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Formulating Equations for Estimating Forest Stand Carbon Stock for Various Tree Species Groups at the Ngao Demonstration Forest, Northern Thailand

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Abstract: Through this study, we established equations for estimating the standing tree carbon stock, based on 24 tree species in multiple size classes in a case study at the Ngao Demonstration Forest (NDF) in northern Thailand. Four hundred thirty-nine wood samples from trees in mixed deciduous forest (MDF), dry dipterocarp forest (DDF), and dry evergreen forest (DEF), were collected using non-destructive methods to estimate above-ground carbon equations through statistical regression. The equations were established based on four criteria: 1) the coefficient of determination (R^2), 2) Standard error of estimate (SE), 3) F-value, and 4) Significant value (p-value, $\alpha \leq 0.05$). The above-ground carbon stock (C) equations for standing trees in the MDF was $C = 0.0199DBH^{2.1887}H^{0.5825}$, for DDF was $C = 0.0145DBH^{2.1435} H^{0.748}$, for DEF was $C = 0.0167DBH^{2.1423}H^{0.7070}$, and the general equation for all species/wood density groups was $C = 0.017543DBH^{2.1625}H^{0.6614}$, where DBH is tree diameter at breast height and H is tree total height. The above-ground carbon stock in the DDF, MDF, and DEF was 142, 53.02 and, 12 tons/ha, respectively, and the estimated above-ground carbon stock in the Mae Huad sector at the NDF was 61 tons/ha.

Keywords: carbon stock; standing-tree carbon equation; mae huad sector; ngao demonstration forest

1. Introduction

Climate change and global warming is a serious environmental issue worldwide [1–4]. Global warming is caused by inordinate emissions of greenhouse gasses [5], with the ensuing climate change and natural disasters affecting human activities and the availability of natural resources. Climate change can result in environmental and financial losses, which can be detrimental for the survival of humans and other species. Carbon dioxide (CO_2) is an important greenhouse gas, which is stored in the ecosystems and specifically in trees, for a long period of time [6]. It has been estimated that forests contain 77% of the carbon stored in land vegetation, out of which approximately 60% of carbon is stored in the tropical forests, 17% in temperate forests, and 23% in boreal forests [7]**.** Plants or trees can potentially trap atmospheric carbon through the photosynthesis process[8], which involves the conversion of carbon from CO_2 to carbohydrates, glucose, and starch that are stored in the leaves, stems, branches, and roots, and contribute to a plant's growth [9]. As such, plants store carbon as living biomass, which becomes a part of the food chain and enters the soil as soil carbon [10].

Normally, the carbon stored in trees is estimated as the product of the volume of biomass and the carbon fraction (generally assumed as 0.47 [11]), based on field data collection methods and estimations of different complexity levels [12–14]**.** Tree biomass can be estimated using either direct or indirect methods. The direct method involves felling of trees and weighing various tree components [15], while the indirect method involves the use of allometric equations for estimating the tree sample biomass [16].

The biomass or tree volume equations to estimate the tree carbon storage specific to Thailand are inaccurate as the commonly used allometric equations are biased (i.e., they tend to over- or under-estimate the tree volume)[17]. Additionally, the existing equations do not cover the major tree species

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frequently found in forests such as *Tectona grandis*, teak[18], or various dipterocarp species [19]. This is primarily due to the fact that the estimations are based on equations constructed using the destructive sampling of a relatively small number of trees. Some volume equations use only the diameter at breast height (DBH) as the independent variable and do not include tree height[20,21]. Also, some equations were constructed only to estimate the traded logged volume and did not include the smaller trees [21]. Therefore, a novel approach is proposed to estimate the standing tree carbon content as a function of tree attributes in a natural forest with different tree size classes. This approach would avoid the felling of trees and would use combustion methods to estimate the real carbon fraction.

This study aims to formulate the standing tree carbon equations to estimate the carbon stocks in three forest types: a mixed deciduous forest (MDF), dry dipterocarp forest (DDF), and a dry evergreen forest (DEF) at the Mae Huad sector, Ngao Demonstration Forest (NDF) in northern Thailand. The Mae Huad sector has a vast forest cover in the NDF, with several tree species and is one of the five most important biosphere reserves area in Thailand [22]. The equations determined in this research to estimate the carbon stock were constructed using specific carbon fraction of tree species, without the need to calculate the biomass to estimate the tree carbon stock. The non-destructive method used to establish the equations for many tree species sampled from the MDF, DDF, and DEF can also be used to estimate the carbon stored in other sites of Thailand.

2. Materials and Methods

2.1. Study area

The Mae Huad Sector was chosen as the study site (Figure 1) and is one of of the four designated sectors in the NDF. The NDF consists of four sectors, Mae Heang, Mae Huat, Mae Ngao, and Mae Teeb and covers an area of approximately 43.431.75 hectares, including several forest types. It is located in the north-western part of the Lampang Province in northern Thailand between 18º 30' and 18º 54' north latitude, and 99º 50' and 100º east. The NDF was established in 1961 and is the only demonstration forest in Thailand, and has a long history of functioning as a base for the introduction, testing, and adaption of new forest management techniques [21]. Most of the land in Mae Huad sector is under forest cover, i.e., 38,557.50 hectares or 84.246 % of the total area. Most of the tree cover is part of the Ngao Demonstration Forest, while a total of 6,526.80 hectares is classified as agricultural land or 14.261 % and is located in the national reserve forest by law. It is expected that the agricultural area will increase over time if the enforcement of the law is weak. Additionally, the area has a porcelain mine which covers an area of 11.00 hectares or 0.24 % of the total area. There are two types of infrastructure in the site, i.e., power lines and paved road (ASEAN highway or the Phaholyothin road). The power lines go underneath the forest, but the roads cover an area of 1.136 square kilometers or 0.248 % of the total area. Ancient settlements, namely Ban (or village) Pong, Ban Tak, Ban Huad, Ban Suan Sak, Ban Pang Lah, and Ban Prow, are also located in this study area, covering an area of 545.90 hectares. This study focuses only on the natural forest of MDF, DEF and DDF. The equations developed in these forest types can be applied to estimate the carbon storage in forest trees in the tropical rain forest.

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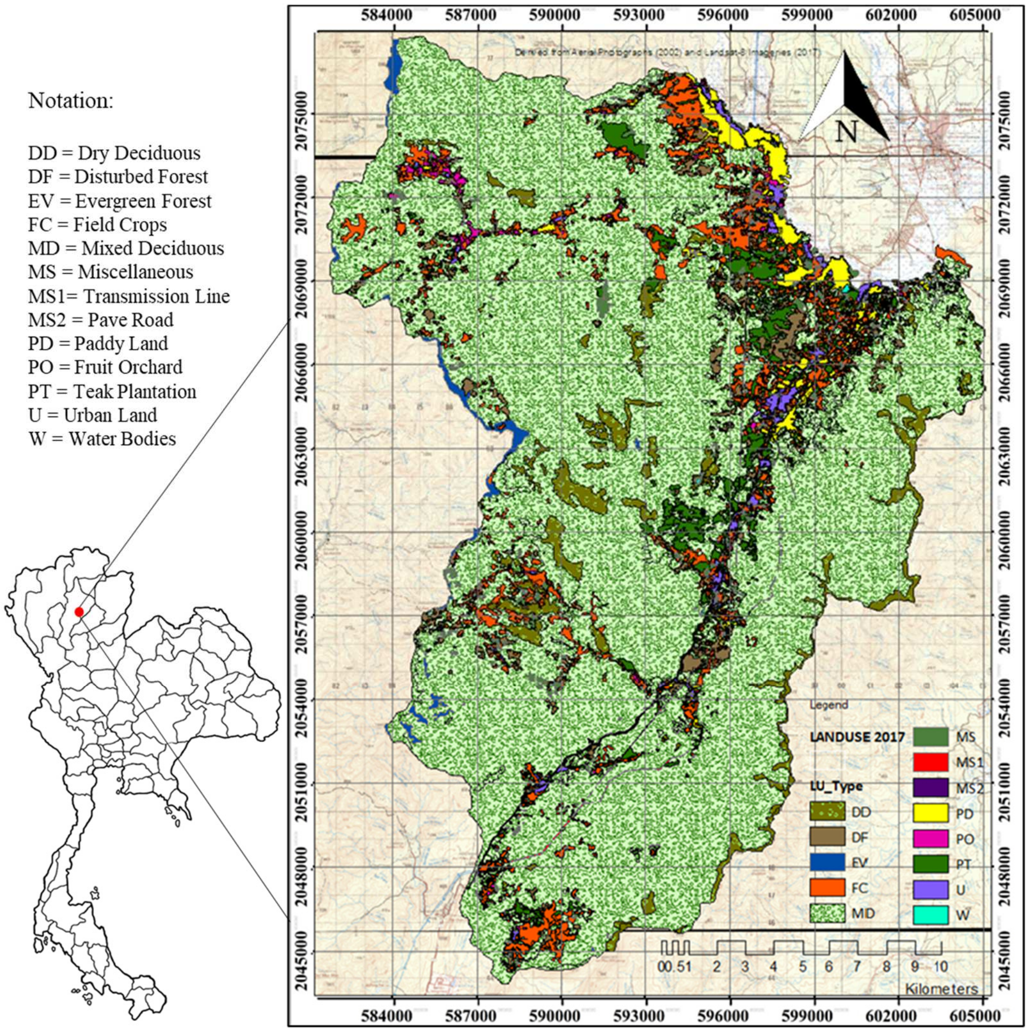

Figure 1. The study area in the Mae Huad sector, NDF in northern Thailand.

2.2. Forest inventory and sample collection

Trees from plotless inventory data are used for the collection of tree samples, wood samples, and calculated stand carbon stock. The distribution of trees in Mae Huad sector NDF, Northern Thailand, was determined using stratified sampling [23,24] and a uniform fixed grid of 3 x 3-kilometer systematic arrangement that covered the whole of the Mae Huad sector. The point sampling technique [25–27] was used to collect tree data which included diameter at breast height (DBH), total height (H), trees species, and forest type at each sample point. This grid and point sampling were part of the APFNET project [21]. The point sampling data were used to calculate the importance value index (IVI), which is the quantitative value for measured dominance of trees species [28], that was used to select the sample trees by diameter classes. The suitable sample size (i.e., the number of sampling points) was calculated using equation 1 [29]

$$\mathbf{n} = \frac{\mathbf{t}^2(\mathbf{cv})^2}{\mathbf{AE}^2} \tag{1}$$

where, n is the target number of sample points, t is the *t*-value at the 95% probability level, cv is coefficient of variation in DBH, AE is allowable sampling error in DBH at point sampling (this research used 10%)

In each forest type, all the selected tree species were grouped into 10 groups based on their wood density. The species with the highest IVI in each group was selected as a representative of the group for tree data and wood sample collection. Each selected species was further classified into one of three

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diameter classes (small, medium, and large) (15 trees sample in each species, total was 450 sample trees).

The bole of each sample tree was measured for the stem diameter by 2-meter sections from the base to the first major branch, to calculate the tree bole volume. Wood samples were collected from the selected sample trees in the north and east directions using an increment borer or a handsaw at 1.3-meter height (2 wood sample in each tree, The total was 900 wood sample) to determine the carbon fraction.

2.3. Sample preparation and carbon fraction analysis

Wood sample preparation: this process was for estimated the wood carbon fraction in sample trees. The wood wet volume of the collected sample wood was calculated using Newton's formula (Equation 2) [27,30]:

$$V_t = \sum_{i=1}^{n} \frac{L}{6}(Ab_i + 4Am_i + Au_i) \quad (2)$$

where, V_t is tree wet volume, Ab_i is cross-sectional area at base of stem segment i, Am_i is cross-sectional area at middle of stem segment i, Au_i is cross-sectional area at upper of stem segment i, L is length of stem segment i (m).

The wet volumes of the wood samples were calculated. The wood samples were weighed and were dried in an air-dry oven at 80 °C for 24 - 48 hours, until their weights became constant, to determine the final dry weights. Two dry samples from the same tree were then pulverized together using a crushing machine to obtain a 100-gram dry weight sample.

Carbon fraction analysis: A 100-gram pulverized sample was analyzed carbon fraction using combustion methods via a carbon analyzer (e.g., PerkinElmer 2400 series II CHNS/O Elemental Analyzer). recommended by Kraenzel *et al.* and Wulzler *et al.* [31,32]

2.4. Data analysis

1) Carbon storage in wood samples: This process was calculated by using the relationships between carbon fraction and wood sample dry weight

The carbon proportion (carbon fraction) was obtained as a percentage of dry weight using the method described by Duangsathaporn *et al.* [20]and Khantawan *et al.* [33] to convert the carbon fraction to carbon weight in a wood sample (Equation 3):

$$C_c = C_w \times W_d \quad (3)$$

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 fraction in a sample core (%).

Furthermore, the carbon wood sample and carbon fraction in each species was used to estimate the carbon stored in the standing tree using Equation 4:

$$C_t = \frac{C_c}{V_w} \times V_t \quad (4)$$

where, C_t is weight of carbon in a standing sample tree bole (kg), Cc is weight of carbon in a wood sample core (kg), V_w is wet volume of wood sample core, and Vt is wet volume of standing tree bole.

2) The calculation of standing tree carbon stock: this process calculated the standing trees carbon storage in tree samples to estimate the carbon equation. The above-ground standing tree carbon was determined through three steps.

In the first step, a piece of sample tree in tree bole was used to estimate the bole volume and carbon. The wet bole volume (V) of every sample from a total of 362 sample trees was calculated using the Smalian's formula (equation 5) [27,30] and the carbon stock in each wood sample core was then estimated using the dry weight carbon in the wood sample core multiplied by the carbon

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fraction in each wood sample core [20]. The whole-bole carbon stock of each sample tree was then calculated using the proportion of dry weight carbon in a wood sample core and the wet volume of wood sample core multiplied by the wet volume of standing tree bole (Equation 4).

$$V_t = \sum_{i=1}^{n} \frac{L}{2}(Ab_i + Au_i) \qquad (5)$$

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, and L is length of stem segment i (m)

In the second step, the branch and leaf carbon stock were estimated using leaf and branch biomass of the tree estimated using the standard equation multiplied by the carbon fraction. The equation recommended in Tsutsumi *et al.* as used to estimate the branch and leaf biomass for trees from the DEF [34], and the equation recommended in Ogawa *et al.* as used to estimate the branch and leaf biomass for trees from the MDF and DDF [35]. These equations for estimating carbon stock in leaves and branches in each tree are shown in Table 1

In the third step, the above-ground carbon stock in each sample tree was obtained by combining stem, branch, and leaf carbon stock. This was then used to develop the tree carbon storage equations.

Table 1. The equation for estimating carbon storage in leaves and branches in individual trees.

Forest type	Equation	location	Source
Dry evergreen forest	$W_b = 0.00893DBH^2H^{0.977}$ $Wl = 0.0140DBH^2H^{0.669}$	Namphom Pitsanulok Thailand	*Tsutsumi et al.*, 1983
Dry deciduous forest	$W_s = 0.0396\ DBH^2H^{0.9326}$ $W_b = 0.003487DBH^2H^{1.0270}$ $W_l = (25.0/W_{sb}+0.025)^{-1}$	Nakon-ratchasema Thailand	*Ogawa et al,1965*
Mixed deciduous forest	$W_s = 0.02903\ DBH^2H^{0.9813}$ $W_b = 0.003487DBH^2H^{1.0270}$ $W_l = (28.0/W_{sb}+0.025)^{-1}$	Nakon-ratchasema Thailand	*Ogawa et al,1965*

Remark: Ws is biomass of stem (kg/tree), Wb is biomass of branches (kg/tree), Wl biomass of leaves (kg/tree), Wsb is biomass of stem + biomass of branches (kg/tree), DBH is diameter at breath height and H is height of tree

3) The construction of standing tree carbon equations: The equations to estimate the above- ground standing tree carbon were constructed using the model $C=aDBH^bH^c$, where C is standing tree carbon stock, DBH is diameter at breast height, H is total height, and a, b and c are model parameters to be estimated. The model parameters were estimated using log transformation and linear multiple regression.

The equations) were fitted for each forest type. In order to select the optimal tree carbon equations, statistics which included the coefficient of determination (R^2), standard error of estimate (SE), F-value, and significance value (*p*-value, $\alpha \leq 0.05$) were evaluated. The normality of the model residuals was also examined using basic program of statistics. The equations of the three forest types were compared with the general equation for all species/wood density groups. This was done by calculating the relative differences and statistics between the mean of the equations of the three forest types and the optimal forest type equations. Data from 30 randomly selected sample trees were used to test the differences between the optimal equation and forest type equations.

4) Estimated stand carbon stock: All trees in point sampling inventory from 2.1 used for calculating stand carbon storage. The carbon stock per hectare (ha) at each sampling point was estimated by summing the estimated carbon content of the sample tree and expressing it on a per unit area basis for the major forest types in the study area, using the Equations 6-9 adapted from van Laar and Akça [26].

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$$C_p = BAF \times \sum_{i=1}^{n} \frac{C_i}{BA_i} \quad (6)$$

where; C_p is carbon stock at sampling point (kg/ha), BAF is basal area factor, C_i is the carbon storage in tree i of point sampling, and BA_i is basal area in tree i of point sampling.

$$C_a = A_t \times \bar{C} \quad (7)$$

where, Ca is mean carbon stock in forest area, A_t is forest area in the study, and $\bar{C}$ is the average carbon stock in all sampling points.

$$C_t = C_a \pm t \times SE_{C_a} \quad (8)$$

and

$$SE_{C_a} = A_t \times SE_{\bar{c}} \quad (9)$$

where, C_t is carbon stock of forest area, SE_{C_a} is standard error in stand carbon stock of forest area, and $SE_{\bar{c}}$ is the standard error of the mean carbon stock in forest area.

3. Results

3.1. Forest inventory for building a species list, sample trees selection, and wood sample extraction.

A 54-sample fixed grid of size 3 x 3 kilometers was established in the the Mae Huad sector. Forty-four sampling points fell in the forested area and classified under either of the three forest types, while the remaining 10 sampling points were in the agriculture field. Seventy-six tree species were found in the Mae Huad sector, with 46 tree species in the MDF, 18 in the DDF, and 31 in the DEF. The IVI was calculated and used to classify and select the sample trees. The highest species IVI in the MDF were *Xylia xlocarpa*, *Tectona grandis*, and *Prerocapus macrocapus*, in the DDF were *Shorea siamensis, Shorea obtusa*, and *P. macrocarpus*, and in the DEF were *Mallorus macrostachyus, Hopea odorata,* and *Duabanga grandiflora*. The *X. xylocarpa*, *Dalbergia oliveri, P. macrocarpus*, *Terminalia corticosa*, *Terminalia. alata,* and *Quercus kerri* were found in all the three forest types. Within the three forest types and 10 species groups for each forest type, the sample trees were grouped into wood density classes, for a total of 30 groups. In each group, the selected species had the highest value of IVI for the sample tree species. The 10 sample trees species per forest type were classified into three DBH classes (small, medium, and large) from inventory data covering a DBH range of 4.50 to 147.00 cm. The wood density range and representative tree species are shown in Table 2.

Table 2. Number of sample trees, carbon content, and carbon stock in sample trees.

Forest Type	Density class	Wood density range*(kg/m³)	Representative species (Scientific name)	DBH range (cm)	No. sample	%Carbon	Carbon stock in sample trees (stem+Branch+Leaf) (kg)		
							min	max	Average
Mixed deciduous forest	1	283-385	*Cananga latifolia.*	4.50-43.00	15	47.75	23.90	454.29	163.37
	2	386-488	*Litsea glutinosa*	4.50-62.40	15	46.86	38.65	1,297.63	505.81
	3	489-591	*Lannea coromandelica*	4.50-58.00	16	45.75	11.19	1,252.27	407.75
	4	592-694	*Tectona grandis*	4.50-71.00	16	49.66	8.18	1,385.72	589.75

	5	695-797	*Albizia odoratissima*	4.50-42.50	15	46.84	12.17	502.36	186.04
	6	798-900	*Terminalia nigrovenulosa*	4.50-61.29	16	47.13	38.10	1,161.93	402.95
	7	901-1,003	*Pterocarpus macrocarpus*	4.50-61.50	15	48.41	20.22	1,489.53	445.37
	8	1,004-1,106	*Xylia xylocarpa*	4.50-66.80	15	48.03	29.40	1,340.78	489.37
	9	1,107-1,209	*Dalbergia oliveri*	4.50-42.80	17	47.13	14.89	724.67	264.32
	10	1,210-1,312	*Terminalia corticosa*	4.50-66.30	15	48.55	22.87	2,006.99	590.11
Dry dipterocarp forest	1	401-485	*Mitragyna brunonis*	4.50-41.00	15	47.57	16.05	496.35	189.90
	2	486-570	*Bridelia pierrei*	4.50-25.80	12	47.16	6.12	186.67	70.35
	3	571-655	*Gardenia sootepensis*	4.50-32.40	15	46.06	23.53	680.13	175.37
	4	656-740	*Haldina cordifolia*	4.50-41.9	15	48.26	8.86	604.76	177.12
	5	741-825	*Dipterocarpus obtusifolius*	4.50-42.50	15	47.62	9.77	505.84	145.02
	6	826-910			*NA*				
	7	911-995	*Pterocarpus macrocarpus*	4.50-61.50	15	48.41	20.22	1,489.53	445.37
	8	996-1,080	*Shorea siamensis*	4.50-58.20	15	46.76	11.99	1,148.05	438.29
	9	1,081-1,165	*Dalbergia oliveri*	4.50-42.80	17	47.13	14.89	724.67	264.33
	10	1,166-1,250	*Terminalia corticosa*	4.50-66.30	15	48.55	23.87	2,006.99	590.11
Dry evergreen forest	1	388-474	*Duabanga grandiflora*	4.50-147.00	15	46.92	59.58	8,673.15	2,572.99
	2	475-561	*Croton roxburghii*	4.50-42.00	15	47.77	16.81	353.85	130.37
	3	562-648	*Careya sphaerica*	4.50-38.30	15	47.47	12.97	256.03	117.36
	4	649-735	*Artocarpus lakoocha*	4.50-47.30	15	48.31	13.12	915.60	269.66
	5	736-822	*Cratoxylum formosum*	4.50-22.60	15	46.83	8.45	119.54	42.31
	6	823-909	*Anogeissus acuminata*	4.50-71.70	15	46.81	56.61	2,365.23	761.73
	7	910-996	*Pterocarpus macrocarpus*	4.50-61.50	15	48.41	20.22	1,489.53	445.37
	8	997-1,083	*Terminalia alata*	4.50-50.00	15	45.75	25.75	1,271.14	410.04
	9	1,084-1,170	*Xylia xylocarpa*	4.50-66.80	15	48.03	29.40	1,340.78	489.37
	10	1,171-1,257	*Quercus kerrii*	4.50-43.7	15	45.43	11.78	499.12	181.19

Source: * Forest Research and Development Bureau (2007; 2010) [36,37].

3.2. Wood carbon fraction analysis

The carbon fraction of tree in NDF analyzed using combustion techniques from PerkinElmer 2400 series II CHNS/O Elemental Analyzer in the laboratory was between 45.75% and 49.66%, with an average of 47.43%. Carbon fraction of MDF for 10 species and 155 sample ranged from 45.75% to 49.66 % with an average 47.61%. The 3rd highest of carbon fraction in each MDF sample species was Tectona grandis, 49.66%, T. corticosa, 48.55%, and (3) Lannea coromandelica, 45.75%, respectively. Carbon fraction of DDF for 9 species and 134 sample ranged from 46.06% to 48.55% with an average 47.50% and each 3rd highest species carbon fraction was T. corticosa ,48.55%, P. macrocarpus, 48.41% and Haldina cordifolia, 48.26%, respectively. Carbon fraction of DEF for 10 species and 150 sample ranged from 45.43% to 48.41% with an average 47.17%, and each 3rd highest species carbon fraction was P. macrocarpus,48.41%, Artocarpus lakoocha,48.31%, X. xylocarpa, 48.03% respectively.. Carbon fraction of sample trees in the Mae Huad sector, NDF are listed in Table 2.

3.3 Carbon storage

The standing trees carbon stock in each species was calculated using Equations (3) - (5), and branch and leaf carbon was calculated using the equations in Table 1. Above-ground carbon stock in sample trees of NDF ranged between 6.12 - 8,673.15 kilogram (kg). In MDF, above-ground cabon stock from 155 sample trees ranged from 8.18 to 2,006.99 kg., above-ground carbon stock in DDF from134 sample trees ranged from 6.12 – 2,006.99 kg, and above-ground carbon stock in DEF from 150 sample trees ranged from 8.45 – 8,673.15 kg. Carbon stock by tree component and the above-ground carbon stock per cubic meter are shown in Table 2. All above-ground carbon stock sample tree data were used to develop stading tree carbon stock equations using regression analysis (Section 3.4).

3.4. Standing tree above-ground carbon equations

The above-ground carbon stock sample data were used to establish standing tree carbon equations for MDF, DDF, and DEF, and a general equation for all the species/wood density groups. Multiple regression analysis was used, where the dependent vairable was carbon stock (C), and the independent variables included DBH and H. The two variable, DBH and H, both showed a high relationships to C more than only DBH or only H (Table 3).

The equations for the MDF, DDF, and DEF were estimated from 10, 9, and 10 species, resectively, and the the general equation was estimated from 24 species. The DBH range of trees used in the construction of equations for MDF, DDF, DEF, as well as the general equation, was between 8.70 - 71.00 cm, 10.00 - 66.80 cm, 9.70 - 147.00 cm, and 8.70 - 147.00 cm, respectively. The suitable equations are shown in Table 4.

Table 3. The regression equations tested to etimate standing tree carbon stock..

Forest type	Variables	Statistic criterion value				Remark
		R^2(%)	SE	F-value	*p*-value	
MDF	DBH	0.9604	0.11	3,708.54	<0.001	
	H	0.7361	0.29	426.8	<0.001	
	DBH, H	**0.9678**	**0.10**	**2,281.89**	**<0.001**	***Best variables**
DDF	DBH	0.9259	0.16	1,649.54	<0.001	
	TH	0.7303	0.30	357.5	<0.001	
	DBH, H	**0.9412**	**0.14**	**1,048.28**	**<0.001**	***Best variables**
DEF	DBH	0.9633	0.13	3,888.38	<0.001	
	TH	0.7039	0.36	351.89	<0.001	

	DBH, H	**0.9770**	**0.10**	**3,127.52**	**<0.001**	***Best variables**
NDF	DBH	0.9526	0.13	8,779.48	<0.001	
	TH	0.7171	0.32	1,107.98	<0.001	
	DBH, H	**0.9642**	**0.11**	**5,870.73**	**<0.001**	***Best variables**

Table 4. Carbon stock equations, DBH range, and statistical goodness of fit values of the constructed general equation.

Forest Type	Equation	DBH Range (cm)	R^2 (%)	SE	F-Value	*p*-value
MDF	$C_{MDF} = 0.0199\ DBH^{2.1887}\ H^{0.5825}$	8.70 -71.00	0.9678	0.10	2,281.89	<0.01
DDF	$C_{DDF} = 0.0145\ DBH^{2.1435}\ H^{0.7480}$	10.00 – 66.80	0.9412	0.14	1,048.28	< 0.01
DEF	$C_{DEF} = 0.0167\ DBH^{2.1423}\ H^{0.7070}$	9.70 – 147.00	0.9770	0.10	3,127.52	< 0.01
NDF	$\mathbf{C_{NDF} = 0.017543\ DBH^{2.1625}\ H^{0.6614}}$	**8.70-147.00**	**0.9642**	**0.11**	**5,870**	**< 0.01**

Remark C_{NDF}, C_{MDF}, C_{DDF}, and C_{DEF} indicate the above-ground standing tree carbon stock in the general equation for all species/wood density groups in the NDF, MDF, DDF, and DEF, respectively (kg/tree), while DBH is diameter at breast height of tree (cm), H is total height of tree (m).

The coefficient of determination (R^2), standard error of estimate (SE), F-value, and significant value (p-value, $\alpha \leq 0.05$)), to determine the best fit equations were determined for each forest type. The R^2 values for the equations constructed for MDF, DDF, DEF, and NDF were 0.9678, 0.9412, 0.9770, and 0.9642, while the SE was 0.101, 0.139, 0.100, and 0.114, respectively.The F-value was 2281.89, 1048.28, 2127.52, and 5870.00, respectively, while the p-value for all the equations was less than 0.01, which was highly significant. All the related statistical values for each forest type are shown Table 4.

The residuals between the actual and estimated carbon stock for the various values of carbon stock are shown in Figure 2. Residuals for the overall model can be seen to be unbiased as were for all species in the MDF, DDF, DEF, and all species in the NDF. In other words, the errors are distributed uniformly with no apparent dependence on any of the potential predictors.

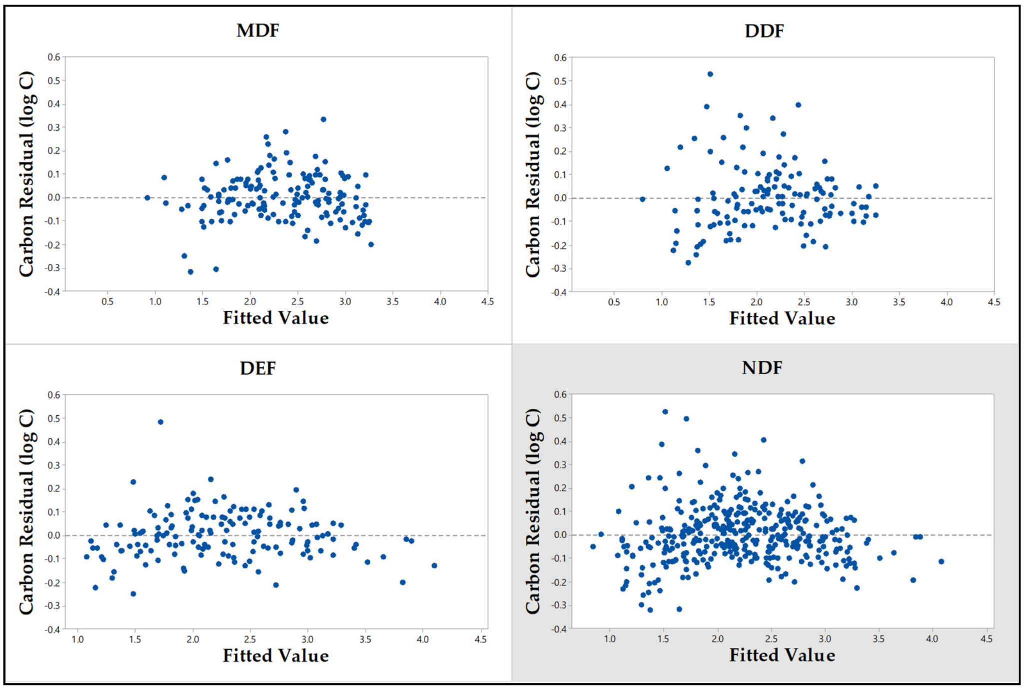

Figure 2. Residuals or the difference between observed and predicted above-ground carbon content in of the selected trees: MDF, DDF, DEF, and Mae Huad sector NDF.

Sample trees were used to estimate the tree carbon stock for each forest type. using tree DBH and H.. The carbon storage of tree samples were estimated using the equations constructed for the MDF, DDF, DEF and the optimal equation of this project. The equations to estimate the carbon content in the MDF, DDF, and DEF were similar to the optimal equation. The relative difference of the two carbon equations was between 0.088 - 2.416%, 0.050 – 2.545%, and 1.076 – 2.191%, respectively. The comparison of the mean between the equations of three forest types and the optimal equation was not significant difference.

3.5. Forest stand carbon stock in the NDF

The standing tree carbon stockwas used to calculate the carbon stock in the NDF forest stand using the equation from van Laar and Akça, (20). The carbon stock of the 44 sampling points ranged from 6.15 to 175.64 ton/ha, with an average per point of 61,837.96 kg/ha (Table 5). Carbon stock per hectare by forest type in the DDF, MDF, and DEF was 142 ton/ha , 53.02 tons/ha and 12 tons/ha, respectively. The carbon stock in the MDF was approximately between 0.932 and 1.4 million tons (1.20 mean million tons), that in the DDF was approximately between 0.289 and 0.454 million tons (0.371 mean million tons), and that in the DEF was approximately between 0.049 and 0.078 million tons (0.063 mean million tons). The carbon storage in the Mae Huad sector forest was approximately between 1.27 and 1.99 million tons (average 1.632 million tons).

Table 5. Carbon stock (CS) per sample point in the Mae Huad sector.

Point NO.	CS (kg/ha)	Forest Type	Point NO.	CS (kg/ha)	Forest Type	Point NO.	CS (kg/ha)	Forest Type
1	88,287.97	MDF	16	126,052.64	DDF	31	9,129.03	DEF
2	17,097.92	DEF	17	20,736.35	MDF	32	23,084.19	MDF
3	69,643.47	MDF	18	42,646.39	MDF	33	64,055.07	MDF
4	7,201.58	DEF	19	47,857.28	MDF	34	22,489.32	DEF
5	128,574.47	DDF	20	165,600.93	DDF	35	106,388.19	MDF
6	100,360.65	DDF	21	38,493.44	MDF	36	67,442.07	MDF
7	58,061.08	MDF	22	11,156.50	MDF	37	148,058.31	DDF
8	6,152.98	DEF	23	59,036.21	MDF	38	43,768.32	MDF
9	27,286.41	MDF	24	162,671.46	DDF	39	79,015.26	MDF
10	63,391.82	MDF	25	38,514.85	MDF	40	70,904.44	MDF
11	59,217.74	MDF	26	42,606.07	MDF	41	133,507.34	DDF
12	46,099.49	MDF	27	63,438.04	MDF	42	57,309.07	MDF
13	28,610.93	MDF	28	63,581.88	MDF	43	46,216.42	MDF
14	8,623.92	DEF	29	9,828.38	DEF	44	11,595.44	DEF
15	61,435.68	MDF	30	175,641.25	DDF	Average	61,837.96 kg/ha	

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4. Discussion

4.1. Carbon fraction

Normally, the carbon fraction is assumed to be 50% of a tree's total biomass [2,12,38]. The carbon fraction in this study ranged from 45.75% to 49.66%, with an average of 47.43%. This is less than the normally assumed value but more than the Intergovernmental Panel on Climate Change (IPCC) carbon fraction value of 47% of tree biomass [11]. However, much research explained the variations in carbon fraction estimates might result from the methods used for different species, the components of a tree or a stand used (stem, roots, and leaves), and the age of the stand [12,39]. For example, the study by Thomas and Martin report the difference of carbon fraction in part of trees, was shown 37%, 76%, 48%, 81% and 63%, respectively, of the variation in bark, branch, twig, coarse root and fine root carbon fraction value[12]. The difference of carbon fractions was confirmed by IPCC reports. The amounts of components of wood tissues such as cellulose, hemicellulose, lignin, and variety of nonstructural chemicals resulted in different amounts of carbon by mass [40]. The carbon fraction of trees growing in plantations of Thailand was reported by Diloksumpun and Staporn who estimated the carbon stock through combustion techniques. They found carbon fraction for *eucalyptus spp.* was 48.36 %[41], while Duangsathaporn *et al.*, who estimated the sequestered carbon in standing teak trees in the Thong Phaphum teak plantation through combustion techniques, reported a carbon fraction of 46.58%[20].

We investigated the relationship between average carbon per cubic meter and wood density; higher density wood had a higher carbon content per cubic meter (Table 6). The relationship between average carbon weight per wood volume (kg/m^3) and wood density class was analyzed using a linear relationship. This linear relationship was not significant (Figure 3), but there was a trend showing variation in the wood samples due to different wood elements (e.g., lignin, cellulose, and hemicellulose) in a unit of tree sample volume. Thus, the carbon stock per volume will be different, similar to the study of Campbell and Sederoff who found the differences of lignin in different tree species in sample trees [42]. A study by Navarro, *et al*. also found that indirect indicators of wood density and carbon fraction affected carbon storage, as high wood density in some species of tropical forests was shown high carbon content [43]. Other studies have also not found such a relationship between carbon storage and wood density. For example, Weber *et al.* studied the variations between tree growth, density, and carbon concentration and did not find any significant relation between wood density and carbon concentration [44].

Table 6. The average carbon per cubic meter in a sample trees and wood density.

Density class	Carbon in a cubic meter (kg) in MDF				Carbon in a cubic meter (kg) in DDF				Carbon in a cubic meter (kg) in DEF			
	Stem	Branch	leaf	Total	Stem	Branch	leaf	Total	Stem	Branch	leaf	Total
1	220.34	60.06	17.76	298.15	289.33	73.00	27.95	390.27	227.50	167.51	9.03	404.03
2	281.49	78.52	22.89	382.90	284.83	84.54	33.00	402.37	260.01	164.63	10.81	435.45
3	221.62	48.75	14.48	284.85	365.20	89.50	34.70	489.40	257.70	187.24	12.10	457.04
4	293.32	94.68	27.66	415.66	301.62	105.00	39.93	446.55	314.15	187.81	11.52	513.47

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5	319.23	68.76	20.35	408.33	317.04	79.18	30.63	426.85	314.15	223.06	15.37	552.57
6	354.41	108.68	31.72	494.81		*NA*			307.47	195.46	10.48	513.40
7	385.07	98.06	28.83	511.96	385.07	98.06	28.83	511.96	385.07	98.06	28.83	511.96
8	345.14	84.59	24.77	454.51	350.46	79.55	29.77	459.77	348.71	162.78	9.69	521.17
9	386.94	68.10	20.10	475.13	386.94	68.10	20.10	475.13	345.14	84.59	24.77	454.51
10	314.15	84.83	24.92	423.91	314.15	84.83	24.92	423.91	342.86	128.51	9.03	480.40

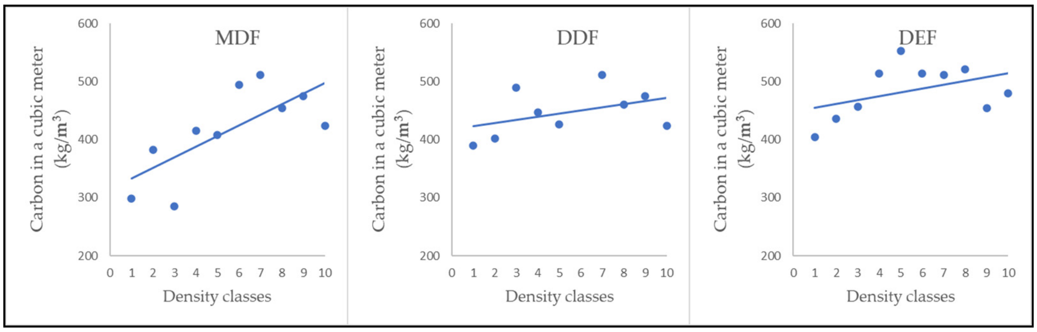

Figure 3. The relationships shown between stored carbon per cubic meter and wood density class.

4.2. Above-ground carbon equation

Generally, equations for estimating carbon storage use indirect methods, such as the product of tree biomass and carbon fraction, to evaluate the carbon stored in a standing tree. In Thailand, to estimate carbon storage, Viriyabuncha used an aggregate of six equations in a mixed species forest [18], Yuan *et al.* used 11 equations in a mixed species forest [45], and the Department of Environmental Quality Promotion used six equations from trees in a mixed deciduous, dry dipterocarp, dry evergreen, pine, and mangrove forest which included mixed species [46]. All of these studies conducted in Thailand used destructive sampling methods [45]. Destructive methods involve the cutting down of all the trees in the sampling area and measuring the weight of the different components such as the tree trunk, leaves, and branches and measuring the oven-dried weight of these components [47,48].

In this research, the equations for estimating carbon storage were constructed by combining the non-destructive method of Montès *et al.*[49] and the collection of the wood samples as proposed by Duongsathaporn, *et al.*[20] and Khantawan, *et al.*[33]. The regression technique was used to estimate the tree carbon storage in only the mixed deciduous, dry dipterocarp, and dry evergreen forest types. In addition, these equations can only be used for estimating the carbon stored in the standing trees with a DBH 8.70 to 147.00 cm, in the three forest types of a tropical forest. Thus, similar studies need to be done in other forest types in Thailand and trees of a wider range of DBH. The advantage of the non-destructive sampling method is that, at present in Thailand, the destructive sampling method cannot be used as there is an ongoing logging ban since 1989 [50].

The most frequently used equations for estimating trees biomass in Thailand are those proposed by Ogawa *et al.*; these equations were based on 90 standing sample trees in MDF and DDF (the coefficient of determination (R^2) = 0.9326) [35]. Another equation widely used is that of Tsutsumi *et al.*, which used six standing sample trees in a DEF (R^2 = 0.97)[34]. All these equations are suitable for estimating tree biomass in the respective forest types, but the estimation of standing tree carbon is arduous as it still requires the estimation of the carbon fraction. Thus, the equations developed in this study are more suitable for directly estimating the carbon stored in standing trees in the MDF, DDF and DEF forest types.

5. Conclusions

The optimal above-ground carbon equations were formulated from a large sample of trees (155, 134, and 150 trees samples in MDF, DDF and DEF, respectively), of various sizes, and trees species (24 tree species in 3 forest types). We conclude that such equations can be used to estimate the carbon stocks in Thailand, and in the assessment of carbon stock. However, the present carbon estimation did not cover other species in other forest types, such as mangrove forests, and would be the endeavor of a future study.

6. Patents

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