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Carbon Stock Estimation by Forest Measurement Contributing to Sustainable Forest Management in Cambodia

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Abstract

A simplified method for estimating CO_2 emissions from deforestation is the calculation of carbon stock change by monitoring forest land and periodically summing up the land area and its averaged carbon stock for important forest types. As a feasibility study for applying this methodology to a tropical dry-land forest, we estimated carbon stock and its chronosequential change in 4 carbon pools (aboveground and belowground biomass, deadwood, and litter) of tropical dry-land natural forests in Cambodia. Carbon stock differed among forest types. Most of the carbon stock (84 ± 12% (SD)) existed in tree biomass. Growth of carbon stock has a positive relationship to the carbon stock itself. By moderately classifying forest types, determining averaged tree biomass of each forest type, and using land-area data on each forest type, a reasonably accurate estimation of carbon stock can be expected. However, considering that rapidly progressing deforestation and wood extraction may reduce the carbon stock in forests, systematic sampling with a sufficient number of extra plots and frequent updating of forest land area and averaged carbon stock data are vital for an accurate estimation of CO_2 emissions from forests under pressure of land-use change and forestry activities.

Discipline: Forestry and forest products
Additional key words: biomass, deforestation, forest degradation, REDD, tropical forest

Introduction

The stand structure of primary forest changes according to the amount and seasonal pattern of rainfall. On tropical dry land, rain forests with a high overstory establish on locations of abundant water supply; toward the drier climate, the overstory height decreases and typically, the forest type changes to semi-evergreen, deciduous, and thorn[15]. By now, a considerable part of the primary forests has been transformed to secondary forest and non-forest vegetation through wood extraction, land-use change, etc. International discussion has focused on mechanisms providing economic incentives to reduce GHG emissions from deforestation (and forest degradation) (COP 13, UNFCCC[24]) adopting a principle of sustainable forest management. Simplified, accurate methodologies for estimating GHG emissions from forests are indispensable for reliable and acceptable operation of these mechanisms. One simplified method for estimating CO_2 emissions from deforestation is the calculation of carbon stock change[7] by monitoring forest land and periodically summing up the land area and its averaged

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carbon stock for various forest types.

As a feasibility study for applying this methodology to tropical dry-land forest, we estimated the carbon stock and its chronosequential change in 4 carbon pools (aboveground and belowground biomass, deadwood, and litter) of tropical dry-land natural forests in Cambodia, using the data sets on forest measurement obtained through the project "Capacity Building for Greenhouse Gas Inventory Development in Asia-Pacific Developing Countries" and subsequent collaborative research between the Ministry of Environment, Kingdom of Cambodia and the Forestry and Forest Products Research Institute (FFPRI), Japan.

Materials and methods

1. Study sites

The study sites were located throughout the region of Cambodia (Fig. 1). Cambodia has a tropical monsoon climate, with a pronounced rainy season from June to October and a dry season from November to May. Evergreen and deciduous are the main types of forest on the dry land in Cambodia[5]. The mean annual temperature range is about 26.5–30.0°C. The main geology[4] is sandy alluvium, shale and other impermeable rock, sandstone and conglomerate on hilly regions and clayey and silty alluvium on lowlands. Mean annual precipitation depends on the region and ranges from about 1,000 mm to over 3,000 mm (Table 1a). Elevation of the research plots (see below) ranges from 23.1 to 688 m (Table 1a). Values of site index were determined by us based on soil type and geology information[4]. Soil is considered to be fertile when the index value is large.

2. Plot establishment and monitoring vegetative growth

In February-April 2005, 4 evergreen forests (Plots G, H, K, and L), 4 deciduous forests (Plots E, F, I, and J), and 4 secondary forests (Plots A, B, C, and D) were selected for research plots (Table 1a). The secondary forests were considered to have originated from primary evergreen and/or deciduous forests. For each selected location, 2 plots were set up by running 20 × 100-m and 5 × 40-m lines through the area and then sampling the trees (including dead standing ones) larger than 30 cm in the 20 × 100-m plot and those between 5 and 30 cm in diameter in the 5× 40-m plot.

For each tree, the vernacular name was recorded for translation to the botanic name using the nomenclature published for Cambodian plants[21]. Stem diameter at 1.3 m high was measured using a measuring tape (DBH), except in the case of trunk irregularities at that height or branching below that height.

Tree height was also measured using a handheld compass (Suunto).

For woody debris on the ground (dead trees on the

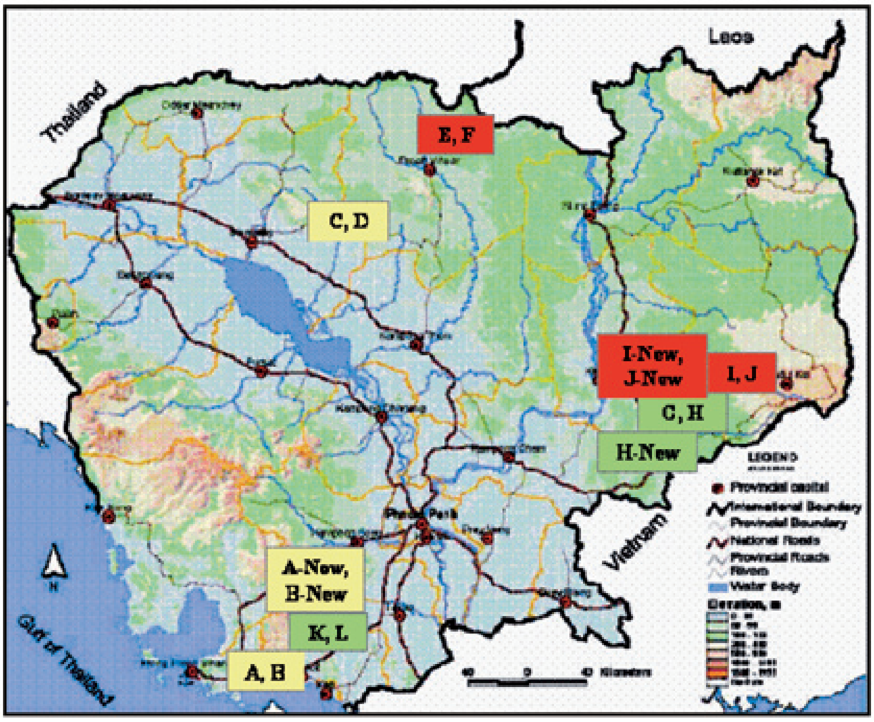

Fig. 1. General map of the study site

A, B, C, D, A-New, and B-New: Plots for secondary forest. E, F, I, J, I-New, and J-New: Plots for deciduous forest. G, H, K, L, and H-New: Plots for evergreen forest.

Table 1a. General description of the research plots

Plot*[1]	Forest type*[2]	Dominant sp.*[3]	Number of tree species*[4] 2,000m^{-2}	Soil type*[5]	Site index*[6]	Mean annual precipitation*[7] (mm)	Elevation (m)	Observation period (year)
A	SF	Eu	13	CC	1.5	3149	29	2005-06
B	SF	At	24	CC	1.5	3149	31	2005-06
A-New	SF	So	11	Ch	2	1022	128	2008-
B-New	SF	So	12	Ch	2	1022	163	2008-
C	SF	Dd	1	Rp	3	1311	23	2005-
D	SF	Dd	1	Rp	3	1311	28	2005-
E	DF	Di	19	Re	3	1987	76	2005-
F	DF	So	14	Re	3	1987	73	2005-
I	DF	Dt	10	Ph	1	1287	68	2005-06
J	DF	Dt	13	Ph	1	1287	69	2005-06
I-New	DF	Dt	7	Al	1	1547	69	2008-
J-New	DF	Tt	7	Al	1	1547	69	2008-
G	EF	Im	22	Pl	2	1298	111	2005-
H	EF	Im	18	Pl	2	1298	89	2005-06
K	EF	Le	18	Pp	2	2074	688	2005-
L	EF	Sl	13	Pp	2	2074	675	2005-
H-New	EF	Dd	19	Re	3	1473	127	2008-

*[1] Position (UTM) and location are A: 1168107.8, 351684.6, Sihanoukville (Ream NP), B: 1168375.5, 352015.8, Sihanoukville (Ream NP), A-New: 1250682, 405467, Kampong Speu (Kirirum NP), B-New: 1250660, 405371, Kampong Speu (Kirirum NP), C: 1476884.4, 390628, Siem Reap (Kulen Prumtep NP), D: 1476720.9, 390468.5, Siem Reap (Kulen Prumtep NP), E: 1539264, 376034.5, Preah Vihear (Wildlife sanctuary), F: 1539441.5, 375941.7, Preah Vihear (Wildlife sanctuary), I: 1347309.3, 660629.8, J: 1347387.2, 660707.4, Kratie -Snoul (Wildlife sanctuary), I-New: 1427696, 629792, Kratie-Sandan (Forestry Administration Area), J-New: 1427654, 629694, Kratie-Sandan (Forestry Administration Area), G: 1341968, 666565.3, Kratie -Snoul (Wildlife sanctuary), H: 1341900.4, 666344.4, Kratie -Snoul (Wildlife sanctuary), K: 1175466.1, 400830.7, Kampot (Bokor NP), L: 1175544.8, 401002.9, Kampot (Bokor NP), H-New: 1339300, 667775, Kratie -Snoul (Wildlife sanctuary).

*[2] SF: secondary forest, DF: deciduous forest, EF: evergreen forest.

*[3] Eu: *Eugenia* sp., At: *Albizia thorelli*, So: *Shorea obtusa*, Dd: *Dipterocarpus dyeri*, Di: *Dipterocarpus intricatus*, Dt: *Dipterocarpus tuberculatus*, Tt: *Terminalia tomentosa*, Im: *Irvingia malayana*, Le: *Lithocarpus elephantum*, Sl: *Syzygium lineatum*.

*[4] In 2005 for Plots A-L and 2008 for Plots A-New, B-New, I-New, J-New, H-New.

*[5] Crocker (1962). CC: Coastal Complex, Ch: Cultural hydromorphics, Rp: Red-yellow podzols, Re: Regrus, Ph: Plinthic hydromorphics, Al: Acid lithosols, Pl: Planosols, Pp: Plinthic podzols.

*[6] Values were determined based on soil type and geology information in Crocker (1962). Soil is considered to be fertile when the index value is large.

*[7] In 2002. Data sourse: National Institute for Agro-Environmental Sciences, Japan.

ground and stumps) having a diameter > 5 cm and length > 0.5 m, diameter and length were measured in the 5 × 40-m plot for estimating volume.

Understory (trees less than 5 cm in DBH and herbaceous plants, only aboveground) was harvested in five 0.5 × 0.5-m quadrates randomly set in the 5 × 40-m plot.

In the same quadrates, coarse litter (woody debris < 5 cm in diameter and/or < 50 cm in length, undecomposed plant material or crop residue, all unburned leaves and branches) was collected. Fine litter (dark colored litter, including all woody roots that had partly decomposed) in a 0–5 cm soil layer was also collected and sorted with a 2-mm mesh sieve. The total fresh samples of understory and coarse and fine litter were weighed and then a set of fresh composite subsamples was immediately taken for weighing and subsequent air-drying by sunlight. The weight of each sample was checked regularly until it became constant. The air-dried samples were brought to the laboratory for oven-drying. Samples were dried in an oven at 70°C for at least 72 h.

In January-February 2006, field measurement was carried out again except for tree height. In February-March 2008, field measurement was conducted again. However, five plots i.e. in 1 evergreen (Plot H), 2 deciduous (I, J), and secondary (A, B) forests were mostly destroyed due to land-use conversion during the period from January-February 2006 to February-March 2008, and one other plot of deciduous forest (Plot E) was damaged by selective heavy logging. Thus, only 6 (Plots C, D, F, G, K, and L) of the 12 plots were left free from intensive human intervention during 2005–2008. We set 5 new plots: one for evergreen forest (H-New), two for deciduous forest (I-New, J-New), and two for secondary forest (A-New and B-New) in February-March 2008.

3. Estimating carbon stock

Measurement in the research plots consists of two parts. One is non-destructive sampling of trees, including stem DBH, tree height, and species, as well as deadwood, while the other is destructive sampling of litter and undergrowth. Biomass consists of tree and understory. Deadwood consists of dead standing trees, fallen deadwood, stumps, etc. The weight of trees and deadwood and subsequent carbon amount were estimated from the diameter and basic density[8] using the following allometric equations (modified from Kiyono et al. (2006)[12] based on 66 species and 509 trees in the tropics and subtropics[1,2,6,9-10,13-14,16-18,22-23]) and conversion factors. Use of basic density can improve the accuracy of estimates[12,20].

$$W_l = 173\ ba\text{^}0.938 \quad (n = 509,\ R^2 = 0.780,\ P < 0.001) \cdots\cdots\cdots\cdots(1)$$

$$W_b = 0.217\ ba\text{^}1.26\ D\text{^}1.48 \quad (n = 509,\ R^2 = 0.910,\ P < 0.001) \cdots\cdots\cdots\cdots(2)$$

$$W_s = 2.69\ ba\text{^}1.29\ D\text{^}1.35 \quad (n = 509,\ R^2 = 0.971,\ P < 0.001) \cdots\cdots\cdots\cdots(3)$$

$$W_r = 0.500\ ba\text{^}1.20\ D\text{^}1.33 \quad (n = 509,\ R^2 = 0.943,\ P < 0.001) \cdots\cdots\cdots\cdots(4)$$

where W_l is leaf weight (kg), W_b is branch weight (kg), W_s is stem weight (kg), W_r is root weight (kg), ba is the basal area of a stem at 1.3 m height (m^2), and D is the basic density of stem wood (kg m^{-3}). Following the methodologies by CDM Executive Board (e.g. AR-AMS0004/Version[3]), D values were chosen with priority from (a) to (b) preference as follows: (a) species-specific or group of species-specific from neighboring countries with similar conditions (Laos[11], Indonesia[12]), (b) globally species-specific or group of species-specific[8].

Values of tree biomass were summed up for stand biomass (biomass per unit land area). For woody debris on the ground and stumps, the basic density of 450 kg m^{-3} (values from Laos in Kiyono et al.[11]) was used in the conversion of volume to carbon weight.

$$Wd = 0.45\ Vd$$

where W_d is weight of deadwood (Mg) and V_d is volume of woody debris on the ground and stumps (m^3).

The value of litter stock in the dry season was tentatively used as the annual mean value in this study. As litter stock is usually larger in the dry season than in the rainy season in the tropics[11], the litter stock in this study is probably overestimated (litter stock in the rainy season is under measurement by us). Assuming that carbon fractions account for 0.50 of the biomass and deadwood stock and 0.37 of the litter stock[7], the carbon stock in the 4 carbon pools (aboveground biomass, belowground biomass, deadwood, and litter) was summed for each plot. Using the data collected in the 17 research plots, we estimated the carbon stock in biomass, deadwood, and litter for 2005, 2006 and 2008 and then calculated the increments per year (Table 1a–d).

4. Estimating number of sample plots for carbon stock measurements for main types of forest in Cambodia

UNFCCC provided the methodological tool of AR-CDM "Calculation of the number of sample plots for measurements within A/R CDM project activities" (http://cdm.unfccc.int/Reference/tools/ar/methAR_tool03_v01.pdf). This tool is applicable if sample plots are used for monitoring purposes and estimates the number of permanent sample plots needed for monitoring changes in carbon pools at a desired precision level and the costs of establishment of the sample plots (Equation (5)). Using this tool, we estimated reasonable number of sampling plots for evergreen and deciduous forests in Cambodia. The costs of establishment of a sample plot for each type of forest were approximated based on the costs in plot establishment in 2005 and others (approximately 800 USD for an evergreen forest plot and 700 USD for a deciduous forest plot).

$$n = [\sum_{i=1}^{L} N_i\ st_i\ C_i^{0.5}]\ [\sum_{i=1}^{L} N_i\ st_i\ C_i^{-0.5}]\ /\ ([NE_1\ /\ z]^2 + \sum_{i=1}^{L} N_i\ (st_i)^2) \cdots\cdots\cdots\cdots\cdots\cdots(5)$$

where n is total number of sample plots required for evergreen and deciduous forests in Cambodia; L is total number of strata, dimensionless (2 in this study); i is index of stratum, dimensionless; N_i is A_i/AP, maximum possible number of sample plots in stratum i; A_i is size of each stratum i, ha (approximately 3,668,902 ha for evergreen and 4,692,098 ha for deciduous forest cover in 2006[5] in this study); AP is sample plot size (constant for all strata), ha (0.2 ha in this study); st_i is standard deviation for each stratum i, dimensionless; C_i is cost of establishment of a sample plot for each stratum i (800 USD for an evergreen forest plot and 700 USD for deciduous forest plot in this study); E_1 is $Q1\ p$; $Q1$ is approximate average value of the estimated quantity of carbon stock in the 4 pools, Mg C ha^{-1}; p is desired level of precision (10% in this study), dimensionless; and z is value of the statistic z (1.9599 in this study implying a 95% confidence level).

Number of sample plots for each stratum was estimated by the following equation (6). The data on costs may be approximated but shall be reflected in relative differences of costs among strata (UNFCCC http://cdm.unfccc.int/Reference/tools/ar/methAR_tool03_v01.pdf).

$$\mathrm{n}_i = [\sum_{i=1}^{L} N_i\, st_i\, C_i^{0.5}]\, N_i\, st_i\, /\, ([NE_1\, /\, z]^2 + \sum_{i=1}^{L} N_i\, (st_i)^2) \qquad \cdots\cdots\cdots\cdots(6)$$

where n_i = number of sample plots required for strata *i*.

Results and discussion

1. Tree floristic composition

Tree flora differed among forest types. Evergreen and deciduous forests differed greatly in dominant species (Table 1a) as well as in some subdominant species. *Memecylon edule*, *Dehaasia cuneata*, and *Syzygium lineatum* are usually found in evergreen forests. *Shorea obtusa*, *Terminalia tomentosa*, *T. mucronata*, *Dipterocarpus tuberculatus*, *Pentacme siamensis*, and *Xylia dolabriformis* are considered as component species of deciduous forests. Studied secondary forests were considered to have originated from evergreen and/or deciduous forests. Some secondary forests contained tree species of evergreen forest as well as deciduous forest and were seemingly complex. Secondary forests sometimes contained pioneer trees such as *Albizia thorelli* and *Anthocephalus chinensis*, while in some other secondary forests, climax or late successional tree species, e.g., *Dipterocarpus dyeri*, formed relatively young pure colonies. The number of tree species found in the plot with 2,000 m^2 of land area (Table 1a) ranged from 13 to 22 and averaged 18 ± 13 (SD) in evergreen forests, which was significantly ($P = 0.030$) larger than that in deciduous forests (7 to 19, 12 ± 5 (SD)). The number of tree species in secondary forests differed greatly (1 to 24) and the averaged value (10 ± 9 (SD)) was not significantly different from that of evergreen and deciduous forests ($P = 0.095$, 0.745, respectively).

2. Carbon stock

(1) Tree biomass

The tree biomass (Mg ha^{-1}; values in 2006 were used and for plots newly established, values in 2008 were used) significantly differed among forest types ($P < 0.025$) and averaged 391.7 ± 68.0 (SD) in evergreen forests (n = 5), 257.8 ± 92.0 (SD) in deciduous forests (n = 6), and 135.7 ± 57.1 (SD) in secondary forests (n = 6), respectively.

(2) Understory biomass

Understory biomass was less (Table 1b–d) in deciduous forests than in evergreen secondary forests. As deciduous forests are prone to catching fire in the dry season, understory plants show inhibited growth.

(3) Deadwood stock

The amount of deadwood was greater in evergreen forests than in the other forest types (Table 1b–d). However, a deciduous forest selectively heavily logged has a large amount of deadwood. Two possible reasons why the evergreen forests have more deadwood than the other forests are 1) deciduous forests are prone to catching fire and deadwood is likely to burn away and 2) in secondary forests, the stems are still young and not likely to die. However, logging can increase the amount of deadwood. The relationship between deadwood stock and tree biomass was not significant in 2005 ($P = 0.111$), while it became significant in 2008 ($P = 0.011$). The weight of deadwood stock significantly increased with time since the last slash-and-burn cropping and the carbon stock in a community's deadwood was related to the overstory height in plant communities in slash-and-burn fallow in Laos[11]. Therefore, deadwood stock is considered to be macroscopically proportional to biomass. As very little work has been done on woody debris during tropical succession[19], further study is required to refine the general relationship between deadwood stock and other stand structural parameters.

(4) Litter stock

Litter stock ranged 12.6 to 40.1 Mg ha^{-1} among the plots and averaged around 20 to 30 Mg ha^{-1} in each forest type. No special tendencies were found in the litter stock among forest types.

(5) The 4 carbon pools

The sum of carbon stock (Mg C ha^{-1}) in tree biomass, understory biomass, deadwood, and litter differed significantly among forest types ($P < 0.016$) and averaged 223.6 ± 35.7 (SD) in evergreen forests (n = 5), 144.4 ± 45.6 (SD) in deciduous forests (n = 6), and 82.9 ± 25.7 (SD) in secondary forests (n = 6) (data in 2006 was used and for newly established plots, data in 2008 was used). Among the 4 carbon pools, most of the carbon stock existed in the tree biomass pool (40–93%, mean 84 ± 12% (SD)).

3. Chronosequential changes in tree and understory biomass, deadwood and litter stock, and total carbon stock in the 4 carbon pools

Tree biomass: Among the less disturbed forests in Plots C–F, K and L, the growth of tree biomass in 2005–2006 was in direct proportion to the tree biomass in 2005 for each forest type and among the forest types (Fig. 2). The relationship between tree biomass in 2006 and tree biomass growth for 2006–2008 did not differ significantly from the relationship in Fig. 2. Tree biomass decreased considerably in Plot E where intensive selective logging was carried out.

Deadwood: Increment of deadwood stock did not differ significantly between 2005–2006 and 2006–2008 except that the deadwood stock clearly increased in forests where a high number of overstory trees were harvested (Plot E) or died for

Table 1b. Values for February-April 2005

February-April 2005

Plot	DBH*[8]	Height*[8]	BA	Tree biomass				
	Top 20% (cm)	Top 20% (m)	(m^2 ha^{-1})	Leaf (Mg ha^{-1})	Branch (Mg ha^{-1})	Stem (Mg ha^{-1})	Root (Mg ha^{-1})	Subtotal (Mg ha^{-1})
A	59.5	20.3	12.4	2.8	16.9	82.6	17.5	119.8
B	7.1	7.2	5.7	1.4	3.5	15.8	4.3	25.0
A-New								
B-New								
C	37.7	19.0	20.9	4.7	26.7	130.3	28.6	190.3
D	20.3	14.3	18.4	4.1	18.8	90.1	21.0	134.0
E	63.0	24.5	36.8	7.6	57.1	284.5	57.8	407.1
F	57.2	20.7	28.5	5.9	46.3	228.6	46.8	327.5
I	47.7	15.5	16.4	3.4	24.7	123.2	25.2	176.6
J	54.0	16.7	12.1	2.4	22.7	114.4	22.2	161.6
I-New								
J-New								
G	49.3	26.8	31.3	6.7	38.8	190.8	41.1	277.4
H	66.0	28.8	38.9	8.0	61.4	305.7	62.1	437.3
K	64.1	33.0	37.0	7.5	66.7	333.9	65.8	473.9
L	59.5	33.0	36.7	8.4	65.7	325.7	66.2	465.9
H-New								
Mean (SF)*[2]	31.1	15.2	14.3	3.3	16.5	79.7	17.9	117.3
Mean (DF)*[2]	55.5	19.3	23.5	4.8	37.7	187.7	38.0	268.2
Mean (EF)*[2]	59.7	30.4	36.0	7.6	58.2	289.0	58.8	413.6

Plot	Understory biomass	Deadwood stock			Litter stock			Carbon stock
	Aboveground (Mg ha^{-1})	Standing (Mg ha^{-1})	Fallen (Mg ha^{-1})	Subtotal (Mg ha^{-1})	Dry season (Mg ha^{-1})	Rainy season (Mg ha^{-1})	Mean (Mg ha^{-1})	(Mg C ha^{-1})
A	12.2	0.0	1.0	1.0	15.1	n/a	15.1	66.0
B	19.4	0.0	12.9	12.9	27.9	n/a	27.9	29.3
A-New								
B-New								
C	15.0	0.0	0.0	0.0	32.6	n/a	32.6	107.2
D	20.4	0.0	0.0	0.0	16.3	n/a	16.3	73.1
E	0.0	0.0	3.8	3.8	22.3	n/a	22.3	213.7
F	8.6	0.0	1.1	1.1	32.4	n/a	32.4	176.3
I	7.6	0.0	0.4	0.4	21.0	n/a	21.0	96.3
J	15.5	0.0	5.4	5.4	20.9	n/a	20.9	91.2
I-New								
J-New								
G	36.4	0.0	4.4	4.4	15.1	n/a	15.1	146.5
H	16.2	0.0	5.8	5.8	19.4	n/a	19.4	228.7
K	20.5	0.0	39.0	39.0	27.4	n/a	27.4	266.5
L	31.3	0.0	15.8	15.8	22.3	n/a	22.3	249.1
H-New								
Mean (SF)*[2]	16.7	0.0	3.5	3.5	23.0		23.0	68.9
Mean (DF)*[2]	7.9	0.0	2.7	2.7	24.2		24.2	144.4
Mean (EF)*[2]	26.1	0.0	16.2	16.2	21.1		21.1	222.7

*[2] SF: secondary forest, DF: deciduous forest, EF: evergreen forest.

*[8] Calculated using trees of the top 20% of the forest for DBH and tree height respectively.

Table 1c. Values for January-February 2006

January-February 2006

Plot	DBH*[8]	Height*[8]	BA	Tree biomass				
	Top 20% (cm)	Top 20% (m)	(m^2 ha^{-1})	Leaf (Mg ha^{-1})	Branch (Mg ha^{-1})	Stem (Mg ha^{-1})	Root (Mg ha^{-1})	Subtotal (Mg ha^{-1})
A	60.1	n/a	13.4	3.0	18.1	88.4	18.8	128.4
B	7.6	n/a	6.5	1.6	4.1	18.8	5.1	29.6
A-New								
B-New								
C	39.2	n/a	21.5	4.9	27.7	135.6	29.7	197.9
D	20.6	n/a	19.1	4.2	19.6	94.1	21.8	139.8
E	63.2	n/a	37.9	7.8	59.0	293.6	59.6	414.8
F	57.3	n/a	29.5	6.1	48.1	237.7	48.5	340.4
I	48.4	n/a	17.2	3.5	26.2	130.7	26.7	187.1
J	54.9	n/a	12.4	2.4	23.4	118.5	22.9	167.3
I-New								
J-New								
G	50.3	n/a	32.8	7.0	41.0	201.6	43.3	292.9
H	66.7	n/a	40.8	8.4	64.9	322.7	65.5	461.4
K	64.4	n/a	38.6	7.8	69.7	349.0	68.7	495.2
L	59.9	n/a	38.6	8.8	68.9	341.9	69.5	489.2
H-New								
Mean (SF)*[2]	31.8		15.1	3.4	17.4	84.2	18.9	123.9
Mean (DF)*[2]	56.0		24.3	5.0	39.2	195.1	39.4	277.4
Mean (EF)*[2]	60.3		37.7	8.0	61.1	303.8	61.8	434.7

Plot	Understory biomass	Deadwood stock			Litter stock			Carbon stock
	Aboveground (Mg ha^{-1})	Standing (Mg ha^{-1})	Fallen (Mg ha^{-1})	Subtotal (Mg ha^{-1})	Dry season (Mg ha^{-1})	Rainy season (Mg ha^{-1})	Mean (Mg ha^{-1})	(Mg C ha^{-1})
A	13.7	0.0	0.7	0.7	15.8	n/a	15.8	70.4
B	18.4	0.0	6.4	6.4	26.9	n/a	26.9	28.0
A-New								
B-New								
C	18.0	0.0	0.0	0.0	12.6	n/a	12.6	103.6
D	10.2	0.0	0.0	0.0	20.1	n/a	20.1	77.3
E	5.0	0.0	2.3	2.3	42.5	n/a	42.5	224.3
F	6.5	0.0	2.4	2.4	13.3	n/a	13.3	176.3
I	11.9	0.0	0.3	0.3	40.0	n/a	40.0	108.5
J	9.4	0.0	5.1	5.1	37.1	n/a	37.1	99.9
I-New								
J-New								
G	11.9	0.0	7.4	7.4	29.5	n/a	29.5	161.1
H	16.9	0.0	5.3	5.3	19.1	n/a	19.1	240.4
K	14.4	0.0	29.8	29.8	37.4	n/a	37.4	276.4
L	11.9	0.0	11.9	11.9	41.4	n/a	41.4	265.9
H-New								
Mean (SF)*[2]	15.1	0.0	1.8	1.8	18.8		18.8	69.8
Mean (DF)*[2]	8.2	0.0	2.5	2.5	33.2		33.2	152.3
Mean (EF)*[2]	13.8	0.0	13.6	13.6	31.9		31.9	236.0

*[2] SF: secondary forest, DF: deciduous forest, EF: evergreen forest.

*[8] Calculated using trees of the top 20% of the forest for DBH and tree height respectively.

Table 1d. Values for February-March 2008

February-March 2008

Plot	DBH*8	Height*8	BA	Tree biomass				
	Top 20% (cm)	Top 20% (m)	(m^2 ha^{-1})	Leaf (Mg ha^{-1})	Branch (Mg ha^{-1})	Stem (Mg ha^{-1})	Root (Mg ha^{-1})	Subtotal (Mg ha^{-1})
A								
B								
A-New	24.3	11.6	21.6	4.8	24.8	118.4	27.1	175.1
B-New	48.4	15.5	21.1	4.7	24.3	116.6	26.4	171.9
C	41.1	20.8	27.5	5.8	34.9	171.2	36.9	248.8
D	20.8	15.1	21.3	4.7	22.3	107.4	24.7	159.2
E	47.7	23.8	31.1	6.2	41.9	206.2	43.3	297.6
F	57.5	21.7	30.5	6.3	44.7	222.9	45.6	319.6
I								
J								
I-New	50.2	31.2	31.2	6.4	48.4	239.7	49.4	344.0
J-New	46.9	18.9	21.2	4.4	33.0	162.7	33.7	233.7
G	53.0	27.8	32.5	6.9	41.5	204.6	43.7	296.6
H								
K	64.5	33.5	42.3	8.6	76.5	382.7	75.5	543.2
L	64.2	31.4	44.8	9.6	75.9	377.2	76.3	539.1
H-New	56.2	34.8	28.7	5.8	46.8	236.4	46.8	335.9
Mean (SF)*2	33.6	15.7	22.9	5.0	26.6	128.4	28.8	188.7
Mean (DF)*2	36.5	17.3	24.5	5.8	42.0	207.9	43.0	298.7
Mean (EF)*2	40.0	18.1	25.5	7.7	60.2	300.2	60.6	428.7

Plot	Understory biomass	Deadwood stock			Litter stock			Carbon stock
	Aboveground (Mg ha^{-1})	Standing (Mg ha^{-1})	Fallen (Mg ha^{-1})	Subtotal (Mg ha^{-1})	Dry season (Mg ha^{-1})	Rainy season (Mg ha^{-1})	Mean (Mg ha^{-1})	(Mg C ha^{-1})
A								
B								
A-New	4.7	0.0	0.0	0.0	45.4	n/a	45.4	104.4
B-New	6.5	0.0	0.1	0.1	17.9	n/a	17.9	92.6
C	2.4	0.0	0.0	0.0	43.9	n/a	43.9	140.7
D	7.8	0.0	0.0	0.0	42.1	n/a	42.1	95.2
E	0.0	16.0	65.4	81.4	23.2	n/a	23.2	198.1
F	9.6	0.0	4.1	4.1	26.4	n/a	26.4	171.6
I								
J								
I-New	1.9	0.0	0.1	0.1	26.0	n/a	26.0	181.7
J-New	5.3	0.0	0.1	0.1	25.0	n/a	25.0	126.1
G	7.5	0.0	1.8	1.8	43.6	n/a	43.6	165.4
H								
K	9.4	0.0	62.9	62.9	80.8	n/a	80.8	332.9
L	4.1	64.9	16.4	81.3	86.1	n/a	86.1	342.1
H-New	11.7	0.0	0.2	0.2	84.0	n/a	84.0	199.1
Mean (SF)*2	5.3	0.0	0.0	0.0	37.4		37.4	108.2
Mean (DF)*2	4.2	4.0	17.4	21.4	25.1		25.1	169.4
Mean (EF)*2	8.2	16.2	20.3	36.6	73.6		73.6	259.9

*2 SF: secondary forest, DF: deciduous forest, EF: evergreen forest.

*8 Calculated using trees of the top 20% of the forest for DBH and tree height respectively.

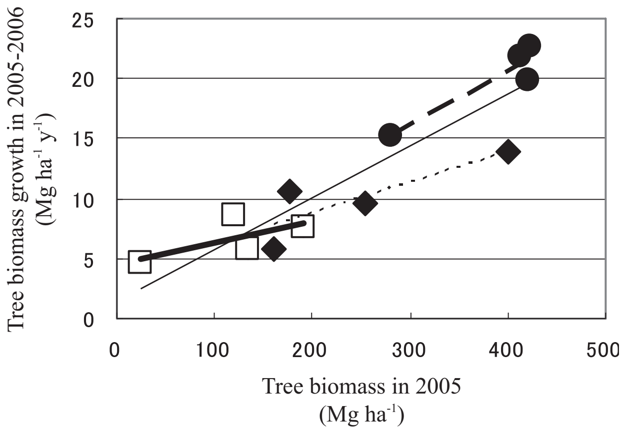

Fig. 2. Relationship between tree biomass and tree biomass growth in three types of forests in Cambodia

The thick line with □: Secondary forest, dotted line with ◆: Deciduous forest, broken line with ●: Evergreen forest. The thin line approximates the relationship for the three forest types.

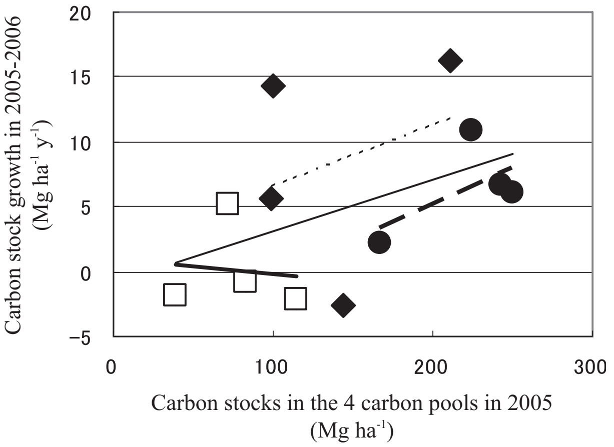

Fig. 3. Relationship between carbon stock in the 4 carbon pools and its growth in three types of forests in Cambodia

The lines and symbols are the same as Fig. 2.

Table 1e. Tree biomass growth for 2005–2008

Plot	Tree biomass growth 2005-2006 (Mg ha^{-1} y^{-1})	Tree biomass growth 2006-2008 (Mg ha^{-1} y^{-1})	Tree biomass growth 2005-2008 (Mg ha^{-1} y^{-1})	Remarks
A	8.6			Converted to non-forest in 2006-2008.
B	4.6			Converted to non-forest in 2006-2008.
A-New				
B-New				
C	7.6	25.4	19.5	
D	5.7	9.7	8.4	Lightly extracted wood in 2006-2008.
E	7.7	-58.6	-36.5	Heavily extracted wood in 2006-2008.
F	12.9	-10.4	-2.6	
I	10.5			Converted to non-forest in 2006-2008.
J	5.7			Converted to non-forest in 2006-2008.
I-New				
J-New				
G	15.5	1.9	6.4	
H	24.2			Converted to non-forest in 2006-2008.
K	21.4	24.0	23.1	
L	23.3	24.9	24.4	Some overstory trees died.
H-New				
Mean (SF)*2	6.6	17.6	13.9	
Mean (DF)*2	9.2	-34.5	-19.6	
Mean (EF)*2	21.1	16.9	18.0	

*2 SF: secondary forest, DF: deciduous forest, EF: evergreen forest.

Table 1f. Carbon stock growth in the 4 carbon pools for 2005–2008

Plot	Carbon stock growth in the 4 carbon pools			Remarks
	2005-2006 ($Mg C ha^{-1} y^{-1}$)	2006-2008 ($Mg C ha^{-1} y^{-1}$)	2005-2008 ($Mg C ha^{-1} y^{-1}$)	
A	5.1			Converted to non-forest in 2006-2008.
B	-1.8			Converted to non-forest in 2006-2008.
A-New				
B-New				
C	-2.1	14.6	9.1	
D	-0.8	8.3	5.3	Lightly extracted wood in 2006-2008.
E	13.1	-14.4	-5.2	Heavily extracted wood in 2006-2008.
F	-1.1	-1.6	-1.4	
I	14.4			Converted to non-forest in 2006-2008.
J	5.6			Converted to non-forest in 2006-2008.
I-New				
J-New				
G	2.4	1.0	1.5	
H	12.1			Converted to non-forest in 2006-2008.
K	6.8	27.0	20.3	
L	7.0	36.1	26.4	Some overstory trees died.
H-New				
Mean (SF)*[2]	0.1	11.5	7.2	
Mean (DF)*[2]	8.0	-8.0	-3.3	
Mean (EF)*[2]	7.1	21.4	16.1	

*[2] SF: secondary forest, DF: deciduous forest, EF: evergreen forest.

unknown reasons (Plot L).

Litter: No special chronosequential tendencies were found in the litter stock.

Carbon stock in the 4 carbon pools: Among the less disturbed forests in Plots C, D, F, K, and L, the increase in the sum of carbon stock in 4 carbon pools (tree biomass understory biomass, deadwood, and litter) in 2005–2006 has positive relationships to the carbon stock in 2005 for each forest type and among the forest types (Fig. 3). By comparison to tree biomass, the relationship shows a larger deviation and is not necessarily clear. Among the less disturbed forests in Plots C, D, F, K, and L, the relationship between carbon stock in 2006 and carbon stock growth for 2006–2008 did not differ significantly from the relationship in Fig. 3. In Plot E where intensive selective logging was carried out, the increase in deadwood balanced the decrease in tree biomass to some extent in the carbon stock of the 4 carbon pools.

Figures 2 and 3 suggest that the severe wood extraction itself causes direct loss of carbon stock and the subsequent decline in carbon stock results in reduced carbon stock growth. Its mechanism is not yet clear but one possible reason is the decrease in leaf biomass because tree leaf biomass can have significant positive relationship to biomass growth (see the next paragraph).

4. Influence of environmental factors on growth of tree biomass and the total carbon stock in the 4 carbon pools

Tree biomass growth ($Mg ha^{-1} y^{-1}$) in 2005–2006 and 2006–2008 ranged from 2.3 to 25.4 and growth of carbon stock in the 4 carbon pools ($Mg C ha^{-1} y^{-1}$) ranged from –2.7 to 26.2 for the Plots A–L that were less disturbed (Table 1e, f). Such values of growth in 2005–2006, using a relatively abundant number of samples, showed no significant relationship with site index or annual precipitation (Data source: National Institute for Agro-Environmental Sciences, Japan) or elevation (Table 1a). Leaf biomass appeared to have a positive relationship to tree biomass growth ($P = 0.00011$), while such a significant relationship was not found with the carbon stock in the 4 carbon pools ($P = 0.28$). As for forest types, evergreen forests grew more quickly than the other forest types ($P < 0.006$) in tree biomass, while for carbon stock in the 4 carbon pools, evergreen forests grew more quickly than the secondary forest ($P < 0.041$) (Table 1e, f).

5. Number of sample plots for carbon stock measurements for main types of forest in Cambodia

Estimated total number of sample plots required for evergreen and deciduous forests in Cambodia was 25.8; 10.8 for evergreen forest and 15.0 for deciduous forest. Because both values of standard deviation and costs did not differ much between evergreen and deciduous forests, the estimated number of sample plots for each forest type depended on area of forest cover[5]. Number of existing plots of evergreen and deciduous forests is only four for each in 2008 (Table 1d). At least an additional seven plots of evergreen forest and eleven plots of deciduous forest should be established with systematical locations in Cambodia for the desired precision in carbon stock estimation. The minimum cost of setting additional plots was estimated at 13,300 (800 × 7 +700 × 11) USD.

Conclusions

This study suggests that carbon stock differs among forest types, most of the carbon stock exists in tree biomass, and growth of carbon stock has a positive relationship to the carbon stock itself in the forests of Cambodia. By moderately classifying forest types, determining averaged tree biomass of each forest type, and using land-area data on each forest type, a reasonably accurate estimation of carbon stock can be expected. Thus, this methodology will contribute to sustainable forest management in Cambodia. However, considering the fact that half the forests in the research plots were destroyed or heavily logged and declining carbon stock occurred during only 3 years of observation, systematic sampling with a sufficient number of extra plots and frequent updating of forest land area and averaged carbon stock data are vital for accurate estimation of CO_2 emissions from forests under pressure of land-use change and heavy wood extraction.

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