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Soil and biomass carbon stocks in forest and agricultural lands in tropical climates

Arika Bridhikitti*

Climate Change and Adaptation Research Unit (CCARE),
Faculty of Environment and Resource Studies,
Mahasarakham University, Kantharawichai, Maha Sarakham, 44150 Thailand

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Abstract

This study aims to assess the carbon storage capability of dominant vegetative land covers in Thailand by estimating biomass, biomass carbon and soil carbon stocks. Above-ground biomass was estimated from allometric equation or actual raw yield. Soil organic carbon was analyzed according to the Chromic acid titration method. Results show that above-ground biomass carbon for irrigated rice, sugarcane, mature Para rubber, degraded rain forest and mixed deciduous forest were 0.8-1.3, 11.1, 91.5, 56.6 and 60.5 tonne C ha^{-1}, respectively; whereas topsoil carbon at 0-30 cm were 14.9-21.3, 11.3-13.8, 34.2, 54.6 and 77.7-136.9 tonne C ha^{-1}, respectively. Additional studies on the roles of leaf litters involving soil carbon and effects of agricultural practices on carbon storage capability should be considered. Furthermore, advantages of bio-fuel over the lost organic carbon in agricultural systems and decline in crop yield could be also taken into account.

Keywords: biomass carbon, soil carbon, carbon stock, agro-ecosystem

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) is highly confident that anthropogenic greenhouse gas emissions significantly contribute to global warming, resulting in high meteorological variability (IPCC, 2014). Carbon sequestrations into biomass and soils are currently emerging as significant carbon sinks. Estimated global carbon stock in forests was in the range of 84-642 tonne C ha^{-1}, highly varying among different forest ecosystems (Keith *et al.*, 2009). Agricultural lands could also fix carbon but with much smaller extent as compared to the forests (Noordwijk *et al.*, 1997; Saha *et al.*, 2010). Deforestation and agricultural land conversion, therefore, could diminish global carbon storage capability and potentially result in furthering climate change (Lal, 2004). Understanding biomass carbon and soil carbon sequestered in different agroecosystems is fundamentally required to justify effects of land conversions to carbon stocks and their global warming potential.

A large fraction of carbon found in the forests is in soil, living biomass, and leaf litter (Brown & Lugo, 1982). The rate of litter decomposition is highly limiting the amount of labile soil carbon and it depends upon multiple factors, including soil water content, pH and temperature (Devêvre & Horwáth, 2000; Gréggio *et al.*, 2008; Knorr *et al.*, 2005; Noordwijk *et al.*, 1997). With the total biomass up to 538 tonne ha^{-1} (Brown & Lugo, 1982), tropical forests could have the highest biomass carbon sequestration capability among all types of vegetation covers (Keith *et al.*, 2009). Some studies, however, report higher potentials for carbon fixation, such as in the rubber forest ecosystem in Huinan Island, China (Chun-man *et al.*, 2007) and Amazonia pasture (Desjardins *et al.*, 2004). Deforestation, therefore, undeniably results in higher atmospheric carbon (Keith *et al.*, 2009). Southeast Asian region experiences rapid forest destruction, mainly attributed to high population growth. Biomass carbon stocks in the

* Corresponding author.
Email address: arika.b@msu.ac.th

forests were then altered to crop plant carbon stocks, which yields lower storage pools (Mutuo *et al.*, 2005). Furthermore, soil carbon stock in the old-growth forest could be lost in the form of harvested crop biomass (Mutuo *et al.*, 2005; Rhoades *et al.*, 2000) and CO_2 into the atmosphere (Noordwijk *et al.*, 1997).

This study aims to assess biomass, biomass carbon and soil carbon stocks in the dominant vegetation covers in Thailand, including forests, sugarcane field, rice paddy and Para rubber plantations. Changes in carbon stocks attributed to forest-to-agricultural conversions are also discussed. Furthermore, additional requirements to reinforce understanding on carbon stock in the tropical vegetation ecosystems are provided for future studies.

2. Methodology

2.1 Study sites

Five land covers are chosen to represent different vegetation land characteristics in Thailand. A detailed description on the sites studied is in Table 1. The first land cover is a demonstration sugarcane field in the Agricultural Research and Development Center, Nakhon Ratchasima, a non-irrigated field under regular fertilizer application. Second, the irrigated rice paddy in Kongchai district, Kalasin was studied while the rice was at growing phase, one month after transplanting. By irrigation, the rice in this area can be cultivated twice a year (the first crop is started by mid-December and harvested in mid-April; whereas the second crop is from mid-May to mid-August). Third, Para rubber plantations are at the Rubber Research Center, Buriram and the Thepa Research and Training Station, Prince of Songkla University (PSU), Songkhla. They are representing the plantations at different years of Para rubber development. Like typical Para rubber plantation, the studied plantations also apply fertilizer once a year, usually around April. Fourth, degraded evergreen forest adjacent to the PSU Para Rubber plantation was also investigated. This forest covered an area of approximately 4 ha and it was later converted to a new Para rubber plantation after the study. The last land cover is the tropical mixed deciduous forest at Dun Lumpun non-hunting area, Maha Sarakham, which is located amid rice fields and covers an area of approximately 55 ha. Both forests are chosen for this study to evaluate the effects of deforestation and forest-to-agricultural land conversion on land carbon stock.

2.2 Above-ground biomass estimation

For the degraded evergreen forest, tree density evaluation over approximately 4 ha was randomly carried out in five 20×20 m^2 plots and tree information from each of the five plots was then combined. For the Dun Lumpun non-hunting area, the tree information was acquired from Seekong and Chareejan (2012), studying structure of trees in the forest using eleven circular plots with a size of 1,000 m^2. The plots were lying across the forest according to line plot sampling approach (Seekong & Chareejan, 2012). Plant densities in Para rubber plantation and sugarcane field were estimated from cropping grid patterns. For rice paddy, three 1-m diameter plastic rings were thrown out to randomly select the plots for plant density evaluation.

For forest and Para rubber trees, the above-ground biomass (AGB) was estimated from tree diameter at breast height (DBH) using allometric equations developed by Brown (1997) and modified by Basuki *et al.* (2009). The equation is:

$$AGB = \exp[c + \alpha \ln(DBH)],$$

where AGB is above-ground biomass in kg per tree, DBH is in cm, c is the intercept, and α is the slope coefficient. In this study, the intercept (c) and slope coefficient (α) for the tropical forest were -1.996 and 2.32, respectively (Brown, 1997). The AGB for deciduous forest was estimated from mixed species model ($c = -1.201, \alpha = 2.196$) and the Para rubber biomass was from commercial species model ($c = -1.498, \alpha = 2.234$) in the work of Basuki *et al.* (2009).

For sugarcane, the AGB was estimated from tonnes of raw cane produced per ha (71 tonne ha^{-1}). The raw cane was then converted and reported in dry weight basis using wet-to-dry weight ratio of 3:1 (Beeharry, 2001). For the rice, the AGB is 3.23 tonne ha^{-1}, estimated from 0.50 tonne dry straw produced per ha for each crop cycle (Delivand *et al.*, 2011) and 2.73 tonne rice grain yield per ha, which is an approximated rice yield as observed in this study.

2.3 Biomass and soil organic carbon

Above-ground biomass organic carbon was estimated using conversion factors, which are fractions of biomass carbon to total biomass for each type of dominant trees and plants in the studied fields. The conversion factors used in this study are either acquired from literatures or estimated using results obtained from literatures as detailed in Table 2. For this study, the rice biomass carbon fraction, 0.25 to 0.414, was assessed from rice straw samples, approximately 200 grams, which are taken from the studied fields. Samples were air dry under room condition for about one week and then analyzed for organic carbon content using Chromic acid titration method, modified by Walkley and Black (1934).

Soil organic carbon (SOC) content in the soil samples collected at 0-15 cm and 15-30 cm depths was analyzed at the MSU Environmental Laboratory using Chromic acid titration method (Walkley-Black method). Before sent to the laboratory, the samples were tightly packed in plastic bags with label attached. The samples were taken from three to five sampling points for approximately 300-500 gram each and analyzed for SOC separately. The SOC was then used to estimate soil carbon stock within 30-cm topsoil using bulk soil density acquired or estimated using the results obtained from literatures, as detailed in Table 2.

Table 1. Land covers, dominant species and locations of the study sites.

Land covers	Dominant species and characteristics	Location	Latitude, °N	Longitude, °E	Elevation, m MSL	Soil air meteorology	Date of observation
Sugarcane field	Sugarcane: Month 10th, 222-247 cm height, tree density of 8,440 ha^{-1}	The Agricultural Research and Development Center, Nakhon Ratchasima, Thailand	14.87837	101.64748	249	Air temperature 23.1-37.2°C, Humidity 45-99%, No rainfall, mean soil temperature 27.4°C	April 27th -28th, 2015
Rice paddy	*Oryza sativa* L.: Month 1st, 32-34 cm height, transplanted and irrigated, plant density of 4.3-4.5M ha^{-1}	Kongchai district, Kalasin	16.19513	103.46616	133	Air temperature 28.4-41.1°C, Humidity 43-80%, No rainfall, mean soil temperature 32.8°C	May 30th-31st, 2015
Para Rubber	*Hevea brasiliensis*: 20th Year, tree density of 495 ha^{-1}	The Rubber Research Center, Buriram	15.23009	103.2120	152	Air temperature 25.3-39.6°C, H umidity 44-99%, Rainfall 6.3 mm, mean soil temperature 28.5°C	June 1st-2nd, 2015
	Hevea brasiliensis: 2nd, 8th-10th, >20th Year tree density of 500 ha^{-1}	The PSU Research and Training Thepa Station, Songkhla	6.79636	100.94749	3.4	Air temperature 19.5-35.2°C, Humidity 51-99%, No rainfall, mean soil temperature 30°C, 28.9°C, 28.1°C for Year 2nd, 8-10th, >20th, respectively	February 5th-8th, 2015
Degraded tropical rain forest nearby Para rubber plantation	*Dipterocarpus kerrii*, *Dipterocarpus gracilis*, *Shorea curtisii*, *Instsia palembanica*, *Borassodendron machadonis*, *Calamus spp.*, 875 trees ha^{-1} for diameter >10 cm and 1,150 tree ha^{-1} for diameter 3-10 cm	The PSU Research and Training Thepa Station, Songkhla Thailand	6.80188	100.94923	3	Air temperature 19.5-35.2°C, Humidity 51-99%, No rainfall, mean soil temperature 27.3°C	February 5th - 8th, 2015
Tropical mixed deciduous forest	For diameter >10 cm 300 trees ha^{-1}: *Eugenia cumini*, *Terminalia alata*, *Streblus asper*, *Vitex pinnata*, *Aglaia edulis* For diameter 3-10 cm 2,900 tree ha^{-1}: *Gluta usitata*, *Leucaena leucocephala*, *Streblus asper*, *Diospyros mollis*	Dun Lumpun non-hunting area, Maha Sarakham	15.77309	103.02587	161	Air temperature 25.1-38.4°C, Humidity 48-96%, Rainfall 6.6 mm, mean soil temperature 28.0°C	June 20th –23rd, 2015 for SOC only

Table 2. Biomass carbon fraction and bulk topsoil density in cropping fields for different tree/plant species used in this study.

Tree/plant species	Biomass C fraction of total AGB	Sources	Note	Bulk topsoil density, Mg m^{-3}	Sources	Note
Sugarcane	0.47	Beeharry (2001)	Estimated from C fractions of all dry components of millable cane, Thailand.	1.51	Usaborisut and Sukcharoenvipharat (2011)	Estimated from soils in sugarcane fields under mechanized farming at 20 and 40 cm depth in Thailand
Rice	0.250-0.414	This study (2015)	Analyzed organic carbon content in rice straw residue	1.58	Saenya *et al.* (2015)	Estimated from wide-range of paddy soil types at 0-40 cm in Si Sa Ket, NE Thailand
Para rubber tree	0.487 (2008)	Wauters *et al.*	Used in the estimate of biomass C of Para rubber tree in Brazil	1.67 (Buriram)	DPT (2016)	Resulted from 4 borehole tests at 0-45 cm depth at Mueng, Buriram with reported soil textures of CL, ML, OL and SM*
				1.39 (Songkhla)	DPT, 2016	Resulted from 2 borehole tests at 1.50-1.95 m depth at Thepa, Songkhla with reported soil textures of SW, SM*
Forest tree	0.470	IPCC, 2006	Default value for forest biomass	1.40	Suwanprapa *et al.*, 2015	Estimated from wide-range of tropical forest types in Thailand

*CL = Clays of low plasticity, ML = Silts of low plasticity, OL = Organic silts and clays of low plasticity, SM = Silty sands, SW = Gravelly sands

3. Results and Discussion

3.1 Above-ground biomass and biomass carbon stock

Estimated above-ground biomasses in this study, shown in Table 3, were 3.23 tonne ha^{-1} for rice (straw + grain) biomass, followed by 23.7 tonne ha^{-1} for dry sugarcane, 13.0 tonne ha^{-1} in 2nd Year to 187.8 tonne ha^{-1} in >20th Year for the Para rubber, 120.5 tonne ha^{-1} for the degraded tropical rain forest and 128.7 tonne ha^{-1} for the tropical mixed deciduous forest. Correspondingly, the estimated biomass carbon stocks were comparatively high for the forests, which were 56.6 tonne C ha^{1} for degraded tropical rain forest and 60.5 tonne C ha^{-1} for tropical mixed deciduous forest. Biomass carbon in cropping fields was much lower, which was 11.1 tonne C ha^{-1} for the sugarcane field and 0.8-1.3 tonne C ha^{-1} for the rice paddy. The biomass carbon for Para rubber plantation was highly dependent on cropping years, ranging from 6.3 tonne C ha^{-1} in 2nd Year to 91.5 tonne C ha^{-1} in >20th Year.

The irrigated rice paddy could produce biomass for ~6.46 tonne ha^{-1} yr^{-1} based upon the typical two cropping cycles a year. This estimated rice biomass and biomass carbon percentages are 65% and 30-49%, respectively, of those found in the eastern Coast of Thailand in the work of Gnanavelrajah *et al.* (2008). The estimated biomass in this study, however, is comparable to those found in Philippines (Witt *et al.*, 2000). Approximately 48% of straw residue is subject to be burnt in the field and this burning releases ~413 kg C (tonne dry straw mass)$^{-1}$ into the atmosphere (Gadde *et al.*, 2009).

Our sugarcane biomass production is comparable to the global average, 14-22 tonne sugarcane ha^{-1}, as reported in the work of Kim and Dale (2004) and the cane production in eastern Thailand (29.1 tonne ha^{-1}) as reported in Gnanavelrajah *et al.* (2008). Approximately 35% of sugarcane biomass is burnt on-field (Yuttitham *et al.*, 2011). The pre-harvest burning is done to get rid of leave, for convenience in cane stalk harvesting, and it could release ~1.7 kg C (in forms of CO and CH_4) per tonne of raw cane (Renouf *et al.*, 2010). After harvest, there is approximately 20% of cane trash left on the field and the cane trash burning could also release large amounts of carbon (34 kg C per tonne of dry trash) (Nguyen & Gheewala, 2008). Excess bagasse from sugar production was ~28% by weight of raw sugarcane stalk (Nguyen *et al.*, 2010). Carbon stocks in Para rubber tree biomass are increasing with increasing age of the plantation. Under ultimate tree canopy development (>20th year), their carbon storage capacity (91.5 tonne C ha^{-1}) could be 1.62 times higher than that of the trees in the adjacent degraded rain forest (120.5 tonne biomass ha^{-1} and 56.6 tonne C ha^{-1}). Para rubber tree biomass in the

20th year varied from field to field, ranging from 62.6 tonne C ha^{-1} in the Buriram plantation (in this study) to 122 tonne C ha^{-1} in Phonpisai soil series, Northeastern Thailand (Saengruksawong *et al.*, 2012a). The tree is usually cut down in the dry season of its 25th year and this continues into the new cropping cycle before the next early rainy season. The cut trees and small branches are mainly used for wood furniture/particleboard productions and solid fuel. Due to rapid tree development, net production of biomass carbon in the Songkhla Para rubber plantation was approximately 3.7 tonne C ha^{-1} yr^{-1}. The biomass carbon is accounting for ~33% of total carbon stock in the Para rubber plantation ecosystem (Chun-man *et al.*, 2007). The largest fraction of carbon (~58%) is fixed in litters (Chun-man *et al.*, 2007). This litter over the topsoil could be decomposed 62-72% within nine months (Gréggio *et al.*, 2008). Litters, therefore, should be a significant soil carbon source in the plantation.

As shown in Table 3, the tropical mixed deciduous forest in Dun Lumpun non-hunting area exhibits slightly higher biomass (128.7 tonne ha^{-1}) and biomass carbon (60.5 tonne C ha^{-1}) than other deciduous forests in Thailand, such as those in Thong Pha Phum National Forest (Terakunpisut *et al.*, 2007), Western Thailand (Chiyo *et al.*, 2011) and lower Northern Thailand (Kaewkrom *et al.*, 2011). Net primary production in tropical forest is ~11-21 tonne ha^{-1} yr^{-1} with 25-65% contributed from leaf litter (Brown & Lugo, 1982). Though the turnover time of biomass was in the order of 34 years, the time of litter was much shorter, <1 year (Brown & Lugo, 1982).

3.2 Soil carbon content and soil carbon stock

Table 4 shows summary on soil carbon content in different agro-ecosystems. Low topsoil carbon content was found in the sugarcane field, 0.40-0.45% at 0-15 cm and 0.10-0.16% at 15-30 cm. Carbon stock in this topsoil layer was 11.3 to 13.8 tonne C ha^{-1}, which was significantly lower than those found in other sugarcane fields, such as those in Ecuador, 72.5 tonne C ha^{-1} at 0-30 cm (Rhoades *et al.*, 2000), and Brazil, 35-39 tonne C ha^{-1} at 0-20 cm (de Resende, *et al.*, 2006) and 29.7 tonne C ha^{-1} at 0-20 cm with pre-harvest burning (Galdos *et al.*, 2009). Interestingly, this low s oil carbon observed in this study was not strongly affecting cane yield, suggested from observing high cane yields of 71 tonne ha^{-1}, which is above the average yield (54-65 tonne ha^{-1}). De Resende *et al.* (2006) suggest that the cane yields can be considerably increased by proper field trash conservation and N fertilizer application. Furthermore, they found that soil carbon stocks were less dependent on these agricultural practices (de Resende *et al.*, 2006).

The low soil carbon content was also observed in the irrigated rice paddy, 0.44-0.58% at 0-15 cm and 0.19-0.32% at 15-30 cm, equivalent to 14.9 to 21.3 tonne C ha^{-1} at 0-30 cm. Rice paddy was flooded and soil organic carbon could be released in forms of CO_2 and CH_4 under anaerobic condition (Devêvre & Horwáth, 2000). Approximately 70% decline in topsoil organic carbon is expected in most rice cropping systems (Naklang *et al.*, 1999). Rainfed rice paddy, experiencing one cropping cycle a year during rainy season, has longer land recession allowing rice straw degradation and soil carbon rehabilitation onto the field. This could attribute to the higher topsoil carbon content as observed in rainfed rice paddy in Ubon Ratchathani province (0.68% at 0-10 cm in the work of Naklang *et al.*, 1999) and Yasothorn province (1.33% at 0-30 cm, in the work of Sudjarit, 2014).

Soil carbon in the Para rubber plantations clearly associated with tree age. At the Songkhla station, higher soil carbon in the plantation was found at an early year of the plantation, 37.5 tonne C ha^{-1} in the 2nd year, and decreasing with tree age (20.2 tonne C ha^{-1} at 8th to 10th year). The typical Para rubber plantation requires intensive fertilizer application every three months in its first year (N:P:K~30:5:18). The fertilizer is later applied yearly during early rainy season. The soil under the full tree canopy development (>20th year), however, has slightly higher soil carbon content and greater carbon stock found in the deeper soil (0.78% at 0-15 cm and 0.86% at 15-30 cm) as compared to that of the younger trees. This dynamic soil carbon stocks could imply significant roles of soil temperature and leaf carbon stock into the soil. Several studies discuss the significant effects of global warming on soil carbon released into the atmosphere (Davidson & Janssen, 2006; Knorr *et al.*, 2005), resulting in low soil carbon

Table 3. Summary of carbon stock in above-ground biomass.

Land covers	Locations	Above-ground biomass, tonne ha^{-1}	Estimated biomass carbon, tonne C ha^{-1}	Source
Sugarcane	Global average	14-22 (dry) 25-40 (wet)	-	Kim & Dale, 2004
fields	Australia	60-110 (delivered to mill)	-	Renouf *et al.*, 2010
	Eastern Thailand	29.1 (dry)	16.0	Gnanavelrajah *et al.*, 2008
		32-120 (means = 54-65)	-	Yuttitham *et al.*, 2011
	The Agricultural Research and Development Center, Nakhon Ratchasima, Thailand	23.7 (dry)	11.1	This study, 2015

Table 3. Continued

Land covers	Locations	Above-ground biomass, tonne ha^{-1}	Estimated biomass carbon, tonne C ha^{-1}	Source
Rice paddy *Oryza sativa* L.	International Rice Research Institute, Philippines	5.0-7.4 (dry)	1.1–1.4 (Carbon from residues)	Witt *et al.*, 2000
	International Rice Research Institution, Philippines	14.2 (NPT2 cultivar), 7.2 (N-22 cultivar) in maturation phase	-	Moya *et al.*, 1998
	Agricultural lands in the eastern Coast of Thailand	9.9	5.4	Gnanavelrajah *et al.*, 2008
	Irrigated rice paddy in Kalasin, Thailand	3.23 (dry)	0.81-1.33	This study, 2015
Para rubber plantation *Hevea brasiliensis*	Hainan Island, China	-	30^{th} Year: 90.51	Chun-man, *et al.*, 2007
	Cambodia and Laos	-	25-143	Ziegler *et al.*, 2012
	Agricultural lands in the eastern Coast of Thailand	190.7	103.1	Gnanavelrajah *et al.*, 2008
	Northeastern Thailand	Phonpisai soil series:		Saengruksawong *et al.*, 2012a
		1^{st} year: 21.2	12.0	
		10^{th} year: 102.4	58.1	
		20^{th} year: 215.4	122.0	
		Chakkarat soil series:		Saengruksawong *et al.*, 2012b
		1^{st} year: 20.2	11.4	
		10^{th} year: 92.6	52.5	
		20^{th} year: 147.8	83.7	
	The Rubber Research Center, Buriram Thailand	20^{th} year: 128.6±56.2	62.6±27.4	This study, 2015
	The PSU Research and Training	>20^{th} year: 187.8±48.9	91.5±23.8	This study, 2015
	Thepa Station, Songkhla Thailand	8–10^{th} year: 64.8±15.8	31.6±7.6	This study, 2015
		2^{nd} year: 13.0±2.3	6.3±1.1	This study, 2015
Tropical forests	SE Asia	-	78-180 (continental), 96-225 (insular)	IPCC, 2006
	Lower Northern Thailand Mixed deciduous forest Dominant species include *Canarium subulatum*, *Pterocarpus macrocarpus*, *Dalbergia cultrate*, *Lagerstroemia tomentosa* and *Xylia xylocarpa* var *kerrii*	50.9 (secondary forest), 104.5 (primary forest)	30.7 (secondary forest), 51.9 (primary forest)	Kaewkrom *et al.*, 2011
	Ratchaburi province, Western Thailand Tropical deciduous forest Dominant species include	30.9 (dry dipterocarp forest), 59.4 (mixed deciduous forest)	14.5 (dry dipterocarp forest), 27.9 (mixed deciduous forest)	Chaiyo *et al.*, 2011
	Thong Pha Phum National Forest, Thailand	275.4 (tropical rain forest), 140.6 (dry evergreen forest), 96.2 (mixed deciduous forest)	137.7 (tropical rain forest), 70.3 (dry evergreen forest), 48.1 (mixed deciduous forest)	Terakunpisut *et al.*, 2007
	The PSU Research and Training Thapa Station, Songkhla Thailand Degraded tropical rain forest nearby Para rubber plantation	120.5	56.6	This study, 2015
	Dun Lumpun non-hunting area, Maha Sarakham, Thailand Mixed deciduous forest	128.7	60.5	This study, 2015 tree dataset is acquired (from Seekong & Chareejan, 2012)

Table 4. Summary of carbon content in topsoil.

Land covers	Locations	Soil carbon content, % by weight	Estimated soil carbon stock, tonne C ha^{-1}	Source
Sugarcane fields	Lower montane region of NW Ecuador	4.5% at 0-15 cm, 2.3% at 15-30 cm	72.9 at 0-30 cm (50 yr)	Rhoades *et al.*, 2000
	Brazil	1.5%-2.0% at 0-20 cm (Pre-harvest burning), 1.7%-2.3% at 0-20 cm (Unburnt)	27.9 at 0-20 cm (burnt), 37.7 at 0-20 cm (unburnt)	Galdos *et al.*, 2009
		1.4% at 0-10 cm, 1.3% at 10-20 cm and 1.2% at 20-40 cm (No N fertilizer application)	35.0-39.0 at 0–20 cm	De Resende, *et al.*, 2006
	The Agricultural Research and Development Center, Nakhon Ratchasima, Thailand	0.40-0.45% at 0-15 cm, 0.10-0.16% at 15-30 cm	11.3-13.8 at 0-30 cm	This study, 2015
Rice paddy	Rainfed rice in central Kerala, India	0.73% at 0-20 cm, 0.50% at 20-50 cm, 0.37% at 50-80 cm	~20.0-35.0 at 0-20 cm, 55.6 at 0-100 cm	Saha *et al.*,2010
	Rainfed rice in Yasothorn, Thailand	1.33% at 0-30 cm	25.2 at 0-30 cm	Sudjarit, 2014
	Rainfed rice in Ubon Ratchathani, Thailand	0.68% at 0-10 cm, 0.38% at 10-20 cm,0.17% at 20-40 cm	–	Naklang *et al.*, 1999
	Aichi-ken Anjo Research and Extension Center, Central Japan	1.4% at 0-15 cm	–	Lu *et al.*, 2003
	Irrigated rice at Kalasin, Thailand	0.44-0.58% at 0-15 cm, 0.19-0.32% at 15-30 cm	14.9-21.3 at 0-30 cm	This study, 2015
Para Rubber	>50th year in central Kerala, India	1.30 % at 0-20 cm, 1.58% at 20-50 cm, 1.16% at 50-80 cm	~30.0-45.0 at 0-20 cm, 119.2 at 0-100 cm	Saha *et al.*,2010
	2-14th year in Western Ghana, Brazil	1.40% at 0-15 cm, 0.77% at 15-45 cm	135.0 at 0-60 cm	Wauters *et al.*, 2008
	14-25th year in Mato Grosso, Brazil	2.03% at 0-20 cm, 1.37% at 20-60 cm	153.0 at 0-60 cm	Wauters *et al.*, 2008
	2nd-6th year plantation in Yasothorn	0.84% at 0-30 cm	48.4 at 0-30 cm	Sudjarit, 2014
	Northeastern Thailand	-	Phonpisai soil series and Chakkarat soil series: 1st year: 14.3 10th year: 18.5 20th year: 13.4	Saengruksawong *et al.*, 2012a,b
	20th year at the Rubber Research Center, Buriram, Thailand	0.58-0.68% at 0–15 cm, 0.33-0.39% at 15–30 cm	22.8-26.8 at 0-30 cm	This study, 2015
	>20th year at the PSU Research and Training Thepa Station, Songkhla Thailand	0.78% at 0-15 cm, 0.86% at 15-30 cm	34.2 at 0–30 cm	This study, 2015
	8-10th year at the PSU Research and Training Thepa Station, Songkhla Thailand	0.60% at 0-15 cm, 0.37% at 15-30 cm	20.2 at 0-30 cm	This study, 2015
	2nd year at the PSU Research and Training Thepa Station, Songkhla Thailand	1.07% at 0-15 cm, 0.73% at 15-30 cm	37.5 at 0-30 cm	This study, 2015

Table 4. Continued

Land covers	Locations	Soil carbon content, % by weight	Estimated soil carbon stock, tonne C ha^{-1}	Source
Aquilaria crassna plantation	Yasothorn, Thailand	1.4% at 0-30 cm	42.0 at 0-30 cm	Sudjarit, 2014
Old-growth forest	Lower montane region of NW Ecuador	6.5% at 0-15 cm, 2.7% at 15-30 cm	95.6 at 0-30 cm	Rhoades *et al.*, 2000
Tropical deciduous forest	Kerala state, India	2.38% at 0-20 cm, 2.69% at 20-50 cm, 2.02% at 50-80 cm	~40.0-60.0 at 0-20 cm, 176.6 at 0-100 cm	Saha *et al.*, 2010
Mature diptocarp trees within the compound of a Buddhist temple	Ubon Ratchathani, Thailand	2.30% at 0-10 cm, 0.68% at 10-20 cm, 0.15% at 20-40 cm	-	Naklang *et al.*, 1999
Degraded tropical rain forest nearby Para rubber plantation	The PSU Research and Training Thepa Station, Songkhla Thailand	1.5% at 0-15 cm, 1.1% at 15-30 cm	54.6 at 0-30 cm	This study, 2015
Tropical mixed deciduous forest	Dun Lumpun non-hunting area, Maha Sarakham, Thailand	3.09-3.81% at 0-15 cm, 0.61-2.71% at 15–30 cm	77.7-136.9 at 0-30 cm	This study, 2015

content. The lowest soil temperature was observed at >20th year of Para rubber plantation (28.1°C), which could minimize the soil carbon released.

Significant decrease in soil carbon content attributed to forest-to-Para rubber plantation conversion was suggested from lower soil carbon stock in Para rubber plantation as compared to that in the nearby degraded forest. The difference in topsoil carbon content between the forest and the plantation ranged from 0.43% C in the 2nd year of the plantation to 0.90% C in 8-10th year. These were similar to the changes in topsoil carbon content attributed to natural forest-to-agricultural land conversion in humid tropical forest zone, which is in the range of 0.5% C to 1.0% C, as reported in the work of Noordwijk *et al.* (1997).

Among various vegetative covers considered in this study, the tropical deciduous forest has distinctively the highest soil carbon stock, 77.7-136.9 tonne C ha^{-1} at 0-30 cm, as well as the highest soil carbon content, ranging from 3.09-3.81% at 0-15 cm and 0.61-2.71% at 15-30 cm. This surface soil carbon stock was comparable to the old-growth forest (95.6 tonne C ha^{-1} at 0-30 cm) in the work of Rhoades *et al.* (2000) but comparatively higher than those found in community forest in the Buddhist temple, Thailand (Naklang *et al.*, 1999), *Aquilaria crassna* plantation in Yasothon, Thailand (Sudjarit, 2014) and degraded rain forest in Songkhla, Thailand (1.5% at 0-15 cm). This finding could imply a positive carbon stock in undisturbed forest ecosystem.

3.3 Suggestions for future studies

Leaf litter is the significant recyclable carbon stock in vegetation and forest ecosystems. Appropriate litter management could improve crop yield and minimize global warming effects attributed to biomass open burnings. Further studies are required to suggest appropriate litter management for different vegetation ecosystems. These would include studies on dynamic decompositions of leaf litters under local wet and dry conditions and contributions of decomposed litter to labile soil carbon and crop yield should also be considered.

Carbon storages in agricultural lands are highly varied from field to field. There are many factors limiting the carbon storage capacity. The factors include fertilizer application, residue management and irrigation. According to the Office of Agricultural Economics of Thailand, rice paddy is the major stable crop, accounting for 21.8% of total cultivation area in the country in year 2015. Many of the rice paddies are under rainfed ecosystem. Although chemical fertilizer application is widely used in most of the paddy area, the organic fertilizer application becomes more attractive due to high market demand. Therefore estimating carbon stock in rice paddies must consider these cropping management factors.

Currently, many studies suggest effective crop residue utilization as bio-fuels for power generation. This application is claimed to minimize greenhouse gas emission compared to typical open burning practices (Beeharry, 2001; Nguyen & Gheewala, 2008; Nguyen *et al.*, 2010; Yuttitham *et al.*, 2011). However, further studies are needed to clarify advantages of the bio-fuels over the lost organic carbon in the agricultural systems and decline in food security.

4. Conclusions

Carbon stocks into biomass and soils are currently being drawn to attention as significant carbon sinks. This study aims to assess biomass, biomass carbon and soil carbon stocks in the dominant vegetation covers for Thailand, including forests (deciduous forest in Mahasarakham and degraded rain forest in Songkhla), sugarcane field (Nakhon Ratchasima), irrigated rice paddy (Kalasin) and Para rubber plantations (Buriram and Songkhla). The changes in carbon stocks attributed to forest-to-agricultural conversions were also discussed. Above-ground biomass for forest and Para rubber trees is estimated from allometric equation, and for rice and sugarcane, they are estimated from actual raw yield. Biomass and soil organic carbon were analyzed according to the Chromic acid titration method.

Results show annual biomass production was highly varied among different vegetation covers, ranging from the lowest of ~3.23 (dry) tonne ha^{-1} for irrigated rice paddy, followed by ~23.7 (dry) tonne ha^{-1} for sugarcane, 120.5 tonne ha^{-1} for the degraded tropical rain forest, 128.7 tonne ha^{-1} for the tropical mixed deciduous forest to the highest of 187.8 tonne ha^{-1} for >20th year Para rubber. Correspondingly, the highest biomass carbon stock was found in the fully developed rubber plantation (91.5 tonne C ha^{-1}), followed by tropical mixed deciduous forest (60.5 tonne C ha^{-1}), the sugarcane field (11.1 tonne C ha^{-1}) and the rice paddy (0.8-1.3 tonne C ha^{-1}). The biomass carbon for Para rubber plantation was highly dependent on cropping year, ranging from 6.3 tonne C ha^{-1} (2nd year) to 91.5 tonne C ha^{-1} (>20th year).

Comparatively low topsoil carbon stock was found in the sugarcane field (11.3-13.8 tonne C ha^{-1} at 0-30 cm) and the irrigated rice paddy (14.9-21.3 tonne C ha^{-1} at 0-30 cm). Topsoil carbon stock in the Para rubber plantations clearly associated with tree age and canopy development. At the Songkhla station, higher topsoil carbon stock in the plantation was found at an early year of the plantation, 37.5 tonne C ha^{-1} at 0-30 cm at 2nd year, and decreased with tree age (20.2 tonne C ha^{-1} at 8-10th year). The tropical mixed deciduous forest had distinctively the highest topsoil carbon, 77.7-136.9 tonne C ha^{-1} at 0-30 cm.

Additional studies on the roles of leaf litters involving soil carbon and effects of agricultural practices on carbon storage capability should be considered. Furthermore, advantages of bio-fuel over the lost organic carbon in agricultural systems and decline in crop yield could be taken into account.

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