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RESEARCH PAPER

# Profiles of carbon stocks in forest, reforestation and agricultural land, Northern Thailand

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**Abstract**: A study was conducted to assess carbon stocks in various forms and land-use types and reliably estimate the impact of land use on C stocks in the Nam Yao sub-watershed (19°05′10″N, 100°37′02″E), Thailand. The carbon stocks of aboveground, soil organic and fine root within primary forest, reforestation and agricultural land were estimated through field data collection. Results revealed that the amount of total carbon stock of forests (357.62 ± 28.51 $\mathrm{Mg \cdot ha^{-1}}$, simplified expression of Mg (carbon)$\cdot \mathrm{ha^{-1}}$) was significantly greater ($P < 0.05$) than the reforestation (195.25 ± 14.38 $\mathrm{Mg \cdot ha^{-1}}$) and the agricultural land (103.10 ± 18.24 $\mathrm{Mg \cdot ha^{-1}}$). Soil organic carbon in the forests (196.24 ± 22.81 $\mathrm{Mg \cdot ha^{-1}}$) was also significantly greater ($P < 0.05$) than the reforestation (146.83 ± 7.22 $\mathrm{Mg \cdot ha^{-1}}$) and the agricultural land (95.09 ± 14.18 $\mathrm{Mg \cdot ha^{-1}}$). The differences in carbon stocks across land-use types are the primary consequence of variations in the vegetation biomass and the soil organic matter. Fine root carbon was a small fraction of carbon stocks in all land-use types. Most of the soil organic carbon and fine root carbon content was found in the upper 40-cm layer and decreased with soil depth. The aboveground carbon:soil organic carbon: fine root carbon ratios (ABGC: SOC: FRC), was 5:8:1, 2:8:1, and 3:50:1 for the forest, reforestation and agricultural land, respectively. These results indicate that a relatively large proportion of the C loss is due to forest conversion to agricultural land. However, the C can be effectively recaptured through reforestation where high levels of C are stored in biomass as carbon sinks, facilitating carbon dioxide mitigation.

**Keywords**: carbon stock; aboveground carbon; soil organic carbon; fine root carbon; land use; Thailand

## Introduction

It is clear that fossil fuel emissions dominate the anthropogenic perturbation of the global carbon cycle. Land use changes currently drive the largest proportion of anthropogenic emissions in a number of tropical regions of Asia (Canadel 2002). According to the Kyoto Protocol, land use, land-use change, and forestry (LULUCF) are recognized as serving the role of carbon source and sink in relation to a change in land cover and carbon stocks. It also influences the amount of biomass and carbon stored in vegetation (IPCC 2000). Land-use changes also affects soil carbon (C) storage because soils are either carbon sources or sinks depending upon the variable response of soil C pools to land-cover change (Power et al. 2004). Forests are the most important carbon pool on land. Approximately 60%–70% of carbon in forests is stored as organic material in the soil (Janssens et al. 1999). Accordingly, the conversion of forests to agricultural land not only reduces C stocks in vegetation but also causes significant losses of soil organic carbon (Post and Kwon 2000). Reduction of soil C stocks are also associated with agricultural management *i.e.* residue removal *via* harvesting or burning, and soil tillage (Hairiah et al. 2001).

A number of recent studies on the association of carbon storage with land-use shifts have focused on *in situ* carbon change in tropical zones. Lasco (2002) found that deforested areas covered with grasses and annual crops, have carbon densities that are typically less than 40 $\mathrm{Mg \cdot ha^{-1}}$ (simplified expression of Mg (carbon)$\cdot \mathrm{ha^{-1}}$). This is much less than the carbon densities found in natural forests. The conversion of natural forests to tree plantations and perennial crops reduce carbon density by at least 50% when compared to natural forests (Lasco 2002). In the lower Mekong basin, paddy fields and grassland have aboveground carbon less than 4% of that in primary dipterocarp forest (Gajaseni 2000).

In Thailand, forest degradation has been identified as a major contributing factor to carbon stock losses. FAO (2003) estimated that Thailand's annual forest loss was at 112 million hectares per year, during the period 1990–2000 (0.7% annually). Over the period 2000-2004, Thailand lost an average of 60 475 ha of natural forest per year (National Park, Wildlife and Plant Conservation Department 2005). The deforestation rate has declined slightly since the period 1990–1995 due to already diminished forest

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cover as well as increasing public and governmental ecological interest (FAO 2003). Estimates of Thailand's $CO_2$ emissions in 1994 were 241 Tg, and the projected level of $CO_2$ emissions in 2020 were approximately 583 Tg to 777 Tg. Total $CO_2$ emissions would continue to increase because of a more than two fold increase in energy consumption between the years 2000 and 2020. The average increase of $CO_2$ emission from the energy and forestry sectors is about 5% annually (OEPP 2000).

Based on current information, reforestation is believed to have the potential to contribute to C storage directly through accumulation of C in biomass and soil (Richter et al. 1999; Silver et al. 2000). Facilitating reforestation by establishing plantations on abandoned and degraded agricultural land in the tropics has been proposed as an effective carbon management approach (Montagnini and Porras 1998). According to FAO (2001), forest plantations account for 187 million hectares in Asia which is the largest amount in any region globally. Reforestation in Thailand often consists of a mix of planted and naturally regenerated species. Both native and exotic species are grown in reforestation areas. In particular, exotic, fast-growing species are often chosen for reforestation when native species are difficult to establish. The presence of planted community is likely to affect carbon dynamics. However, reforestation and forest plantation in Thailand seem to be more concerned with improvement of degraded forest ecosystems than carbon management and climate change mitigation. Despite the abundance of estimates of forest biomass in Thailand, the data is not capable of facilitating direct comparisons across various land use types. Lack of distinctions between forest, reforestation and agricultural land and incomplete measurements of carbon pools in each land use make comprehensive analysis difficult. This lack of information hinders any attempt to optimally utilize the findings in the studies. On this basis, the understanding of carbon stocks in land use is essential to addressing Thailand climate change mitigation efforts.

In order to reliably estimate the impact of land use on C stocks, this study included the estimates of C storage in various forms including aboveground, fine root and soil C within forests, reforestations and agricultural lands in Nam Yao sub-watershed. This area is also known as the main catchment of Nan watershed, which covers an area of 34 331 km$^2$ in Thailand. The objectives of this study are: (i) to assess carbon stock in various forms in different land-use types; and (ii) to estimate the relative amounts of carbon stocks between aboveground and belowground for use in climate change mitigation.

## Methods

### Study site

The study area is located in Nam Hean watershed management unit area, Num Yao sub-watershed, Nan province (19°05′10″N, 100°37′02″E). The land area is approximately 19 000 ha (Fig. 1). The elevation ranges from 215 to 1 674 m a.s.l. The soil parent material consists of sandstone, shale stone and lime stone. Soils are mainly Red Yellow Podzolic soils and Reddish Brown Lateritic soils. The average air temperature is 16.9°C during the dry season and 32.5°C during the wet season. Average annual precipitation is 1 405 mm. The land cover types consist of hill evergreen and mixed deciduous forest, reforestation, orchard, cornfields, paddy fields, and small part of other crop cultivations. In this area, the natural forest has been severely degraded during the past thirty years due to legal and illegal logging, shifting agriculture, and uncontrolled forest fires. Because of the severe deterioration of the forest conditions, reforestation initiatives have become a high priority to the Royal Thai Government. Since the 1960s, reforestation activities have been implemented in the degraded areas of Nam Hean watershed. Farmland and heavily eroded areas were replanted with fruit and economic trees by hill tribes and Thais. In the late 1970s, plans to reforest depleted areas by planting native and exotic species for the purpose of watershed conservation were designed and implemented (Royal Forest Department 1998).

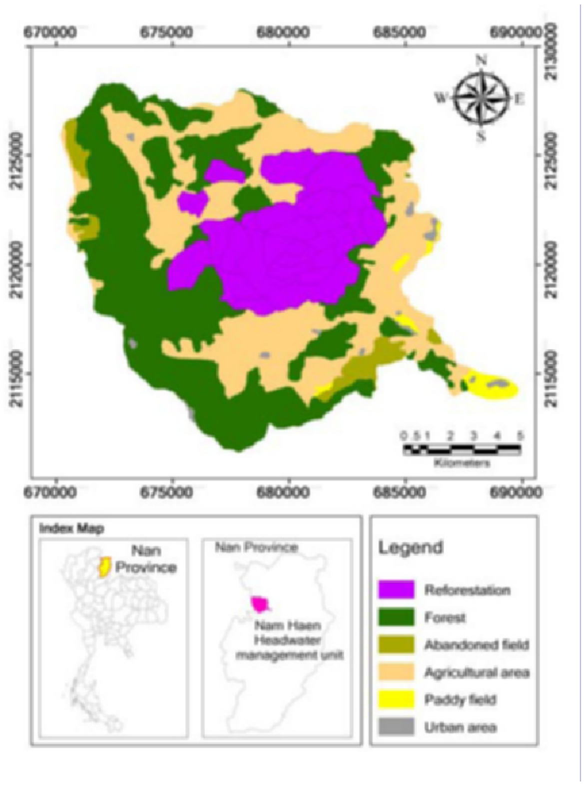

**Fig. 1 Location of the study area**

The study was conducted in three main land-use types: forest, reforestation, and agricultural land. All five natural forest sites had been protected from logging for over half a century, three of which were hill evergreen forest, and two were mixed deciduous forests (Table 1). The reforested sites were planted with four native species and two exotic species in 1979 (Table 1). The agricultural sites were cleared prior to 1957 after which these areas were privately owned and cultivation of small grain and corn was practiced by illegal private owners. The agricultural sites included fallow land (6-year fallow), orchard (*Litchi chinensis* Sonn. spp.), paddy fields, and corn fields which still employ conventional tillage and chemical fertilizers (Table 1).

**Table 1. Sample collection: location and ownership of forest sites, reforestation sites and agricultural sites within Num Haen Watershed Management unit**

| Sites | | Location | Type/plantation | Plot size ($m^2$) | Ownership |
|---|---|---|---|---|---|
| Forest | F1 | 47Q 0672289 UTM 2125707 | Hill evergreen forest | 50 x 50 | National Park Reserves |
| | F2 | 47Q 0672583 UTM 2124503 | Hill evergreen forest | 50 x 50 | National Park Reserves |
| | F3 | 47Q 0671989 UTM 2126546 | Hill evergreen forest | 50 x 50 | National Park Reserves |
| | F4 | 47Q 0680732 UTM 2115809 | Mixed deciduous forest | 50 x 50 | National Park Reserves |
| | F5 | 47Q 0685006 UTM 2116909 | Mixed deciduous forest | 50 x 50 | National Park Reserves |
| Reforestation | RF1 | 47Q 0684082 UTM 2122527 | *Gmelina aborea* Roxb. (exotic) | 50 x 50 | Num Haen Watershed Management Unit |
| | RF2 | 47Q 0680748 UTM 2119676 | *Eucalyptus camaldulensis* Dehn. (exotic)<br>*Tectona grandis* Linn. (native) | 50 x 50 | Num Haen Watershed Management Unit |
| | RF3 | 47Q 0683003 UTM 2122381 | *Tectona grandis* Linn. (native) | 50 x 50 | Num Haen Watershed Management Unit |
| | RF4 | 47Q 0679903 UTM 2119368 | *Tectona grandis* Linn. (native)<br>*Pterocarpus macrocarpus* Kurz. (native)<br>*Afzelia xylocarpa* (Kurz) Craib. (native) | 50 x 50 | Num Haen Watershed Management Unit |
| | RF5 | 47Q 0680990 UTM 2119752 | *Tectona grandis* Linn. (native)<br>*Pterocarpus macrocarpus* Kurz. (native)<br>*Afzelia xylocarpa* (Kurz) Craib. (native)<br>*Acacia catechu* (L.f.) Willd (native) | 50 x 50 | Num Haen Watershed Management Unit |
| Agriculture | A1 | 47Q 0683820 UTM 2123305 | Fallow land (6-year fallow) | 50 x 50 | Private landowner |
| | A2 | 47Q 0673679 UTM 2126388 | Orchard (*Litchi chinensis* Sonn. spp.) | 50 x 50 | Private landowner |
| | A3 | 47Q 0681248 UTM 2117440 | Paddy field (*Oryza sativa* Linn.) | 1 x 1 | Private landowner |
| | A4 | 47Q 0673788 UTM 2126210 | Corn field (*Zea mays* L.) | 1 x 1 | Private landowner |
| | A5 | 47Q 0681215 UTM 2124023 | Corn field (*Zea mays* L.) | 1 x 1 | Private landowner |

**Note:** location codes refer to Fig. 1

## Data collection

### *Aboveground carbon and carbon stocks*

To assess the biomass, plots of 50 m × 50 m were established in all land-use types. The number of plots chosen for each land-use type was based on its distribution in the study area and the expected variability in the amount of carbon. In the forest, the most common type of hill evergreen and mixed deciduous areas were expected to have a high degree of variability in the amount of carbon thus a larger number of plots ($n = 32$) were selected. Reforested areas, were expected to have lower variability in the amount of carbon, and fewer plots ($n = 20$) were chosen. For agricultural land, the selected plots were located in various fields ($n = 28$). In fallow land and orchards, selected plots of 50 m × 50 m were established ($n = 8$). Corn fields and paddy fields were selected with the plots size of 1 m × 1 m ($n = 20$) regarding the homogenous pattern and limited damage to the farmers. All individual trees of ≥ 4.5 cm diameter at breast height (dbh) at 1.30 m height above the ground were measured and identified. Trees were divided into two size classes of dbh: small tree (≤ 25 cm) and large tree (> 25 cm). Density ($\text{individual}\cdot\text{ha}^{-1}$), basal area ($\text{m}^2\cdot\text{ha}^{-1}$) and biomass ($\text{Mg}\cdot\text{ha}^{-1}$) were calculated. The aboveground biomass was calculated using the developed allometric equations in Thailand for hill evergreen forest (Tsutsumi et al. 1983), mixed deciduous forest (Ogawa et al. 1965), *Gmelina aborea* Roxb. (Sritulanont et al. 1983) *Eucalyptus camaldulensis* Dehn. (Kamo 1999), *Tectona grandis* Linn. (Viriyabuncha et al. 2001), and Bamboo (*Thyrsostchys siamensis*, Suwannapinunt 1983; *Gigantchloa albociliata* and *Bambusa tulda*, Kutintara et al. 1995). We developed the following equations for *Litchi chinensis* Sonn. spp. tree at the site as follows:

$$\text{Log } Ws = 0.8712 \log D^2H - 1.5735 \qquad r^2 = 0.9941$$
$$\text{Log } Wb = 0.8023 \log D^2H - 1.7695 \qquad r^2 = 0.9858$$
$$\text{Log } Wl = 1.2113 \log D^2H - 2.5229 \qquad r^2 = 0.9823$$

Where $D$ is the diameter at breast height (cm) and $H$ the height (m); $Ws$ the stem dry weight, $Wb$ the branch dry weight, and $Wl$ is the leave dry weight; $n = 10$.

The biomass of the understory layer consisting of < 4.5 cm diameter trees (saplings) were analyzed in the 25 sub plots of 4 m × 4 m in each plot of 50 m × 50 m. Seeding and herbs were analyzed in the 25 sub plots of 1m × 1 m in each sapling plot in forest, reforestation, fallow land, and orchards. Mean wet weight was obtained from each species by measuring wet weight of individuals. Sub samples were oven-dried to determine the ratio of dry-wet weight. The ratios were then applied over the entire sample of each species for conversion to dry weight. All aboveground components were assumed to have 50% C content (Brown and Lugo 1984; Levine et al. 1995).

### *Fine root carbon and soil carbon stocks*

The soil samples were collected consisting of five random samples in each 50 m × 50 m plot across land-use types. The number of soil samples in forest, reforestation and agricultural land was 160, 100 and 115, respectively. The soil was sampled by soil cores, hereafter referred to as soil profiles, to a depth of 100 cm and separated into layers 0–20, 20–40, 40–60, 60–80, and 80–100 cm. In order to detect the soil organic carbon (SOC) storage change without destroying soil structure, soils bulk density was measured by using a cutting ring. Root size ≤5 mm in diameter was separated by hand sorting and then successively sieved through 5 mm and 2 mm mesh sieve to remove the remaining root fragments from each layer. Roots were weighed fresh and then oven-dried at

90°C for 12 h to constant weight. Wet-dry weight ratio was determined for each sample. Organic carbon contents in root and soil were determined based on three replicates using the Walkley-Black method (Walkley and Black 1934). This method oxidizes only the organic carbon while avoiding interference by carbonates (Hesse 1971). The SOC content of each layer was calculated for bulk density and summed for the entire soil profile to estimate total SOC content. The distribution of fine root carbon (FRC) in each profile was calculated from the soil confined to a depth of 100 cm.

### Soil properties

Soil was passed through a 2-mm mesh sieve and air-dried approximately for 48 h. Soil texture was analyzed by the hydrometer method after dispersion with sodium hexametaphosphate (Sheldrick and Wang 1993). Soil pH was measured by a glass electrode in the supernatant of a 1:1 soil/water suspension. Bulk densities were measured by volume and weight (Blake and Hartge 1986). Soil nitrogen was analyzed by the Kjeldahl Method. The mean amount of SOC for any specific soil depth was calculated as the average for all soil profiles of each layer.

## Results and discussion

### Aboveground biomass and aboveground carbon (ABGC)

According to the results of the study, variances in biomass of ≥ 4.5 cm dbh. individual trees between the forest and the reforestation were large (Table 2). Trees compose a large proportion of basal area and biomass, with significant differences observed between the forest and the reforestation. Although the reforestation areas have more trees than in the forest, most trees are ≤ 25 cm in dbh representing highest biomass density. In the forest, the most aboveground biomass accumulation was found in trees > 25 cm dbh. The total basal area decreased from 32.62 ± 10.27 m$^2$·ha$^{-1}$ in the forest to 8.51 ± 1.08 m$^2$·ha$^{-1}$ in the reforestation. However, the proportion of trees ≤ 25 cm dbh increased and dominated in terms of basal area and biomass in the reforestation. Trees ≤ 25 cm dbh accounted for 8.96% of total biomass in the forest while 50.47% of that in the reforestation. On the other hand, the trees > 25 cm dbh accounted 89.49% and 29.36% of the total biomass in the forest and the reforestation, respectively (Table 2).

**Table 2. Density, basal area, biomass and total aboveground carbon in different land-use type.**

| Class | Forest | | | Reforestation | | | Agriculture |
|---|---|---|---|---|---|---|---|
| | Density (stem·ha$^{-1}$) | Basal area (m$^2$·ha$^{-1}$) | Biomass (Mg·ha$^{-1}$) | Density (stem·ha$^{-1}$) | Basal area (m$^2$·ha$^{-1}$) | Biomass (Mg·ha$^{-1}$) | Biomass (Mg·ha$^{-1}$) |
| Understory | - | - | 4.23a ± 0.65 | - | - | 12.07b ± 1.38 | - |
| Dbh ≤ 25 cm | 200.85a ± 24.36 | 4.55a ± 0.74 | 24.34a ± 5.15 | 432.25b ± 45.27 | 6.00b ± 1.03 | 30.20b ± 4.83 | - |
| Dbh > 25 cm | 133.05a ± 12.25 | 28.07a ± 3.50 | 243.17a ± 36.42 | 85.60b ± 9.14 | 2.51b ± 1.58 | 17.57b ± 3.16 | - |
| Total | 333.90a ± 19.66 | 32.62a ± 10.27 | 271.74a ± 45.15 | 517.85b ± 43.31 | 8.51b ± 1.08 | 59.84b ± 8.21 | 12.20c ± 1.66 |

Mean followed by the different letters (a, b and c) within the same row indicate significant differences ($P < 0.05$).

With increasing forest age and development, the biomass of understory layer (saplings, seeding and herbs) declined and became a very small proportion of the total biomass (Table 2). The biomass of understory layer in the reforestation was significantly greater than that in the forest. The understory biomass of the forest accounted for only 1.56% of total aboveground biomass. Comparison of total aboveground biomass in different land-use types indicated that the total aboveground biomass in forest was significantly higher than that in the reforestation and the agricultural land ($P < 0.05$). The amounts of total aboveground carbon storage in the forest, reforestation and agricultural land were estimated at 135.87 ± 22.57 Mg·ha$^{-1}$, 29.92 ± 4.10 Mg·ha$^{-1}$ and 6.10 ± 0.83 Mg·ha$^{-1}$ (simplified expression of Mg (carbon)·ha$^{-1}$), respectively. Therefore, the levels of aboveground biomass are directly reflected the variability of carbon stock in different land-use types.

C stocks in biomass of the reforestation and the agricultural land account for only 22.02% and 4.49% of the original content in natural forest (Table 2). This proportion was found to be lower than other secondary forests when compared to original content (32%, Jampanin and Gajaseni 2004; 29%, Viriyabuncha et al. 2002; and 28%, Bonino et al. 2006). It can be compared to the proportion found in the shrubby grassland (5%) in the Chancaní reserve in Mexico (Bonino et al. 2006). We concluded that the natural forest possesses a high potential for aboveground carbon storage. Unfortunately, it is easily degraded or lost by land-use change. Therefore, it is essential to establish forest protection and conservation policies due to the long period required to accumulate carbon through reforestation. Lands with degraded vegetation cover are identified as having potential for restoration (Iverson et al. 1993), because it contains a lower carbon biomass density than the maximum potential value for the site and type of vegetation. Greater development of the understory and small trees (dbh ≤ 25 cm) in reforestation is a very important component of aboveground biomass. Furthermore, these main groups will have great potential for sequestration in the future if the area is managed appropriately.

The aboveground carbon storage of forest (135.87 ± 22.57 Mg·ha$^{-1}$) falls to the range of other forests in Thailand (63.00 Mg·ha$^{-1}$, Ogawa et al. 1965; 197.02 Mg·ha$^{-1}$, Sangtongpraow and Sukwong 1990; 98.76 Mg·ha$^{-1}$, Tanee 1997; and 70.29 Mg·ha$^{-1}$, Teerakunpisut 2003). Compared to studies in neighboring countries, our results were fairly similar to the natural forests in Malaysia (100.00–160.00 Mg·ha$^{-1}$, Abu-Aker 2000 cited in Lasco 2002), Philippines (86.00–201.00 Mg·ha$^{-1}$, Lasco et al. 1999 cited in Lasco 2002) and Indonesia (161.00–300.00 Mg·ha$^{-1}$, Murdiyarso and Wasrin 1995 cited in Lasco 2002). These results suggest that a large proportion of the net accumulation of above-ground biomass in tropical forests occurs as continued growth of large trees as opposed to ingrowths of smaller individuals (Lugo and Brown 1992). While reforestation demonstrated relatively low carbon storage within the range for mixed deciduous in Thailand (15.97–87.75 Mg·ha$^{-1}$, Viriyabuncha et al. 2002). It must be noted that the carbon storage of reforestation in this study was lower than findings in other studies (165.50 Mg·ha$^{-1}$, Ogawa et al. 1965; 48.14 Mg·ha$^{-1}$, Teerakunpisut 2003; and 93.12 Mg·ha$^{-1}$, Jampanin and Gajaseni 2004).

### Soil properties

All soils in the study were strongly acidic regardless of land-use types. Average pH ranged from 4.38 ± 0.56 to 4.91 ± 0.28 and increased with soil depth (Table 3). Soil pH was significantly higher in the agricultural land than that in the forest and the reforestation, whereas no significant difference ($P < 0.05$) was observed between the forest and reforestation.

**Table 3. Mean and standard deviation of soil characteristics and soil organic carbon in 0-100 cm soil depth in different land-use type.**

| Land use | Soil depth (cm) | pH | Bulk density (g·cm$^{-3}$) | % clay | C:N ratio | Soil organic C (Mg·ha$^{-1}$) | Total soil organic C (Mg·ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Forest | 0-20 | 4.38a ± 0.56 | 1.19a ± 0.22 | 20.25a ± 14.62 | 11.42a ± 0.68 | 58.96a ± 8.48 | 196.24a ± 22.81 (100.00 %) |
| | 20-40 | 4.41a ± 0.35 | 1.34a ± 0.22 | 24.75a ± 13.73 | 11.43a ± 0.55 | 50.37a ± 6.26 | |
| | 40-60 | 4.55a ± 0.41 | 1.58a ± 0.62 | 34.00a ± 13.56 | 11.34a ± 0.48 | 43.41a ± 4.82 | |
| | 60-80 | 4.61a ± 0.30 | 1.74a ± 0.90 | 36.85a ± 14.06 | 11.29a ± 0.62 | 24.58a ± 2.83 | |
| | 80-100 | 4.64a ± 0.22 | 1.89a ± 0.07 | 40.08a ± 15.04 | 11.30a ± 0.74 | 18.92a ± 3.24 | |
| Reforestation | 0-20 | 4.40a ± 0.27 | 1.10b ± 0.28 | 39.70b ± 7.33 | 11.36ab ± 0.59 | 52.51b ± 9.82 | 146.83b ± 7.22 (74.82 %) |
| | 20-40 | 4.42a ± 0.20 | 1.28b ± 0.54 | 46.94b ± 3.87 | 11.16b ± 0.67 | 33.93b ± 2.28 | |
| | 40-60 | 4.56a ± 0.36 | 1.39b ± 0.04 | 52.68b ± 3.78 | 11.09b ± 0.52 | 27.55b ± 2.72 | |
| | 60-80 | 4.60a ± 0.33 | 1.52b ± 0.04 | 53.84b ± 3.53 | 11.01b ± 0.70 | 22.34b ± 2.97 | |
| | 80-100 | 4.66a ± 0.31 | 1.68b ± 0.05 | 55.60b ± 3.59 | 10.37b ± 1.50 | 10.50b ± 1.35 | |
| Agriculture | 0-20 | 4.55b ± 0.46 | 1.39c ± 0.12 | 36.71c ± 10.28 | 10.22c ± 0.88 | 42.08c ± 7.80 | 95.09c ± 14.18 (48.45 %) |
| | 20-40 | 4.61b ± 0.39 | 1.53c ± 0.14 | 38.15c ± 9.29 | 9.83c ± 0.95 | 25.42c ± 6.94 | |
| | 40-60 | 4.70b ± 0.35 | 1.73c ± 0.16 | 39.55c ± 8.89 | 9.77c ± 0.93 | 14.22c ± 2.13 | |
| | 60-80 | 4.79b ± 0.37 | 1.89c ± 0.14 | 41.22c ± 8.80 | 9.52c ± 1.08 | 8.19c ± 1.90 | |
| | 80-100 | 4.91b ± 0.28 | 2.02c ± 0.11 | 42.80c ± 9.00 | 9.62c ± 0.86 | 5.18b ± 1.63 | |

Mean followed by the different letters (a, b and c) within the same column indicate significant differences ($P < 0.05$)

The average bulk density in all soil layers was significantly higher in the agricultural land than in the forest and the reforestation ($P < 0.05$). The bulk density tended to increase as the soil depth increased. This is possibly due to more organic matter in topsoil than subsoil.

The clay content of soil differed among the three land-use types. The average clay percentage was significantly higher ($P < 0.05$) in the reforestation than in the agricultural land and the forest. The soil in the forest had the lowest clay content (< 40%). The subsoil had noticeably higher clay content than the surface soil in all land-use types. In addition, the surface soil in the forest was found to be rich in sand particles and is likely due to leaching of clay particles to the subsoil by rainfall but clay content in subsoil in the forest was not greater than that in the reforestation and the agricultural land.

Changes in land use also effected carbon-nitrogen (C:N) ratios. The mean C:N ratios in all soil layers in the forest (but not in top layer) were significantly higher ($P < 0.05$) than the reforestation and the agricultural land. In each land-use type, the C:N ratios narrowly varied less than 1 throughout the soil profile.

We concluded that land use changes significantly affect soil bulk densities and the C:N ratios. These factors also induce SOC variation. Organic C content shows a negative relationship with bulk density. This relation is observed in the field when organic C content increases as bulk density decreases (Sonja et al. 2005). For instance, the conversion of grassland into cropland indicates the increase of bulk density and the decrease of SOC (Evrendilek et al. 2004). Moreover, some other soil properties (*i.e.* total porosity and C:N ratio), affect root development and are closely related to soil organic matter concentration (Prévost 2004).

### Soil organic carbon (SOC) and fine root carbon (FRC)

The vertical distribution of SOC also varied among the three land-use types. The overall average proportion of SOC was higher in the forest and the reforestation than in the agricultural land. In all land-use types, the deposition of SOC was generally higher in the top soil (0–20 cm) and decreased with soil depth. The highest proportion of SOC content was deposited in the 0–20 cm depth. SOC content was found to be 30.04%, 35.76 and 44.25%, in the forest, reforestation and agricultural land respectively. The total SOC content in the forest (196.24 ± 22.81 Mg·ha$^{-1}$) was significantly higher than the content in the reforestation (146.83 ± 7.22 Mg·ha$^{-1}$) and the agricultural land (95.09 ± 14.18 Mg·ha$^{-1}$) (Table 3).

The vertical distribution of FRC also varied among land-use types (Table 4). At all soil depths, the average FRC in the forest was much higher than in the reforestation and the agricultural land. Regardless of land use, the deposition of FRC as soil organic matter was generally higher in the top soil and decreased with soil depth. The study also found that the highest proportion of FRC content was in the top layer of soil in the agricultural land

(70.68%), followed by the reforestation (49.08%) and the forest (42.81%). However, the plant composition in each land-use type evolves differently due to the root structure of annual and perennial plants. The total root carbon content decreased from 25.51 ± 4.01 Mg·ha$^{-1}$ in the forest to 18.50 ± 3.53 Mg·ha$^{-1}$ in the reforestation and 1.91 ± 0.42 Mg·ha$^{-1}$ in the agricultural land (Table 4).

**Table 4. Mean and standard deviation of fine root carbon 0–100 cm soil depth in different land-use type.**

| Land use | Soil depth (cm) | Root carbon (Mg·ha$^{-1}$) | Total (Mg·ha$^{-1}$) |
|---|---|---|---|
| Forest | 0-20 | 10.92a ± 2.20 | 25.51a ± 4.01 (100.00 %) |
| | 20-40 | 8.26a ± 1.09 | |
| | 40-60 | 4.04a ± 0.92 | |
| | 60-80 | 1.48a ± 0.15 | |
| | 80-100 | 0.81a ± 0.11 | |
| Reforestation | 0-20 | 9.08b ± 1.45 | 18.50b ± 3.53 (72.52 %) |
| | 20-40 | 6.06b ± 1.03 | |
| | 40-60 | 2.17b ± 0.15 | |
| | 60-80 | 0.88b ± 0.21 | |
| | 80-100 | 0.31b ± 0.19 | |
| Agriculture | 0-20 | 1.35a ± 0.08 | 1.91c ± 0.42 (7.49 %) |
| | 20-40 | 0.46c ± 0.03 | |
| | 40-60 | 0.07b ± 0.02 | |
| | 60-80 | 0.02b ± 0.01 | |
| | 80-100 | 0.01c ± 0.00 | |

Mean followed by the different letters (a, b and c) within the same column indicate significant differences ($P < 0.05$)

SOC pool and soil properties are heavily influenced by land use (Ussiri et al. 2006). The SOC is generally found to decrease rapidly following the conversion from a natural to agricultural ecosystem. It is clear that the conversion of forest into reforestation and agricultural land decreased SOC by 74.82% and 48.45%, respectively (Table 3). The result corresponds to the study of Mendoza-Vega (2003) where the open land (grassland and cropland) in the highlands of Mexico contained only 20%–60% of SOC observed in the forests. Rationally, soil C loss in the agricultural land is caused by cultivation along with removal of crop production and crop residues. This reduces decomposition and affects soil C deposition. Based on previous research on soil properties after deforestation in Thailand, the reduction of organic matter decomposition was found to be the major contributing factor causing decreases of total C content in the surface soil layers of crop fields (Obara et al. 2000). However, agricultural land has the potential to increase soil C sequestration if proper agricultural practices and management are implemented (Sperow et al. 2003). Soil C can be sequestered in reforestation overtime, even during the later stages of succession (Silver et al. 2004).

In terms of SOC and soil depth, the results clearly demonstrated the vertical distribution. The highest SOC was found at the surface soil (Mendoza-Vega et al. 2003, Chowdhury et al. 2007). This study indicated that more than 55% of total SOC in soil deposited in the 0–40 cm depth. In order to maintain soil productivity, special care must be taken in preserving the first 40 cm depth since less drastic changes in deeper layers have been observed (IC-SEA 2000).

Fine root carbon tends to accumulate in surface soil. Fine root located in the upper part of the soil profile appears to be influenced by the availability of nutrients in the soil (Schmid and Kazda 2002). Very few studies have estimated FRC in the tropics. In Chiapas highlands in Mexico, Mendoza-Vega et al. (2003) estimated the fine root carbon at 29.00–42.70 Mg·ha$^{-1}$ (in the depth of 0–100 cm) in forest and 4.20 Mg·ha$^{-1}$ in open land. Their findings were higher than the findings in this study largely due to a greater availability of aboveground and soil organic carbon in the highlands of Mexico. Moreover, differences in vegetation and soil type play an important role in the FRC pool. The fine roots may grow from C that has been stored in the tree at times and may take up C from the soil during or subsequent to initial growth (Trumbore et al. 2006).

### Total carbon stock (TCS) and changes

TCS (sum of ABGC, SOC and FRC to 1 m depth) varied significantly over land-use types. The ABGC portion of TCS in the forest, reforestation and agricultural land was 37.99%, 15.32% and 5.92%, respectively. SOC accounted for a large proportion of TCS, representing 54.87% in the forest, 75.20% in the reforestation and 92.23% in the agricultural land. FRC represented 7.13% in the forest, 9.47% in the reforestation and 1.85% in the agricultural land. The TCS among the three land-use types varied significantly which decreased from 367.62 ± 28.51 Mg·ha$^{-1}$ in the forest to 195.25 ± 14.38 Mg·ha$^{-1}$ in the reforestation and to 103.10 ± 18.24 Mg·ha$^{-1}$ in the agricultural land (Table 5).

Changes TCS are associated with shifts in land use and/or land management practices. The estimates of TCS varied greatly over land-use types in this study. The greatest TCS loss overall occurred in the agricultural land, with the major contribution in ABGC. ABGC in the forest is five and twenty two times higher than in the reforestation and the agricultural land, respectively. SOC in the forest is higher than the reforestation and the agricultural land by one and two times respectively. FRC in the forest is higher than the reforestation and the agricultural land by approximately one and seven times, respectively. In this study, SOC content was found to be larger than ABGC content over the land-use types. SOC showed the least drastic changes among them. The data indicated that the ABGC pool is highly responsive to land-use change while the SOC is more resistant than other pools. However, it can be concluded that the SOC accumulates more slowly than ABGC. The slow SOC turnover rates, as compared to aboveground vegetation, suggests that soil C level does not react as quickly to change in land use (see also Walker and Desanker 2004). Growing vegetations tend to maintain SOC level by continuously supplying C from root turnover when compared with bare land, which tends to deplete C (Sanchez et al. 2002). The ABGC:SOC:FRC ratios represent C fractions among pools and can be used to estimate the proportion of C stocks in different land uses in this region. The ratios indicated that the conversion of forest to agricultural land caused high C allocation shift from 5:8:1 to 3:50:1. This effect was substantial in aboveground C, while the C storage in the soil was less susceptible to depletion (Table 5).

For the area of this study (19 000 $\text{ha}^{-1}$), the forests, the reforestations and the agricultural land cover a large proportion of total area (20%, 23% and 47%) and the total amount of carbon stored were 1 358.96 Gg C, 853.24 Gg C and 920.68 Gg C, respectively. These results indicate that a relatively large proportion of the C loss was due to the conversion of forest to agricultural land. However, this C may be recaptured in the reforestation projects, which would be an effective C mitigation by sequestering C in above-and belowground.

**Table 5. Total carbon stocks in different land-use type**

| Land use type | ABGC ($\text{Mg·ha}^{-1}$) | % of TCS | SOC ($\text{Mg·ha}^{-1}$) | % of TCS | FRC ($\text{Mg·ha}^{-1}$) | % of TCS | TCS ($\text{Mg·ha}^{-1}$) | % of TCS | Ratio ABGC : SOC : FRC |
|---|---|---|---|---|---|---|---|---|---|
| Forest | 135.87a ± 22.57 | 37.99 | 196.24a ± 22.81 | 54.87 | 25.51a ± 4.01 | 7.13 | 357.62a ± 28.51 | 100.00 | 5:8:1 |
| Reforestation | 29.92b ± 4.10 | 15.32 | 146.83b ± 7.22 | 75.20 | 18.50b ± 3.53 | 9.47 | 195.25b ± 14.38 | 100.00 | 2:8:1 |
| Agriculture | 6.10c ± 0.83 | 5.92 | 95.09c ± 14.18 | 92.23 | 1.91c ± 0.42 | 1.85 | 103.10c ± 18.24 | 100.00 | 3:50:1 |

Mean followed by the different letters (a, b and c) within the same column indicate significant differences ($P < 0.05$)

## Conclusion

We found a large variation of carbon pools in different land-use type in northern Thailand. The ABGC, SOC and FRC are potentially sequestered highest in the forest and decreased in the reforestation and the agricultural land significantly due to the different biomass production. These findings indicate that C loss related to land-use change in northern Thailand, which has removed the aboveground biomass, soil organic carbon and even fine root carbon from each land-use type. These ABGC:SOC:FRC ratios are highest in the forestation (5:8:1) followed by the reforestation (2:8:1) and the agricultural land (3:50:1), respectively. It means that if we convert the forest to the agricultural land, the C loss from aboveground biomass will be greater than the other carbon pools. In the SOC content, the top soil (0-20 cm) can sequester highest C which is similarly found in all land-use types. In conclusion, it confirms that the forest is playing the important role as a carbon sink in terrestrial ecosystem. Nevertheless, it is essential to understand the potentiality of C sequestration in different carbon pools (ABGC, SOC, and FRC) particularly in forest ecosystem comparing to the other land-use types which will be an substantial information for the carbon mitigation and the implementation of “Land Use, Land-Use Change and Forestry (LULUCF)” concept for carbon sink.

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