.00	27.16	38.83	30.05
16	22.00	13.70	50.79	77.77	34.70
17	53.90	27.00	546.56	753.18	27.43
18	41.90	12.40	195.08	231.90	15.88
19	53.70	31.70	598.56	866.93	30.96
20	25.70	17.60	83.24	130.29	36.11

PART VIII: CONCLUSIONS

This project has successfully demonstrated a novel approach for constructing standing tree Carbon equations. This methodology can be applied throughout Thailand or elsewhere. However, the tree carbon equations developed in this project are specific to Mae Huad sector in Ngao Demonstration Forest. It is suggested that Thailand expand this study sites into all regions and all forest types of Thailand to produce national carbon equations. The national equations would support national plans on forest management and carbon stock reporting.

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