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CARBON STOCK ASSESSMENT AND SOIL CARBON MANAGEMENT IN AGRICULTURAL LAND-USES IN THAILAND

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ABSTRACT

The organic carbon pool in agricultural land-uses is capable of enhancing agricultural sustainability and serving as a potential sink of atmospheric carbon dioxide. A study was carried out to estimate and map carbon stock of different agricultural land-uses in a sub-watershed of Thailand and to assess the land-use sustainability with respect to carbon management. A quadrat sampling methodology was adopted to estimate the biomass and its carbon content of 11 different land-uses in the study area. Existing soil data were used to calculate the soil carbon. GIS was used for integrating biomass carbon, soil carbon and carbon stock mapping. Roth carbon model was used to project the soil carbon of present land-uses in the coming 10 years and based on which the sustainability of land-uses was predicted. The total carbon stock of agricultural land-uses was estimated to be 20·5 Tg, of which 41·49 per cent was biomass carbon and 58·51 per cent was soil carbon. Among the land-uses, para rubber had the highest average biomass C (136·34 Mg C ha^{-1}) while paddy had the lowest (7·08 Mg C ha^{-1}). About four-fifths of agricultural land-uses in the watershed are sustainable in maintaining the desired level of soil carbon in coming 10 years while one-fifths are unstable. Such information on carbon stock could be valuable to develop viable land-use options for agricultural sustainability and carbon sequestration. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: biomass; modelling; carbon stock; agricultural sustainability; land-use; Thailand

INTRODUCTION

Sustaining soil organic matter (SOM) is of paramount importance with respect to availability of plant nutrients and improvement of the soil's physical, chemical and biological properties (Kundu *et al*., 2006) for eventual increase in agricultural productivity. Maintenance of soil organic carbon (SOC), a major component of SOM, is essential for the sustainable agricultural production as declining SOC generally leads to decreased crop productivity (Lal, 2006).

Deforestation and inappropriate land-use practices have resulted in several environmental problems including declining SOC through decreased carbon sequestration and increased carbon dioxide (CO_2) emission to the atmosphere (Paustian *et al*., 2000) causing global warming. Biomass burning or decomposition and release of SOC following cultivation due to enhanced mineralization brought about by change in soil moisture, temperature regimes and low rate of return of biomass to the soil are among the causes of C emission (Korschens, 1998). The net release of C from agricultural activities is substantial as such amount accounts to 14 per cent of that emitted from the fossil fuel usage in 1995 (Lal *et al*., 1997). Yet, agriculture can be indeed a part of the solution of C sequestration if properly managed. C sequestration can be enhanced through different options, such as judicious land-use, improved soil and plant management technologies, conservation tillage and restoration of degraded soils (Lal *et al*., 1997). Similarly, the positive effect of increased soil C on soil quality and crop yield is well established. The improvement in land-uses and management systems that enhance and maintain high level of SOC pools can be considered as an important feature of agriculture sustainability (Lal, 2006). Alike is the concept of sustainable

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land-use that it maintains production at or above its present level without progressively degrading the productive capacity (FAO, 1993).

Despite the widespread view that the forest land-use is best suited for C sequestration it is inconceivable with forest and reforestation alone in the lack of land for reforestation has given the acute problem of food security in the Asian developing countries. Identifying agricultural land-use and management practices that are capable of increasing C sequestration will be a better option in developing countries as it will be a win–win option which would help to address production problems and environmental problems, such as land degradation and loss of biodiversity (Greenland *et al*., 1997).

Organic carbon in tropical soils appears to be more easily degradable than that of temperate soils (Derpsch and Moriya, 1998) and hence increasing SOC content of soils of the tropics and subtropics is not an easier task (Lal and Bruce, 1999). However, several studies conducted in the tropics have demonstrated the positive impacts of residue retention or manure application on SOC concentration and increase in crop yield. These include the studies conducted in India with various crops, for example pearl millet (*Pennisetum typhoides*) by Aggarwal *et al.* (1997), mustard (*Brassica juncea*) by Shankar *et al.* (2002) and wheat (*Triticum aestivum*), mustard, sunflower (*Helianthus annuus*) and ground nut (*Arachis hypogaea*) by Ghosh *et al.* (2003). Similarly, some studies (Kanchikerimath and Singh, 2001; Wani *et al*., 2003; Manna *et al*., 2005; Rudrappa *et al*., 2005; Kundu *et al*., 2006) conducted in India have also reported that cropping systems with different combinations of fertilizers and manures contributed towards an increased SOC. Similarly, few studies conducted in Nepal suggested that CO_2 evolution (Shrestha *et al*., 2004a) and SOC content (Shrestha *et al*., 2004b) are affected by land-use change and SOC loss due to change in cropping pattern (Tiwari *et al*., 2006). Petchawee and Chaitep (1995) reported an increased grain yield of maize in Thailand due to increase in SOM.

Forest conversion to agriculture is a typical land-use conversion process elsewhere. Several Asian developing countries have experienced a rapid forest decline in the recent past including Thailand where the remaining forest area is 25 per cent of the total area and the agriculture is a dominant land-use covering 41 per cent of the area (FAO, 2005). C sequestration studies of agricultural systems, therefore, hold particular importance in Thailand but such studies are largely limited, except few plot level studies (Matsumoto *et al*., 2002; Shirato *et al*., 2005). Nonetheless, it is essential to assess the C pool of present agricultural land-uses at sufficiently large scales where there is marked effect of soil, climate and management conditions. Such studies will help decision makers in identifying sustainable land-use options enabling a successful land-use planning.

SOC is an important index of soil quality because of its relationship to crop productivity (Lal *et al*., 1997). As SOC is dynamic in nature and modified by climatic and anthropogenic factors, monitoring of SOC could aid in the assessment and maintenance of land quality. Since SOC estimation through plot level field observation is highly resource demanding, modelling exercise is relatively quicker for C stock assessment under present and future agricultural management scenarios to eventually examine the sustainability of present land-uses. Such information can be valuable for C trading as well. The objective of this study was to estimate and map the C stock of current agricultural land-uses in the Khlong Yai sub-watershed and to assess the sustainability of present agricultural land-uses in terms of soil C management.

MATERIALS AND METHODS

Study Site

The study site, Khlong Yai sub-watershed covering 170 175 ha, is located between 12° 65′ to 13° 14′ N latitudes and 101° 03′ to 101° 44′ E longitudes in the Eastern coastal region of Thailand (Figure 1). The climate of the study area is tropical monsoon with the rainy season extending from May to October. The average annual rainfall is 1383 mm in annual rainy days of 120. The average annual temperature is 28·3°C. More than 75 per cent of the sub-watershed has flat to gently undulating topography. The rest of the watershed area has rolling, undulating or steep topography. Among the 28 soil series found in the study area, the dominant soil series are Map Bon (Typic paleudults),

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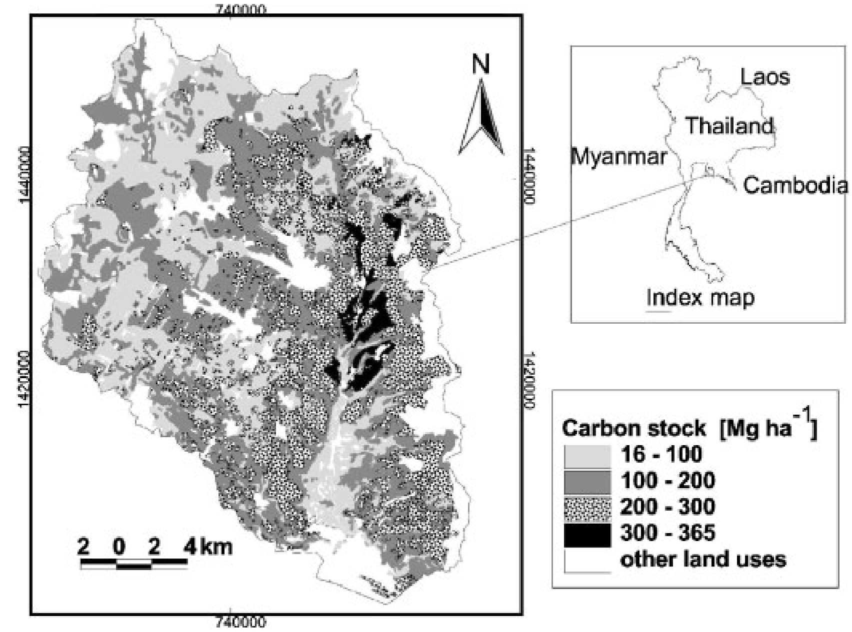

Figure 1. Location of study area and distribution of carbon stock.

Phangnga (Typic Paleudults) and Satuk (Oxic Paleustults) covering 16, 14 and 10 per cent of watershed, respectively.

A range of land-uses, such as different annual mono-crop, mixed orchard, perennial mono-crop and perennial-annual inter-crop are found in the area. Among the agricultural land-uses, upland crops occupy 80 per cent of the total land area and lowland paddy (*Oryza sativa*) occupies 4 per cent. Pará rubber (*Hevea brasiliensis*), pineapple (*Ananus comosus*), mixed orchard and cassava (*Manihot esculanta*) are the dominant agricultural land-uses. Rest of the areas are occupied by land-uses, such as water bodies, forest and industrial and built up areas.

Data Collection

Data on biomass of present agricultural land-uses of the study area was collected using quadrat sampling method during the field survey. Based on the proportionate area under each land-use type, number of sampling quadrats for each land-use type was determined. Thus, a total of 75 quadrats in the entire study area were sampled and the quadrats for each land-use type ranged from 4 to 12. The sampling frame was designed in such a way that each sample quadrat included a nested quadrat sampling technique containing quadrats of decreasing size, 20 × 20 m, 10 × 10 m, 5 × 5 m and 1 × 1 m nested within each other. Quadrats of 20 × 20 m size were used to measure diameter at breast height (DBH) and height of trees in mixed orchards. Quadrats of 10 × 10 m size were used to measure the same tree parameters in mono-cropped perennials, such as para rubber, eucalyptus and coconut or coconut-cassava intercropping. Quadrats of sizes 5 × 5 m and 1 × 1 m nested within the larger quadrats were used to measure parameters of biomass estimation in the shrub and herb layers, respectively. In the shrub layer, height and diameter were measured whereas all the aboveground biomass was collected for the herb layer.

A household survey of the farmers managing the respective fields used for quadrat sampling was also conducted by administering a structured questionnaire in order to collect information regarding the amount, type and timing of organic matter input, residue management practices and other farm household data. The secondary data used in the study included (i) the soil map of 2003, which gives soil classification at series level and respective soil profile description and characteristics, (ii) land-use map of 2000 from Department of Land Development, and (iii) climate data (1994–2005) namely, rainfall, temperature and evaporation from Meteorological Department. In addition, crop data such as harvest index, litter fall and wood density obtained from various sources were also used.

Biomass Estimation

The biomass of tree, shrub and herb layers has to be separately estimated in order to finally compute the total biomass per unit area. In each layer, all species in the quadrats were considered for biomass estimation. The biomass of trees in a quadrat was estimated using the following linear regression equation for tropical forest given by FAO (1997).

$$Y = \exp\{^{-}1{\cdot}996 + 2{\cdot}32 \times \ln(\mathrm{DBH})\},$$

where Y is the biomass in kg, DBH is the diameter at breast height in cm. By summing up the biomass of all trees in the quadrat, biomass per quadrat was measured and eventually converted to biomass per hectare. The biomass of coconut trees was estimated according to the method to estimate biomass of palms as described by FAO (1997). The biomass of shrub layer present in the perennial tree crop land-uses was estimated by measuring the stem volume and multiplying this with the respective wood density values of each species. Since the contribution of shrub volume due to foliage is considered negligible (Ponce-Hernandez *et al*., 2004), foliage was not considered in the overall estimation of total biomass. Shrub layer biomass of shrub crops was estimated using the average yield data for each crop obtained from household survey and harvest index values of respective crops obtained from secondary sources (Howeler, 1985; Bhattacharyya and Bhattacharyya, 1992; Kawashima *et al*., 2001). Herb biomass in all type of land-uses was estimated by harvesting all above ground biomass and measuring their oven dry weight. The belowground biomass of each quadrat was considered equivalent to 30 per cent of aboveground biomass as suggested for broad leaf vegetation by Ponce-Hernandez *et al.* (2004).

The total biomass was calculated and expressed as Mg ha^{-1} (1 Mg = 1 MT) by summing up the aboveground and belowground biomass for herb, shrub and tree layers. Land-use-wise biomass was calculated by averaging the biomass of all quadrats surveyed in a particular land-use type. Statistical tests such as Analysis of Variance (ANOVA) and Duncan multiple range test (DMRT) were carried out for land-use-wise biomass components and total biomass to examine the differences in biomass among different land-uses.

Carbon Stock in Present Land-Uses

The total carbon stock includes both biomass carbon and SOC. The estimated biomass of each land-use was used to compute the respective biomass C using a conversion factor of 0·55 as suggested by Winrock (1997). SOC was estimated from SOM using a conversion factor of 0·58 as suggested by Nelson and Sommers (1982). For each soil series, organic carbon per hectare was calculated by considering SOC value of each soil horizon, bulk density and soil depth. Carbon stock was computed and mapped by summing up biomass carbon and SOC in Geographic Information Systems (GIS) environment.

Soil Carbon Modelling

It is important to know the status of future soil C of present land-use practices, which are likely to continue in the future as the C level relates to the sustainability of agricultural lands. This will help to identify those present land-uses that can retain or increase the level of soil C in future. Among many existing C estimation models, Roth C-26·3 model was used in this study because of its simplicity and low data requirement. Though the model has been developed in the temperate zone it has been shown to perform well in tropical ecosystems as well (Smith *et al*., 1997), including in Kenya, Zimbabwe (Jenkinson *et al*., 1999) and in Thailand (Wu *et al*., 1998). However, Shirato *et al.* (2005) in their study conducted in Thailand reported that the model overestimated soil C while predicting for a long time horizon of 28 and 30 years particularly in the situation of high organic matter incorporation. Hence, in this study the model was run for 10 years to avoid the danger of overestimation.

A detailed description of the model is given in Coleman and Jenkinson (1999). In brief, Roth C model separates the incoming plant residues to the soil into decomposable plant materials (DPM) and resistant plant materials (RPM), both undergoing decomposition to produce microbial biomass (BIO) and humified organic matter (HUM)

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and to evolve CO_2. The clay content of the soil determines the proportions that go to CO_2 or to BIO + HUM. BIO and HUM both undergo further decomposition to produce more CO_2, BIO and HUM. The model also includes a pool of inert organic matter (IOM). Each compartment, except for IOM, undergoes decomposition by first-order kinetics at its own characteristic rate, which is determined by using modifiers for soil moisture, temperature and plant cover. The input parameters include monthly average air temperature, monthly precipitation, monthly open-pan evaporation, and soil clay content, monthly C input from plant residues or farmyard manure and monthly information on soil cover, whether the soil is bare or covered by plants.

The Roth C model requires three sets of data namely soil, climate and management. Climate data included mean monthly temperature, total monthly precipitation and total monthly pan evaporation as required by the model. Land-use data, soil data and climate data were overlaid to prepare agro-ecological zone data. The management data required by the model, for example amount and time of organic manure and residues application (Table I), were derived from the household survey data and were encoded in the land-use map.

GIS was used to extract the data needed to parameterize and run the model. Each agro-ecological zone, represented as polygons in GIS file, required a land management file and a weather file to model soil C. Land management files for each land-use include data on monthly plant residue incorporation and monthly organic manure incorporation both in $\mathrm{Mg\,C\,ha^{-1}}$ and data on surface cover during the month. The weather files contained mean monthly temperature, mean monthly rainfall and mean monthly evaporation extracted from climate data as

Table I. Carbon incorporation from organic manure and residues in different land-uses

Land-use	C from OM ($\mathrm{Mg\,ha^{-1}}$)	Time of OM incorporation	C from residues ($\mathrm{Mg\,ha^{-1}}$)	Time of RI or LF	Fallow period
Cassava	1·19	March	8·36	Nov–Dec	Nov–Dec
Coconut	0·01	June	0·48	Jan–Mar	—
Coconut–cassava	1·10	May	7·69	Dec	—
Eucalyptus					
Year 1	—	—	1·21	Jan–Dec	—
Year 2	—	—	3·16	Jan–Dec	—
Year 3–5	—	—	3·76	Jan–Dec	—
Year 6	—	—	3·79	Jan–Dec	—
Year 7	—	—	4·11	Jan–Dec	—
Year 8	—	—	11·15	Jan–Jun	—
Mixed orchard	1·22	May	3·15	Jan–Dec	—
Para rubber					
Year 1	1·80	Jan	0	None	—
Year 2	—	—	6·40	Aug	—
Year 3, 5	1·80	Jan	1·69	Jan–Dec	—
Year 4, 6	—	—	7·69	Jan–Dec	—
Year 7–29	0·26	Jan	3·56	Jan–Dec	—
Year 30	—	—	14·99	Jan–May	Jan–May
Pineapple					
Year 1	—	—	8·40	Jan, Aug	Jan, Aug
Year 2	1·80	Jan	0	None	—
Pineapple–cassava					
Year 1	—	—	8·40	Jan, Aug	Aug
Year 2	1·80	Jan	0	None	—
Year 3	1·19	March	8·36	Nov–Dec	Nov–Dec
Sugarcane	2·52	April	5·49	Jan	Jan
Sugarcane–cassava					
Year 1–3	1·19	March	8·36	Nov–Dec	Nov–Dec
Year 4–6	2·52	April	5·49	Jan	Jan
Paddy	—	—	8·28	Nov–Jan	Feb–Jun

Source: Questionnaire survey, field measurements and secondary data.
OM, organic manure; RI, residue incorporation; LF, leaf fall.

well as soil depth and clay per cent extracted from soil data. After parameterization, the model was run under current conditions of soil, climate and management for a period of 10 years. The modelled value for each polygon was encoded back to GIS again for visualization.

Trends of soil C accumulation of different land-uses were studied by analysing the initial and modelled C of each land-use in different soils. Average net accumulation for each land-use was estimated by calculating the difference between average of modelled C in all soil series and initial C of the same in respective land-uses. The trend in total soil C accumulation was also estimated using modelled values and respective areas of each combination land-use and soil series. Since the model is not recommended for lowlands and wetlands (Coleman and Jenkinson, 1999) possibly because of different pathways of C dynamics in such land-uses, paddy land-use was not considered for modelling purpose in this study.

Sustainability Analysis

The important role of SOC for sustainable agriculture is well established (Lal, 2006). In this regard, it was important to examine the change in SOC over time for different land-uses from the viewpoint of agricultural land-use sustainability. It is also important for identifying the required level of C management in case of different land-uses and soils.

The limits of SOM requirement for each land-use as suggested by Department of Land Development (DLD, 1992) to evaluate land suitability for individual crop or land-use was considered to estimate the limits of SOC for sustainability. The concept of land suitability as given in the FAO framework of land evaluation (FAO, 1976) was used for setting the SOC threshold limits. According to the framework, land evaluation yields four suitability classes, namely highly, moderately, marginally and not suitable. The factor rating value of highly suitable (S_1) category was taken as threshold of sustainability as the S_1 class has no limitation and thus suppose to provide sustained production without negatively affecting the productive capacity of a given land area for relatively longer period of time. The values lower than this limit in rest of the suitability classes were considered as unstable. This limit was selected based on the assumption that if SOM level falls below the given minimum level of S_1 suitability class, the yield for respective land-uses will be below potential yield which will ultimately lead to unstable situation. The respective SOM content for each soil series extracted from soil map were converted to Mg of C ha^{-1} based on the bulk density of respective soil series calculated up to the depth of 20 cm as plough layer. If the modelled value for each parcel of land-use is higher than the limit for sustainability, that particular land-use is considered sustainable and vice versa. This means that even after 10 years of a particular land-use, the soil C will not be depleted below the required level for potential yield. Sustainability assessment is a complex analytical process and there are several land-use sustainability indicators suggested or in practice (Dumanski and Pieri, 2000; Shrestha, 2004). In this study, modelled C was used as an indicator of land-use sustainability considering the dynamic nature of SOM.

RESULTS AND DISCUSSION

Biomass of Agricultural Land-Uses

Among the land-uses in the study area, land-use under para rubber had the highest average total biomass of 247·89 Mg ha^{-1} while paddy land-use had the lowest biomass of 12·87 Mg ha^{-1} (Table II). Although the total biomass of mixed orchard was about three-fourth of para rubber (189·43 Mg ha^{-1}) no statistical difference was observed between the biomass of these two land-uses. The land-uses having lower biomass included the shrub crops or the land-uses which do not have tall trees, such as pineapple, cassava, pineapple–cassava rotation, sugarcane and sugarcane–cassava rotation. Among the tree crops, coconut, coconut–cassava and eucalyptus had less total biomass compared to mixed orchard and para rubber because of high plant spacing and less intense management of coconut and eucalyptus plantations.

Shrub biomass, which is the total biomass of all species in shrub layer, was found highest in sugarcane (28·59 Mg ha^{-1}) possibly because of sugarcane being a C_4 plant, which is an efficient biomass producer (Ando

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Table II. Average biomass of agricultural land-uses

Land-use	Above ground			Below ground	
	Tree biomass	Shrub biomass	Herb biomass (Mg ha^{-1})	Biomass	Total biomass
Cassava	0	20·36^{b}	1·86^{c}	6·66^{a}	28·89^{a}
Coconut	100·70^{ab}	4·81^{a}	1·5^{bc}	32·10^{bc}	139·17^{bc}
Coconut–cassava	100·72^{ab}	20·43^{b}	1·20^{b}	36·71^{bc}	159·07^{bc}
Eucalyptus	60·14^{b}	0	1·80^{c}	18·58^{b}	80·52^{bc}
Mixed orchard	141·76^{bc}	1·31^{a}	2·63^{d}	43·71^{cd}	189·43^{cd}
Paddy	0	9·13^{a}	0·77^{a}	2·97^{a}	12·87^{a}
Para rubber	187·53^{c}	1·39^{a}	1·75^{c}	57·20^{d}	247·89^{d}
Pineapple	0	18·50^{b}	0·85^{a}	5·8^{a}	25·17^{a}
Pineapple–cassava	0	22·71^{b}	1·25^{b}	7·19^{a}	31·15^{a}
Sugarcane	0	28·59^{c}	0·47^{a}	8·72^{a}	37·79^{a}
Sugarcane–cassava	0	21·36^{b}	1·47^{bc}	6·85^{a}	29·69^{a}

Means with same letter along the columns are not statistically different according to Duncan Multiple Range Test.

et al., 2001). All perennial tree crops, except coconut–cassava intercrop, had significantly lower shrub biomass than all shrub crop land-uses except paddy. Among shrub crop category, sugarcane and pineapple had the lowest herb biomass because of intense weed management practiced in the area and the close spacing and canopy structure of these crops. Cassava, pineapple–cassava rotation and coconut–cassava intercrop had higher herb biomass compared to other shrub land-uses because of less intense management of cassava in the study area which leads to higher weed growth. Perennial tree land-uses had higher herb biomass compared to shrub type land-uses because of less competition and less intense weed management. As there are no trees in shrub crop land-uses they recorded zero tree biomass. Eucalyptus, coconut and coconut–cassava have lower tree biomass compared to mixed orchard and para rubber. This is because of less biomass per tree of coconut and higher spacing in the field compared to orchard or rubber trees. In case of eucalyptus, lower biomass is also attributed to the relatively younger age of plantations in the study area, average age being 3 years. The tree biomass of mixed orchard (141·76 Mg ha^{-1}) was lower than para rubber (187·53 Mg ha^{-1}), however, no statistically significant difference was observed. The biomass of sugarcane (37·79 Mg ha^{-1}) is comparatively less to that of the reported value of 42·61 Mg ha^{-1} by Prammanee (2005) in Thailand under research conditions. However, other reports cited much higher biomass values (from 46·32 to 63·25 Mg ha^{-1}) for sugarcane (De Silva and De Costa, 2004). Similarly, shrub biomass of cassava (20·36 Mg ha^{-1}) is comparable to that earlier reported (22·74 Mg ha^{1}) by Howeler (1985). All tree crop land-uses had higher biomass ha^{-1} compared to the shrub crop land-uses indicating the importance of tree crop species for C sequestration in cultivated landscape. It is also interesting to note that the inter-crop of coconut–cassava had higher biomass than either cassava or coconut.

Biomass Carbon

The total biomass C from agricultural land-uses in the study area was 8·51 Tg (1 Tg = 1 million Mg) of which the major share came from para rubber (51 per cent) and mixed orchard land-uses (33 per cent), respectively as these land-uses occupied 23·3 and 19·79 per cent of agricultural area in the watershed (Table III). The other land-uses in contributing the proportion of total biomass C in decreasing order were pineapple (3·8 per cent), cassava (3·34), sugarcane–cassava (2·84), pineapple–cassava (1·91) and eucalyptus (1·08 per cent). The combined share of biomass C contribution of land-uses, namely coconut, coconut–cassava, paddy and sugarcane was about 2 per cent basically due to smaller areas (less than 1 per cent) except paddy which occupied 6·07 per cent of total agricultural area.

The average tree biomass C estimated for few land-uses in this study were 33·09 Mg ha^{-1} in case of eucalyptus, 103·14 Mg ha^{-1} in para rubber and 77·97 Mg ha^{-1} in mixed orchard which differ slightly from some of the reported

Table III. Land-use-wise carbon contribution, and biomass and soil C

Land-use	Area (%)	Contribution to total C (%)	Contribution of BMC (%)	Ratio BMC:SC
Cassava	12·97	9·16	3·34	0·18
Coconut	0·56	0·53	0·63	1·20
Coconut–cassava	0·44	0·34	0·69	3·14
Eucalyptus	1·50	1·30	1·08	0·53
Mixed orchard	19·79	24·49	33·36	1·30
Paddy	6·07	2·89	0·70	0·11
Para rubber	23·30	37·59	51·40	1·31
Pineapple–cassava	6·90	4·16	1·91	0·24
Pineapple	16·95	11·92	3·80	0·15
Sugarcane–cassava	10·76	7·12	2·84	0·20
Sugarcane	0·75	0·51	0·25	0·26
Total	100	100	100·00	0·71

Total area: 137,363 ha; total C: 20·5 Tg; BMC, biomass carbon; SC, soil carbon. Soil C derived for each soil series based on respective profile depth ranging from 70 to 200 cm in the study area. Bulk density of horizons of soil series ranges 1·17–1·58 Mg m^{-3}.

studies on biomass C conducted elsewhere, for example 50·7 Mg ha^{-1} for eucalyptus (Miehle *et al*., 2006), 97 Mg ha^{-1} for para rubber (Noordwijk *et al*., 2000) and 12–228 Mg ha^{-1} for orchards (Albreacht and Kandji, 2003).

Soil Carbon in Agricultural Land-Uses

The total soil C in the agricultural land-uses amounted to 12 Tg, of which land-uses, such as para rubber, mixed orchard, pineapple, cassava and sugarcane–cassava contributed 27·79, 18·21, 17·69, 13·28 and 10·58 per cent, respectively. As stated earlier, there are several soil series in the study area. Map Bon soil series (Typic paleudults), a dominant series covering 20 per cent of the area, has a soil C of 78·98 Mg ha^{-1}. Other major soil series, such as Phangnga (Typic Paleudults), Satuk (Oxic Paleustults) and Huai Pong (Typic Paleudults), covering 16, 10 and 10 per cent area, have soil C 121·26, 28·86 and 78·23 Mg ha^{-1}, respectively (Table IV).

Total Carbon Stock in Agricultural Land-Uses

The spatial distribution of C stock in the agricultural land-uses is presented in Figure 1. The total C stock in agricultural land-uses was 20·5 Tg, of which 41·49 per cent was biomass C and 58·51 per cent was soil C. Para rubber covering nearly one quarter (23·3 per cent) of agricultural land-uses contributed 39·59 per cent of total C stock. Land-use under mixed orchard, covering 24·49 per cent of area, contributed 19·79 per cent of total C stock. While comparing the contribution of soil C and biomass C to C stock, the contribution of soil C to C stock was normally higher than biomass C in shrub crop land-uses but was lower in case of tree crop land-uses. Even though para rubber had the highest biomass ha^{-1}, the highest ratio of biomass C to soil C was recorded for coconut–cassava (3·14) due to the fact that contribution of soil C is lower in coconut–cassava than in all other land-uses (Table III). Some land parcels with shrub crops containing higher soil C have more C stock than the land-uses under perennial tree crops.

The overall BMC:SC ratio for the study area is 0·71, indicating relatively higher contribution of soil C to carbon stock. However, for individual land-uses the ratio varies from 0·15 to 3·14. It is interesting to note that the land-uses with shrub crop species, for example pineapple ($\leq$0·26) have lower BMC:SC ratio compared to land-uses having tree crop species, for example coconut ($\geq$0·53). Similar BMC:SC ratios for shrub crops, such as sorghum (0·11–0·19) and cotton (0·07–0·15), have been reported earlier in USA (Sainju *et al*., 2005). BMC:SC ratio in case of primary forest plots in tropical Colombia was 0·69 (Sierra *et al*., 2007) whereas the ratio was 0·53 for agro-forestry and 1·19 for secondary forestry plots in Brazilian Amazon (Schroth *et al*., 2002). These findings are similar to that of present study, in which BMC:SC of land-uses having tree species ranges between 0·53 and 3·14 indicating the effect of tree crops in an increased ratio of BMC:SC.

Table IV. Soil C in different soil series of agricultural land-uses

Soil series local name	Soil series Taxonomic name	Soil C ($\mathrm{Mg\,ha^{-1}}$)	Soil depth (cm)	Area in agricultural land-use (%)
Ban Bung	Sandy, siliceous, isohyperthermic, Aquic Quartzipsamments	119·84	150	4·66
Bang Lamung	Halic Psammaquent	35·58	100	3·08
Ban Thon	Sandy, siliceous, isohyperthermic, Typic Tropohumods	182·62	136	1·07
Bangnara	Fine clayey, kaolinitic, isohyperthermic, Typic Paleaquults	36·64	100	0·28
Chalong	Fine loamy, mixed, isohyperthermic, Typic Paleudults	228·34	140	5·17
Chon Buri	Fine loamy, mixed, isohyperthermic, Typic tropaqualfs	26·88	150	0·11
Huai Pong	Fine clayey, kaolinitic, isohyperthermic, Typic Paleudults	78·23	75	10·25
Hup Krapong	Coarse loamy, siliceous, isohyperthermic, Ustox Dystropepts	24·97	180	2·66
Kabin Buri	Clayey skeletal, kaolinitic, isohyperthermic, Typic Paleustults	107·3	115	0·01
Khlong Nok Krathung	Fine loamy, mixed, isohyperthermic, Typic Paleudults	95·23	100	1·56
Kohong	Coarse loamy, siliceous, isohyperthermic, Typic Paleudults	60·05	100	0·33
Khok Khain	Fine loamy, mixed, isohyperthermic, Typic Paleaquults	31·02	100	3·08
Khok Kloi	Fine clayey, kaolinitic, isohyperthermic, Typic Paleudults	92·84	100	3·83
Map Bon	Fine loamy, mixed, isohyperthermic, Typic Paleudults	78·98	120	19·98
Nong Mot	Clayey, kaolinitic, isohyperthermic, Oxic Paleustults	130·56	130	1·46
Phangnga	Clayey, kaolinitic, isohyperthermic, Typic Paleudults	121·26	110	16·14
Phattaya	Sandy, siliceous, isohyperthermic, Aquic Quartzipsamments	170·67	150	0·11
Phon Phisai	Clayey skeletal, Mixed, isohyperthermic, Typic Plinthustults	77·09	160	0·04
Phuket	Clayey, kaolinitic, isohyperthermic, Typic Paleudults	58·45	100	1·34
Ratchaburi	Fine, mixed, isohyperthermic, Aeric Tropaquepts	149·14	115	0·56
Rayong	Sandy, siliceous, isohyperthermic, Typic Quartzipsamments	53·25	140	0·13
Sattahip	Sandy, isohyperthermic, Typic Quartzipsamments	39·21	120	4·26
Satuk	Fine loamy, siliceous, isohyperthermic, Oxic Paleustults	28·87	200	10·26
Tha Sae	Fine loamy, mixed, isohyperthermic, Typic Paleudults	41·74	100	0·14
Thai Muang	Clayey, kaolinitic, isohyperthermic, Typic Tropudults	105·72	135	2·88
Thung Wa	Coarse loamy, siliceous, isohyperthermic, Oxic Dystropepts	74·23	100	6·42
Wan Priang	Sandy, siliceous, isohyperthermic, Typic Tropaquepts	57·19	120	0·04

Bulk density of soil horizons of existing soil series in the area ranges between 1·17 and 1·58 $\mathrm{Mg\,m^{-3.}}$

Trend of Soil Carbon Accumulation

Overlay of land-use and soil map resulted into number of land unit characterized by unique combination of land-use and soil. The results of Roth C modelling of all resulting land unit areas are presented in Table V. Most of the land units had a range of modelled C value because they occur in more than one climate zone and C accumulation pattern depends on climate as well. It was found that the land-uses, such as cassava and mixed crop of coconut–cassava, can accumulate C better as these land-uses had higher modelled C values compared to the initial C values in all cultivated soil series, evidenced by the positive values of per cent increase in soil C in all soils. These land-uses also recorded higher average net C accumulation (difference between initial soil C of all cultivated soils and modelled C of a particular land-use) of 14·69 $\mathrm{Mg\,ha^{-1}}$ in mixed land-use of coconut–cassava and 5·95 $\mathrm{Mg\,ha^{-1}}$ in cassava alone. This can be attributed to the additional organic C added annually to the soils in these land-uses in the form of both poultry manure and plant residues compared to other land-uses as presented in Table I. However, the higher per

Table V. Forecasted per cent increase of soil C in different land-uses and soils

Soil series	Initial C* (Mg ha^{-1})	Clay %	Cassava	Coconut	Coconut–cassava	Eucalyptus	Mixed orchard	Para rubber	Pineapple	Pineapple–cassava	Sugarcane	Sugarcane–cassava
Ban Bung	15·97	5·00	48–56			15–23	17–31	16–26	14–20	40–45	37–49	35–42
Bang Lamung	16·11	5·35					17	19	15	53		
Ban Thon	58·46	5·07					¯20–¯21	21–22				
Bang Nara	26·19	27·00					3	7				
Chalong	28·01	19·00	22			3	4	1–3	1–5	16–20	20	16–19
Chon Buri	11·76	5·85	84				36	35–41	32–34	72–84		
Huai Pong	43·69	22·40	3–6			¯9–¯14	¯11–¯12	¯8–¯12	¯8–¯11	1–2	50	0·4
Hupkrapong	8·44	11·24	149–150	¯15	176	75	75–79	83		123–124	119–126	118
Kabin Buri	45·54	21·00										¯1
Khlong Nokkratung	37·40	13·50	5–7	¯26		¯8-¯11	¯7-¯10	6–13	¯7·0–¯8			3
Khohong	30·27	6·50					¯8	7				
Khok Khain	19·54	15·50					13–15	14–17				
Khok Koi	30·97	11·50	12–15			¯7–¯9	¯3–¯7	¯3–¯6	¯2–¯4	10–12	11–12	9–11
Map Bon	18·46	12·92	46–51	¯20–¯22		13–18	15–18	16–22	14–17	38–41	40–42	36–43
Nong Mot	45·74	28·40		–26		¯11–¯12	¯10–¯11	¯9–¯10	¯9–¯14	0–¯3	4	¯2–1
Phang Nga	38·01	4·20	1	–28		¯12–¯17	¯12–¯15	¯11–¯14	¯13–¯14	¯1–¯4	¯1–4	¯8–3
Phattaya	22·61	2·00					0·35					
Phon Pisai	30·09	34·80										34
Phuket	25·96	21·78	29			6–7	3·0–4	2–10	5–6	22–25	22–29	20–27
Ratchburi	42·40	44·40	6–8				¯10	¯10	¯7			
Rayong	11·17	0·50					34					
Sattahip	10·85	1·00	82–83	¯19		36–37	38–39	40	34	70–71		
Satuk	8·14	4·50	134–136	¯16–¯17	171	54–67	59–81	73–74	61–64	113–123	108–128	104–117
Tha Sae	24·41	13·00					3		5	11		
Thai Muang	30·35	15·34	16–17	¯27		¯1	¯3–¯4	¯2–¯4	¯2	4	11–12	
Thung Wa	20·04	6·00	30–36	¯28		6	6–10	5–14	7–17	27–30	27–34	23–31
**Av.Net C Mg ha^{-1}			5·95	¯6·05	14·69	¯0·5	0·13	¯0·52	0·89	4·98	5·29	4·42

*C in 20 cm depth.

**Av.Net C—The difference between the averages of modelled C of all soil series of one land-use and average of initial C of the same.

cent increase of soil C in coconut–cassava land-use than cassava alone may be due to the effect of vegetative cover provided by coconut on soil C dynamics. The vegetative cover can effectively reduce soil temperature, which in turn can reduce C depletion. On the other hand, the single crop of coconut ranked last in the C accumulation as shown by lower-modelled C values compared to the initial C content in all soil series indicated by negative values of per cent increase in soil C and average net C of $-6{\cdot}05\,\mathrm{Mg\,ha^{-1}}$. This can be attributed to the poor management of organic matter in this land-use as no organic manures or residues are incorporated in coconut land-use except the herb biomass added during the dry season. It is interesting to note that coconut–cassava land-use which is an intercropping of cassava between coconuts had remarkably higher modelled soil C compared to coconut alone because of addition of organic manure and cassava residues. Even though there was no organic manure added in eucalyptus field as well as to that of coconut, eucalyptus had notably higher percentage of soil C increase compared to coconut land-use for the potential reason of higher litter fall of eucalyptus ($1{\cdot}3$–$11\,\mathrm{Mg\,ha^{-1}}$) depending on age (Davidson, 1993). Similarly, mixed orchard and para rubber also showed positive increase in C in most of soil series as a result of C addition through leaf litter and incorporation of organic manure.

Modelled soil C was found to vary among the different land-uses even in the same soil series. On the other hand, modelled soil C of same land-use was found to vary in different soil series. These situations indicate that both land-use and soil have influence on C dynamics. Soil series with C less than $10\,\mathrm{Mg\,ha^{-1}}$ had more than 50 per cent increase in modelled C in all land-uses. Likewise soil series having soil C between 10 and $30\,\mathrm{Mg\,ha^{-1}}$ had resulted into soil C increase in 10 years in all land-uses. However, soil series with higher initial soil C ($>30\,\mathrm{Mg\,ha^{-1}}$), namely Ban Thon (Typic Tropohumods), Huai Pong (Typic Paleudults), Phangnga (Typic Paleudults), Nong Mot (Oxic Paleustults) and Ratchburi (Aeric Tropaquepts), recorded reduced modelled soil C for most land-uses probably due to the reason that as C depletion from the soil is a function of initial soil C (Coleman and Jenkinson, 1999), soils with higher initial C need much more C input to maintain or enhance the soil C. Therefore, cultivation of shrub crops or shrub-tree intercrops with addition of manures and residues in the soil series with initial higher soil C content would help reduce soil C depletion. Since some land-uses lead to reduced soil C in a particular soil series while other land-uses increase soil C, it is possible to increase soil C by changing land-uses in those soils. For example, in Khlong Nok kratung (Typic Paleudults) soil series, a reduced rate of SOC was observed for all other land-uses except cassava and sugarcane–cassava. Therefore, changing land-uses to cassava or sugarcane–cassava can improve SOC in this soil series.

The current and projected total soil C of current land-uses for the next 10 years is presented in Table VI. The result shows that, in the study area, the total soil C accumulation in 10 years is equivalent to 0·215 Tg. Land-uses, like cassava, sugarcane–cassava and pineapple–cassava were found to have higher calculated C accumulation with 0·097, 0·077 and 0·060 Tg C, respectively. The land-uses with less C accumulation were coconut–cassava, mixed orchard, sugarcane, eucalyptus and pineapple with corresponding C amount of 0·009, 0·007, 0·007, 0·002 and

Table VI. Total soil C accumulation in different land-uses

Land-use	Present soil C (Tg)	Soil C in 10 years (Tg)	Average rate of change over 10 years ($\mathrm{Kg\,ha^{-1}\,y^{-1}}$)
Cassava	1·593	1·689	595
Coconut	0·049	0·046	605
Coconut–Cassava	0·017	0·026	1469
Eucalyptus	0·174	0·176	50
Mixed orchard	2·184	2·191	130
Paddy	0·533	0·533	0
Para rubber	3·334	3·291	52
Pineapple	2·122	2·123	89
Pineapple–cassava	0·689	0·749	489
Sugarcane	0·082	0·089	529
Sugarcane–cassava	1·218	1·295	542
Total	11·995	12·210	299

Total carbon estimated for profile depth ranging from 70 to 200 cm. Soil C modelling was done up to 20 cm.

0·001 Tg, respectively. On the other hand, in case of para rubber and coconut land-uses, about 0·043 and 0·003 Tg of soil C, respectively are estimated to be depleted in 10 years of time. The average rate of change of soil C in the study area was 299 kg ha^{-1} y^{-1}. This rate was highest in coconut–cassava (1469 kg ha^{-1} y^{-1}) and the lowest in eucalyptus (50 kg ha^{-1} y^{-1}). Contrary to the general belief that the soil C is depleted in agricultural land-uses (Paustian *et al*., 1997; Korschens, 1998; Woomer *et al*., 1998), the modelled SOC values in this study indicate the increase in SOC primarily due to the farmers' management practices of incorporating organic manures and crop residues in the agricultural fields in the study area.

Sustainability of Present Soil Carbon Management

The examination of C maintenance in given land-use types over a 10-year period was the purpose of sustainability analysis. The spatial distribution of sustainable and unstable areas is presented in Figure 2. The analysis indicated that 83 per cent of agricultural land-uses are sustainable and only 17% is unstable (Table VII), that is even after 10 years of continuous cultivation of present land-uses 83 per cent of the land-uses can maintain organic C required to be classified as being at a highly suitable level for each of the relevant land-uses. Among the land-uses, cassava, pineapple–cassava and coconut–cassava are sustainable in all cultivated areas. Land-uses, like para rubber, pineapple, eucalyptus and mixed orchards had 97 per cent, 89 per cent, 84 per cent and 75 per cent of the areas, respectively, under sustainable category. However, no areas under coconut land-use were sustainable. Similarly, sugarcane and sugarcane–cassava also had relatively lower per cent of area, 21 per cent and 30 per cent, respectively, under sustainable category. This is mainly due to the higher requirement of SOM (2·5 per cent SOM) for highly suitable level of coconut and sugarcane compared to other land-uses (1 per cent SOM) (DLD, 1992).

It is to note that biomass C is higher in land-uses under tree crops compared to shrub crops while the opposite is true in case of soil C accumulation. However, intercropping of tree-shrub (coconut–cassava) had high biomass and soil C accumulation. This finding opens up an opportunity for future land-use planning and research in terms of C stock management in agricultural land-uses in the sense that although 83 per cent of land-uses are sustainable there is still scope to increase the soil C accumulation by changing the land-uses. This is possible because different land-uses accumulate or deplete soil C in different rates in different soils and agro-ecological zones.

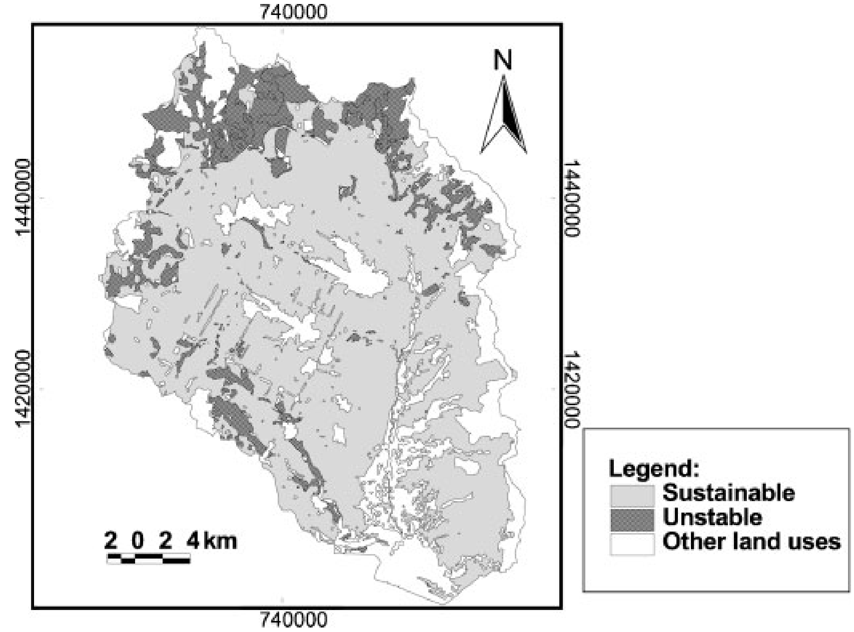

Figure 2. Land-use sustainability in terms of soil carbon management.

Table VII. Sustainability of land-use in maintaining soil C

Land-use	Total area (ha)	Sustainable (%)	Unstable (%)
Cassava	17 858	100	0
Coconut	769	0	100
Coconut–cassava	628	100	0
Eucalyptus	2073	84	16
Mixed orchard	27 637	75	25
Para rubber	32 066	97	3
Pineapple	23 335	89	11
Pineapple–cassava	9445	100	0
Sugarcane	1031	21	79
Sugarcane–cassava	14 760	36	64
Total	129 602	83	17

CONCLUSION AND RECOMMENDATIONS

The total biomass C, soil C and total C stock of the agricultural land-uses in the study area were 8·5 Tg, 12·0 Tg and 20·5 Tg, respectively. Land-uses under tree crops have relatively higher biomass compared to shrub crops, such as sugarcane, sugarcane–cassava, pineapple–cassava, cassava and pineapple. Among tree crops, para rubber and mixed orchard had higher biomass per unit area than coconut, coconut–cassava and eucalyptus.

The results of sustainability analysis in terms of soil C management indicate that 83 per cent of the total agricultural land-uses in the study area are sustainable whereas 17 per cent are unstable. All the areas under cassava, pineapple–cassava and coconut–cassava, and 97, 89, 84 and 75 per cent of para rubber, pineapple, eucalyptus and mixed orchard, respectively, are sustainable. None of the land-use parcels of coconut was found to be sustainable.

The results of soil C modelling in combination with biomass of the respective land-uses of an agro ecological zone will be valuable information in selecting land-use options that contribute in C sequestration. In general, the study reveals that tree crop species improve biomass C while shrub crop species enhance soil C. This indicates the potential for adopting a mixed land-use of tree and shrubs for better C sequestration due to complementary effect of combining them. Nevertheless, sustainability encompasses much broader concept, and hence further studies on other factors, such as land degradation, plant diversity and socioeconomic factors are also essential for a comprehensive view of land-use sustainability.

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