Forest carbon budgets in Southeast Asia following harvesting and land cover change

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Abstract Terrestrial ecosystems play an important role in the global carbon (C) cycle. Tropical forests in Southeast Asia are constantly changing as a result of harvesting and conversion to other land cover. As a result of these changes, research on C budgets of forest ecosystems has intensified in the region over the last few years. This paper reviews and synthesizes the available information. Natural forests in SE Asia typically contain a high C density (up to 500 Mg/ha). Logging activities are responsible for at least 50% decline in forest C density. Complete deforestation (conversion from forest to grassland or annual crops) results in C density of less than 40 Mg/ha. Conversion to tree plantations and other woody perennial crops also reduces C density to less than 50% of the original C forest stocks. While much information has been generated recently, there are still large gaps of information on C budgets of tropical forests and its conversion to other land uses in SE Asia. There is therefore a need to intensify research in this area.

Keywords: carbon budgets, tropical forests, Southeast Asia, land cover change.

There is considerable interest in the role of terrestrial ecosystems in the global carbon (C) cycle. It is estimated that about 60 Pg[1)] C is exchanged between terrestrial ecosystems and the atmosphere every year, with a net terrestrial uptake of (0.7 ± 1.0) Pg C[1]. The world's tropical forests which cover 17.6×10^6 km^2 containing 428 Pg C in vegetation and soils[2]. However, land use change and forestry (LUCF) activities, mainly tropical deforestation, are significant net sources of CO_2, accounting for 1.6 Pg/a out of the total anthropogenic emissions of 6.3 Pg/a[2,3]. Therefore, tropical forests have the largest potential to mitigate climate change amongst the world's forests through conservation of the existing C pools (e.g. reduced impact logging), expansion of C sinks (e.g. reforestation, agroforestry), and substitution of wood products for fossil fuels[4]. In tropical Asia, it is also estimated that forestation, agroforestry, regeneration and avoided deforestation activities have the potential to sequester 7.50, 2.03, 3.8—7.7 and 3.3—5.8 Pg C between 1995—2050[4].

During the last few decades massive deforestation has taken place and land use/cover change in the tropics and Southeast Asia has been no exception. In fact, tropical deforestation is the dominant land use change in the tropics[5]. Deforestation rates in tropical Asia were estimated to be 2.0×10^6 ha in 1980 and 3.9×10^6 ha during 1981—1990[6]. In Southeast Asia, the 1990 annual

1) 1 Pg= 10^{15} g; 1 Tg= 10^{12} g; 1 Mg = 10^6 g= 1 ton.

deforestation rate was about 2.6×10^6 ha/a[7].

In spite of their importance to the C cycle, there is little information on the effects of land use change and management activities on the C budgets of forest ecosystems in the tropics. For example, one of the major researches needs to be identified in the Second Assessment Report of the IPCC is how different silvicultural and other management practices would affect the C dynamics in forests[4]. In the last few years, the research on C stocks and dynamics in forest ecosystems in Southeast Asia has been intensified and new data have been generated[8,9]. This paper attempts to review the available information on C budgets of forest ecosystems in Southeast Asia in response to land use change and management activities such as harvesting and deforestation.

1 Carbon budgets following logging operations in natural forests

1.1 Carbon stocks of natural forests in Southeast Asia

Using GIS, Brown et al.[10] estimated that in 1980 the average C density of tropical forests in Asia was 144 Mg C/ha in biomass and 148 Mg C/ha in soils (up to 100 cm), which corresponds to total estimates of 42 and 43 Pg C for the whole continent, respectively. It was noted that C densities and pools in vegetation and soil varied widely by ecofloristic zone and country. Actual biomass C densities range from less than 50 to more than 360 Mg C/ha with most forests having 100—200 Mg C/ha.

A similar study[11] reported an average maximum aboveground biomass C stock in forest lands in tropical Asia of 185 Mg C/ha with a range of 25 to more than 300 Mg C/ha. Palm et al.[12], as reported by Houghton[13], showed that the forests in tropical Asia have C densities between 40—250 Mg/ha and 50—120 Mg/ha in vegetation and soils, respectively. Southeast Asian forests have an aboveground biomass range of 50—430 Mg/ha (25—215 Mg C/ha) and >350—400 Mg/ha (175—200 Mg C/ha) before human incursion[14]. For national GHG inventories, the IPCC[15] recommends a biomass density default value of 275 Mg/ha (or 138 Mg C/ha) for wet forests in Asia.

There are limited data on C densities of natural forests in the specific Southeast Asian countries. Indonesian forests have been estimated to have a C density ranging from 161—300 Mg C/ha in aboveground biomass[16], 150—254 Mg C/ha in above ground biomass and upper 30 cm of soil[17] and 390 Mg C/ha in above ground biomass and below ground pools[18]. Recent studies showed that Philippine natural forests contain 86—201 Mg C per ha in aboveground biomass[19,20]. The IPCC Revised Guidelines[15] estimates that old-growth forests in the Philippines contain 370—520 Mg/ha of aboveground biomass equivalent to about 185—260 Mg C/ha at 50% C content.

For Thailand, various forest types have a C density in aboveground biomass ranging from 72 to 182 Mg/ha[21]. Malaysian forests have C density ranging from 100 to 160 Mg/ha and from 90 to 780 Mg/ha in vegetation and soils, respectively[22] Cairns et al.[23], citing various sources, reported that mature lowland forests have aboveground biomass and root density of 431 and 43 Mg/ha, respectively, being equivalent to 216 and 22 Mg C/ha, respectively.

1.2 Carbon budgets after logging operations

Natural forests in the Southeast Asian region have been one of the world's foremost sources of tropical hardwoods.

Timber harvesting leads to a reduction of C stocks in the forest as biomass is reduced by the extraction of wood. C is released upon the decomposition or burning of slash and litter. However, regenerating trees sequester C back to biomass over time. In general, the biomass and C of tropical forests in Asia decline by 22%—67% after logging (table 1).

Table 1 Aboveground carbon density after logging of Asian and Indonesian forests

Forest type and region/country	Biomass C density/Mg • ha^{-1}		Original C (%)	Source
	undisturbed	logged		
Closed-broadleaf/Asia	98.2*	46.6*	47	[24]
Closed-conifer/Asia	72.5*	56.3*	78	[24]
Open forest/Asia	39.5*	13.2*	33	[24]
Indonesia	390	148.2	38	[18]
Indonesia	254	150	59	[17]
Indonesia	325	245	75	[16]

*Calculated from biomass data by assuming 50% C content.

In the Philippines, Lasco et al.[25] studied the C density of logged-over forest plots with varying ages after logging. Right after logging, C density declined by about 50% of the C density of a mature forest (198 Mg C/ha). There was no other similar study in the other Southeast Asian countries which tracks the decline of C density after logging. However, measurements have been taken on the logged-over forests which could be compared to the primary forests in those countries. In Indonesia, estimates of C density of logged-over forests range from 38%—75% of the original forest (table 1).

In summary, logging is typically a very destructive practice with regard to the preservation of ecosystem C stocks. In addition, extracting 8—15 trees (80 m^3; ca. 22 Mg C/ha) in Malaysian forest damaged as many as 50% of the remaining trees[26]. Out of the initial 348 Mg C/ha, 95 Mg C/ha are transformed to necromass which is eventually converted into CO_2 and released to the atmosphere via decomposition. In the Philippines, for every tree cut greater than 75 cm dbh, 1.5 or 2.6 trees are damaged in favorable and unfavorable conditions, respectively[27].

However, logging damage, and therefore C losses could be significantly reduced by directional felling and well-planned skid trails[26]. These practices are collectively known as reduced impact logging (RIL). In Sabah, Malaysia, Pinard and Putz[28,29] have reported that about one year after logging, the forest areas logged conventionally and under RIL contained 44% and 67% of their pre-logging biomass, respectively. The C density of RIL was 88 Mg C/ha higher than conventional logging. In addition, because of lower damage, there were 86 Mg C/ha less necromass in

RIL compared to conventional logging which will translate to lower CO_2 emissions from decomposition.

2 Carbon budgets following conversion from forest to non-forest cover

2.1 Impacts of deforestation on carbon budgets

To the author's knowledge, there are no studies that directly follow the changes in the C budget through the deforestation process. However, there are studies that have quantified the C stocks in the deforested lands, typically covered with grasslands or annual crops. For instance, in Indonesia, various reports show that aboveground C density in grasslands and shifting cultivation areas is less than 40 Mg C/ha (table 2). In the Philippines, grassland and crop lands contain 3.1—13.1 Mg C/ha in aboveground biomass. In both countries, these are vastly lower than the C density of the natural forests they replaced.

Table 2 Aboveground biomass density of grasslands and annual crops in Indonesia and the Philippines

Land cover	AGB carbon density /Mg • ha^{-1}	Reference
Indonesia		
Chromolaena sp.	4	[30]
Imperata sp.	1.9	[31]
Cassava	1.7	
Cassava/*imperata* sp.	74	[17]
Upland rice/bush fallow rotation	39	
Cultivated agricultural lands	5	[16]
Shifting cultivation	15—50	
Grasslands	15—20	
Grasslands	6.0	[32]
Philippines		
Imperata sp.	8.5	[19]
Sacharrum sp.	13.1	
Rice	3.1	
Sugarcane	12.5	
Banana	5.7	
Imperata sp.	1.7	biomass from ref. [33]; converted to C

2.2 Conversion to tree plantations and perennials crops

After commercial logging, natural forest areas usually can be converted to plantations of forest trees or perennial crops. This land-use change also results in reduced C stocks. By comparing the C stocks of the resulting land use with the C stocks of a natural forest we can provide a first calculation of the magnitude of change. In Indonesia, oil palm and coffee plantations have C stocks that are 6%—31% lower than natural forests (table 3)[30]. Agroforestry and plantation farms have C stocks that are 4%—27% lower than an undisturbed forest[18]. These data also show how C stocks vary with the age of rubber plantation, with older rubber agroforests having almost seven times more C than a 5-a old plantation. In a lowland peneplein in Indonesia, rubber and oil palm plantations are estimated to contain 36%—46% of the C of the natural forest[17], and other land cover types are estimated to contain only 14%—63% of that in natural forests.

Table 3 C density of various land cover in Indonesia

Land cover	C density	Natural forest (%)*	Carbon pools measured	Source of data
Oil-palm (10 a)	62	19	aboveground biomass	[30]
Oil-palm (10 a)	31	10		
Oil-palm (14 a)	101	31		
Oil-palm (19 a)	96	30		
Coffee	18	6		
Natural forest	325	–		
Mature agroforest (rubber jungle)	104	27	aboveground and below ground	[18]
5-a old rubber	15.6	4		
Oil palm plantation	62.4	16		
Coffee mixed garden	18	5		
Undisturbed rainforest	390	–		
Rubber agroforests	116	46	aboveground biomass and upper 30 cm of soil	[17]
Rubber agroforests with selected planting material	103	41		
Rubber monoculture	97	38		
Oil palm monoculture	91	36		
Natural forest	254	–		
Rubber jungle	35.5	14*	aboveground biomass	[32]
Home gardens	35—40	20*	tree biomass	[30]
Oil palm (30 a)	40.3	16*	aboveground biomass and necromass	[34]
Cinnamon	39	15*	aboveground biomass	[31]
Cinnamon	44	17*	aboveground biomass	[31]
A. mangium	80	32*	aboveground biomass and necromass	[35]

* Natural forest assumed to contain 254 Mg C/ha based on Noordwijk et al.[17].

In Mindanao, Philippines, tree plantations of fast growing species contain 3%—45% of the C of a natural dipterocarp forest (table 4). Another example is a mature coconut plantation in Leyte Province containing 86 Mg C/ha in aboveground biomass[19], which is about 43% of a natural forest in the same area (259 Mg C/ha)[37].

Table 4 Aboveground biomass C density of tree plantations in Mindanao, Philippines

Species	Age/a	AGB/Mg • ha^{-1}	C density/Mg C • ha^{-1}	Dipterocarp forest (%)
Albizzia falcataria 1	4	69.5	31.28	26
A. falcataria 2	5	75.6	34.02	28
A. falcataria 3	7	96.4	43.38	36
	7	8.1	3.65	3
A. falcataria 4	9	108.2	48.69	41
	9	28.7	12.92	11
Gmelina arborea 1	7	85.7	38.57	32
G. arborea 2	9	87.4	39.33	33
G. arborea 3	9	120.7	54.32	45
Dipterocarp*		265.4	119.43	

*Harvested 20 years ago; biomass data from ref. [36]; C content assumed to be 45%[9].

Agroforestry systems have been widely promoted as an alternative technology to slash-and-burn farming. They involve planting of tree and perennials in conjunction with agricultural crops. Various forms of agroforestry exist in the Philippines[38]. A *Leucaena leucocephala* fallow field in Cebu, Philippines has a mean C density of 16 Mg C/ha during its 6-a cycle (table 5) compared to 39 Mg C/ha of a coconut-based multistorey system in Mt. Makiling, which is still only about 15% of the C of adjacent natural forests[40].

Table 5 C density and MAI of a *Leucaena leucocephala* fallow field in Cebu, Philippines[39]

Years under fallow	Mean dry Wt. of aboveground Biomass/t • ha^{-1}	Leaves (%)	C in biomass /t • ha^{-1}	Annual rate of C accumulation/t • ha^{-1} • a^{-1}
1	4.3 d	36.5	2.2	2.2
2	16.1 cd	13.8	8.1	5.9
3	17.6 cd	8.9	8.8	0.7
4	36.4 bc	7.4	18.2	9.4
5	53.8 ab	5.3	26.9	8.7
6	63.6 a	6.1	31.8	4.9
Mean	32		16	5.3

Means in a column with the same letter are not significantly different using DMRT at 0.05.

In conclusion, it appears that tree and perennial crop plantations typically have C stocks in aboveground biomass that are 50% less than that of natural forests they replace.

In the process of converting natural forests to agricultural and tree plantations burning is often used for site preparation. In Indonesia, changes in C stocks during land clearing from old jungle rubber/secondary forest for replanting rubber varied depending on whether burning is used[17]. “Slash and burn” lost 66% C from ca. 80 Mg C/ha to 25 Mg/ha while “slash and mulch” (no burning) lost only 20% C (ca. 110 Mg/ha to 90 Mg/ha). In North Lampung, the biomass declined from 161 to 46 Mg/ha because of burning[41].

Once tree and perennial crop plantations have been established, they begin to accumulate C. Noordwijk et al.[17] reported a C accumulation rate of 2.5 Mg C/ha^{-1} • a^{-1} in natural fallows (secondary forests), agroforests and more intensive tree-crop production systems in Indonesia. Table 6 shows the rate of annual C accumulation by various forest plantations as used in the first Indonesian national communication to the UN Framework Convention on Climate Change (UNFCCC). It ranges from 0.50 to 12.50 Mg/h^{-1} • a^{-1}. For example, a 7-a old cinnamon plantation in Indonesia accumulates C at the rate of 4.49 to 7.10 kg C/tree (table 7). In the Philippines, commercial tree plantations of fast growing species sequestered C at the rate of 0.50—7.82 Mg C/h^{-1} • a^{-1} (table 8).

Soil organic matter/C (SOC) is also affected by the change in land use. C in the soil is a significant pool. It has the longest residence time among organic C pools in the forest[43]. However, there is little information on the exact effect of land use change on SOC in tropical forests, specially the rates and direction of change.

Table 6 Annual C accumulation rate of various forest plantations used in the national GHG inventory of Indonesia[42]

Land use type	Species/forest type	Annual growth rate /Mg • ha^{-1}	Annual C accumulation /Mg C • ha^{-1} • a^{-1}
Forest plantation (Java)	*Tectona grandis*	3.90	1.95
	Pinus merkusii	6.93	3.47
	Swietenia spp.	7.97	3.99
	Paraserianthes falcataria	19.07	9.54
	Rimba	4.3	2.15
Timber estate (outside Java)	*Acacia* spp.	25.00	12.50
	Paraserianthes falcataria	19.07	9.54
	Dipterocarp	5.78	2.89
Reforestation	*Pinus merkusii*	6.93	3.47
	Tectona grandis	2.41	1.21
	Acacia spp.	25.00	12.50
	Eucalyptus spp.	14.00	7.00
	others	6.82	3.41
Other forests	production forest	1.61	0.81
	conversion forest	2.11	1.06
	protection +conversion forest	2.78	1.39
	others	2.22	1.11
Afforestation	*Pinus* spp.	6.93	3.47
	Acacia spp.	25.00	12.50
	Aucalyptus spp.	14.00	7.00
	Paresiranthes falcataria	19.07	9.54
	others	4.30	2.15
Estate	*Hevea braziliensis*	12.00	6.00
	coconut	15.00	7.50
	oil palm	10.00	5.00
	others	1.00	0.50

Table 7 Rate of biomass and C accumulation (in kg) of a 7-a old cinnamon plantation in Indonesia[31]

In Blui Tinggi						
Tree	Root	Biomass	Total	R/S	C density	MAI
1	18.94	91.58	110.52	20.7	49.73	7.10
2	15.05	59.36	74.41	25.4	33.48	4.78
3	18.72	67.17	85.89	27.9	38.65	5.52
4	19.32	58.85	78.17	32.8	35.18	5.03
5	18.42	70.98	89.4	26.0	40.23	5.75
In Bukit Suban						
Tree	Root	Biomass	Total	R/S	C density	MAI
1	10.8	45.54	56.34	23.7	25.35	3.62
2	12.03	72.61	84.64	16.6	38.09	5.44
3	13.23	88.03	101.26	15.0	45.57	6.51
4	7.01	62.81	69.82	11.2	31.42	4.49
5	7.18	64.7	71.88	11.1	32.35	4.62

Table 8 MAI of biomass and carbon of tree plantations in Mindanao, Philippines

Species	Age/a	Tree biomass MAI/Mg • ha^{-1} • a^{-1}	C MAI/Mg C • ha^{-1} • a^{-1}
Albizzia falcataria 1	4	20.20	7.82
A. falcataria 2	5	11.20	6.80
A. falcataria 3	7	8.40	6.20
	7	2.20	0.52
A. falcataria 4	9	5.30	5.41
	9	3.70	1.44
Gmelina arborea 1	7	11.30	5.51
G. arborea 2	9	10.50	4.37
G. arborea 3	9	9.60	6.04
Sweitenia macrophylla	16	19.60	7.33
Natural forest*	100	4.90	1.19

* Harvested 20 years ago; assumed to be 100 years old. Biomass data obtained by destructive sampling[36]

3 Conclusions and recommendations

On the basis of the foregoing review of C budgets after harvesting and land cover change, the following conclusions emerge:

(i) C density in aboveground biomass declines by at least 50% after logging.

(ii) Deforested areas covered with grasses and annual crops have C density less than 40 Mg C/ha, much lower than natural forests.

(iii) Conversion of natural forests to tree plantations and perennial crops reduce C density by at least 50% relative to natural forests.

The following research topics need to be further pursued:

(i) Generation of country-specific allometric equations for biomass and C density.

(ii) Assessment of C dynamics associated with key land use/cover change.

(iii) Effects of silvicultural treatments and management practices on C budgets of forest ecosystems.

(iv) Comprehensive C stocks assessment of LUCF activities including aboveground biomass, belowground biomass and soil carbon, with a major effort on the latter two ones given the lack of current information.

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