

Research Article

CARBON SEQUESTRATION IN AGROSILVICULTURE AGROFORESTRY SYSTEMS: PRELIMINARY RESULTS FROM THREE VILLAGES IN UTTARADIT PROVINCE, NORTHERN THAILAND

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ARTICLE HIGHLIGHTS

- Agroforestry boosts carbon storage, reducing greenhouse gas emissions significantly.
- Diverse tree-based farming enhances biodiversity, soil health, and climate resilience.
- Carbon sequestration in agroforestry supports sustainable agriculture and environmental balance.
- Agroforestry practices mitigate climate change by storing carbon in trees and soil.
- Combining trees with crops provides multiple ecological and economic benefits.

ABSTRACT

One of the processes for compensating greenhouse gas emissions is atmospheric carbon removal and storage in the terrestrial biosphere. Agricultural systems to which trees are returned for careful management alongside crops and animals are thought to be substantial CO₂ sinks. People are increasingly realizing the importance of agroforestry because it is good for the environment and farming. In this study, total carbon pools from the aboveground biomass carbon (ABGC), forest floor carbon (FFC), and soil organic carbon (SOC) were investigated and carbon storage data for some agroforestry practices native to Uttaradit in northern Thailand were analyzed. The role of these carbon pools in reducing CO₂ concentrations in the atmosphere was also discussed. The results showed differences in the total carbon stock sourced from traditional agroforestry (TAF), applied agroforestry (AAF), and developed agroforestry (DAF). The total carbon store (ABGC + TFFC + SOC) of TAF, AAF, and DAF was 267.05 Mg C/ha, 226.48 Mg C/ha, and 324.70 Mg C/ha, respectively. SOC contributed 47.64%, 54.26%, and 44.81% and ABGC contributed 22.75%, 19.79%, and 23.90% to the total carbon stock in TAF, AAF, and DAF, respectively. The CO₂ adsorption was 979.27 Mg CO₂/ha, 830.50 Mg CO₂/ha, and 1,190.6 Mg CO₂/ha in TAF, AAF, and DAF, respectively. It is clear that agroforestry systems serve as carbon sinks in terrestrial ecosystems. Although the comparison of agroforestry practices and other land use types is important for carbon mitigation and the implementation of the “Land Use, Land Use Change, and Forestry” concept for CO₂ sinks, it is also crucial to compare the potential of carbon sequestration in different CO₂ pools.

Keywords:

agroforestry, agrosilviculture, carbon sequestration, carbon stock, thailand

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INTRODUCTION

Land use change is one of the most important sources of global human carbon emissions (IPCC 2014) and is intricately tied to biodiversity and the biogeochemical cycle (Romshoo 2004; Nagendra *et al.* 2013). Human caused climate change has a negative impact on a wide variety of industries and

populations, most notably those that rely on rain-fed agriculture. According to the World Meteorological Organization (2007), increased atmospheric concentrations of greenhouse gases (GHGs) are the primary cause of climate change. The increasing concentration of the GHG carbon dioxide (CO₂) in the atmosphere has a substantial effect on the global climate (Malhi *et al.* 1999).

The current concentration of CO₂ in the atmosphere is at least 400 parts per million. The enormous increase in the CO₂ concentration has resulted in an increase of 0.17 °C every decade in the Earth's average temperature.

Deforestation and forest degradation are the primary sources of GHG emissions in the majority of tropical countries. Thus, the terrestrial ecosystem's role in the global carbon cycle has roused the interest of researchers and policymakers alike. The exchange between the atmosphere and vegetation is bidirectional, with CO₂ fixation into biomass by photosynthesis roughly balanced by CO₂ emission via decomposition and burning. Each year, around 60 Pg of carbon is transferred (both ways) between terrestrial ecosystems and the atmosphere, resulting in a net terrestrial uptake of 0.710 Pg C (Lasco 2002). As widely known, the near-surface air and oceans of the Earth have been warming in recent years and are likely to continue to do so in the future (Asako 2007).

A critical method of mitigating climate change aims to reduce the concentrations of GHGs, notably CO₂, in the atmosphere. This is accomplished via the carbon sequestration process (Nair 2011), in addition to lowering emissions at their source. Carbon sequestration is possible in terrestrial ecosystems, such as forests and agroforests, as well as woodland and scrubland. Agroforestry is the practice of combining trees with crops or pasture (Nair *et al.* 2010). It is a tree-based agricultural approach adopted over many years in a variety of countries, including Thailand. Over the last four decades, agroforestry has gained recognition as an integrated strategy for sustainable land use due to its productivity and environmental benefits. It has received increased attention as a result of its recent certification as a Kyoto Protocol global climate change mitigation strategy (Nair *et al.* 2009). The majority of carbon in trees and shrubs is stored as aboveground biomass, with 50% of the total biomass acting as a carbon sink (Aklilu *et al.* 2015). The aboveground carbon (ABGC) stock is the estimated quantity of carbon that makes up 50% of the total vegetative biomass (ICRAF 2006; Lal 2005). Belowground biomass, the fraction of vegetation occurring belowground

as roots, accounts for around 25-30% of the aboveground biomass, depending on the species, root structure, and ecological conditions (ICRAF 2006; Lal 2005). Kumar and Nair (2011) defined total biomass carbon as the accumulation of both above- and belowground carbon in vegetation.

Agroforestry is an umbrella term that refers to a diverse range of systems and approaches in which parklands are one of the practices. Typically, parklands are defined as landscapes of cultivated or recently fallowed fields interspersed with mature trees (Abdelkadir & Bishaw 2003) or as the coexistence of woody plants and grasses in subtropical and tropical savanna habitats (Bayala *et al.* 2006). Individual trees and shrubs are planted across vast swaths of cropland, while understory crops are cultivated. Some of these trees were left behind after the natural forest was converted to other land uses; others regrew after farmers cleared the land and still others are intentionally retained or planted on farms (ICRAF 2006) to provide a range of products and services, including soil structure enhancement, local temperature regulation, erosion risk reduction, and carbon sequestration. Agroforestry systems increase smallholder farmers' resilience by enhancing water efficiency, the microclimate, soil productivity, and nutrient cycling, facilitating the management of pests and diseases, increasing agricultural production, and diversifying and increasing farm income, all the while sequestering carbon (Lasco *et al.* 2014).

Carbon pools can be managed more effectively by better understanding the aboveground biomass of trees and soil organic carbon reserves. However, additional research is necessary before agroforestry systems are considered for inclusion in global carbon sequestration agendas (Nair *et al.* 2010). Agroforestry technologies and techniques help to address a range of economic and environmental concerns. To date, the majority of research on agroforestry systems has been on their spatial design, food production, soil fertility management, and system interactions, with little emphasis on their ecosystem services, such as biodiversity protection and carbon sequestration (Negash 2013).

Uttaradit Province is an important agroforestry area in the northern region of Thailand. Agroforestry is implemented in three districts, Mueang, Laplae, and Tha Pla. Most of the agroforestry areas are located on high mountains. The highest elevation of the agroforestry sites is 700 masl, with a slope of 5-100%. One of the factors influencing the growth in agroforestry in Thailand is the change in the agricultural system from subsistence to commercialization due to population increase. The cultivation of cash crops, such as durian and longkong, has increased after the transformation of the original forest for planting fruit trees, thus causing the forest area to rapidly decrease. The ecological transition from the original natural ecosystem to an agricultural ecosystem causes land degradation due to continuous monocultures and horticultural crops, resulting in lower crop yields year after year and higher production costs.

This study collected and documented critical data on the significance of parkland agroforestry for the Uttaradit Province's climate change mitigation efforts through carbon sequestration. This study will contribute to the understanding of

how to conserve these unique agroforestry systems and their ecosystem services to local communities, such as food production and income, soil and water protection, and soil fertility maintenance, as well as other services, such as carbon sequestration for climate change mitigation and conservation of biodiversity (Negash 2013). The purpose of this study was to ascertain the carbon storage capacity of agroforestry parklands in Uttaradit Province, northern Thailand. It evaluated the carbon stored in the study area's various agroforestry types, aboveground and belowground biomass, and soil carbon pools and assessed the tree species with the highest carbon stock potential in the study area.

MATERIALS AND METHODS

Site Description

The study area was located in Uttaradit Province, Thailand, and consisted of three sites: the Mae Phun Subdistrict, Laplae District (LP-AF); the Ban Dan Na Kham Subdistrict, Mueang Uttaradit District (DK-AF); and the Nang Phaya Subdistrict, Tha Pla District (NP-AF). The study areas are shown in Figure 1.

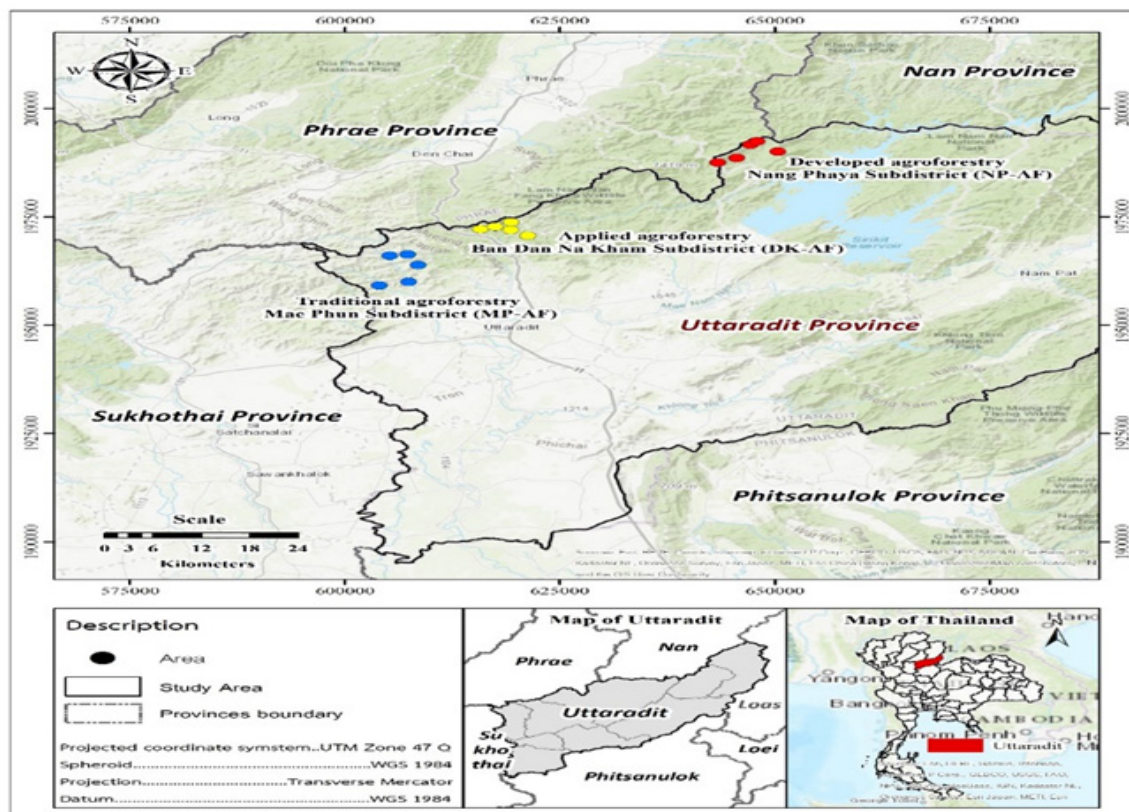


Figure 1 The locations of the study areas in the three villages investigated in Uttaradit Province, Thailand

Traditional Agroforestry (TAF), age 20 years

Traditional agroforestry is the indigenous understanding of agroforestry practices passed down through generations of farmers. In TAF, the plants thrive in a variety of climates and terrains. It is easy to practice and requires minimal capital, especially in inhabited or abandoned regions. The inhabited land is tended by weeding undesired plants in specific locations and sowing seeds (in rows or non-rows) of desired plants. Because these plants do not require much maintenance and care to develop shoots and root systems, their chances of survival are greater than those of grafted plants or cuttings. Unwanted plant species that are introduced or purposefully left to compete for growth can also be eventually harvested and used, yielding benefits comparable to those of “ladang” in Indonesia, where these plants are used to construct dwellings and animal shelters and for fuel.

Applied Agroforestry (AAF), age 18 years

The AAF system enhances the structure and quality of production to meet market demands under current circumstances. This type of agroforestry is sometimes a continuation of TAF. The canopies of indigenous cultivars grown from seed can be converted to be similar to those of other popular cultivars by altering persistence, bark, branches, shoots, etc. These alterations are considered to conserve the original species at the same time, because when the altered part is cut off, the relevant component of the original species grows to replace it. The garden’s cross-sectional structure is diminished as a result of this alteration. Harvesting is simple. Revenue may increase since the goods can be sold at a higher price because the canopy has been changed to a variety that the market requires.

Developed Agroforestry (DAF), age 15 years

DAF is a modern agroforestry system that combines current techniques and approaches to forest management with agroforestry. For example, the planting of the garden may start with digging, grading, and setting up and drilling holes in rows. Then, good plant material obtained as cuttings or grafts are planted in the prepared soil in alternate rows, alternating strips, or a combination of the

two. This form of agroforestry plantation has a structural profile of less than 20 meters. The canopy layer and the age layer are very similar. An irrigation system and a production control scheme may be necessary depending on needs.

Sampling and Data Collection Methods

A survey of the plants in the different agroforestry regimes was carried out from December 2020 to May 2021 using the plant community analysis method. Using stratified random sampling, 15 sample plots, each of 0.16 ha (40 m × 40 m), were established on the summit, shoulder, and foot slopes of the site. The altitudinal range of these plots was 700-900 masl. Each plot was divided into 16 subplots (10 m × 10 m). The data collected included measurements of stem girth over bark at breast height (1.3 m above the ground) and the heights of all tree species taller than 1.5 meters, as well as of seedlings, undergrowth, climbers, other vegetation, and standing dead trees. In addition, litter from all plants growing on the surface was collected and weighed. Litter samples were oven-dried at 80 °C for 48 hours or until reaching a constant weight and then weighed. Tsutsumi *et al.* (1983) used allometric equations to determine the amount of plant biomass of each agroforestry system. They used the biomass equations for mixed forests based on the mixed deciduous-dry evergreen forest of Chai Ya Phum Province, as follows:

$$WS = 0.0509 (D^2H)0.919 \quad R^2 = 0.978$$

$$WB = 0.00893 (D^2H)0.977 \quad R^2 = 0.890$$

$$WL = 0.0140 (D^2H)0.669 \quad R^2 = 0.714$$

$$WR = 0.0313 (D^2H)0.805 \quad R^2 = 0.981$$

where:

WS = tree stem biomass (kg)

WB = branch biomass (kg)

WL = leaf biomass (kg)

WR = root biomass (kg)

D = tree stem diameter over bark at 1.30 m above ground (cm)

H = tree height (m)

To estimate Soil Organic Carbon (SOC), soil samples were collected from a depth of 0-15 cm and of 15-30 cm at five random locations in each 50 m × 50 m plot. After air drying and crushing, the soil samples were sieved through a 2-mm mesh sieve, removing roots, other plants, and garbage. The SOC content was determined using the Walkley and Black technique (Walkley & Black 1934). The bulk density of the soil was determined using undisturbed soil samples. The ABGC store per unit area (Mg C/ha) and the biomass content of all plants were measured. The amount of carbon stock was calculated by multiplying the aboveground and belowground biomass by 0.47 (IPCC 2006).

Sequestered Carbon Dioxide

The absorption rate of CO₂ can be calculated as the carbon stock in biomass multiplied by the weight of a molecule of carbon. CO₂ is composed of one molecule of carbon and two molecules of oxygen. The atomic weights of carbon and oxygen are 12.00 and 15.99, respectively. Therefore, the weight of CO₂ is 44.01. The ratio of CO₂ to C is 44.01/12.00 = 3.67. To determine the weight of CO₂ sequestered in the carbon stock, the weight of carbon must be multiplied by 3.667 (McPherson 1998). The equation to calculate CO₂ sequestration is as follows:

$$\text{Sequestered CO}_2 = Cs \times 44.01/12.00$$

where:

Cs = carbon stock (t/ha)

C = atomic weight of carbon

Evaluation of Carbon Stock in Different Parts of the Agroforestry System

The carbon stocks in different parts of trees and in soil were determined with the adjusted equations for carbon stock in plants (Vashum & Jayakumar 2012), litter, and trees (Zheng *et al.* 2008) as follows:

$$Cs_t = \sum_{i=1}^n CS + \sum_{i=1}^n CB + \sum_{i=1}^n CL + \sum_{i=1}^n CG + \sum_{i=1}^n CLI + \sum_{i=1}^n SOC$$

where:

CSt = carbon stock (t/ha)

$\sum_{i=1}^n CS$ = stem carbon stock

$\sum_{i=1}^n CB$ = branch carbon stock

$\sum_{i=1}^n CL$ = leaf carbon stock

$\sum_{i=1}^n CG$ = groundcover plant carbon stock

$\sum_{i=1}^n CLI$ = litter carbon stock

$\sum_{i=1}^n SOC$ = SOC of the agrosilviculture agroforestry system

RESULTS AND DISCUSSION

Characteristics of Agrosilviculture Types in Practice

The diameter at breast height (DBH) of trees in the agroforestry system appeared to be higher than those in other forest types in general. TAF, AAF, and DAF systems in Uttaradit Province had a DBH of 12.16±8.84 cm, 86.89±6.81 cm, and 27.60±7.38 cm, respectively (Table 1). The average DBH of tropical moist deciduous forest individuals was found to be lower; sal-dominated forests had a DBH of 18.4 cm (ranged from 5.09 cm to 86.62 cm), whereas tropical moist deciduous forests had a DBH of 18.25 cm (ranged from 5.09 cm to 93.63 cm) (Manas *et al.* 2020).

Table 1 Agroforestry plots in types of agrosilviculture agroforestry in practice

Type	Density (tree/ha)	Mean slope (%)	Mean elevation (m)	Diameter at breast height (cm)		
				Min	Max	Mean ± SD
TAF	532	30	321	1.11	26.12	12.16±7.84
AAF	387	32	445	10.18	38.12	26.89±6.81
DAF	350	31	683	13.30	36.11	27.60±7.38

Note: TAF = traditional agroforestry; AAF = applied agroforestry; DAF = developed agroforestry.

The association between average DBH and tree density showed that due to increased competition between trees for resources, such as nutrients, space, and sunlight, the trees growth rate can be slower in dense forests (Ram *et al.* 2020). Similarly, Takahashi *et al.* (2018) also noted the large DBH and low tree density of evergreen conifers in the Shizumo Forest Reserve.

Species richness of a degraded forest is the result of the responses of different species to disturbances (Sagar *et al.* 2003). The majority of plant species observed on site were similar to those found in Uttaradit Province's general agroforestry and mixed deciduous forest. In our study, *Durio zibethinus* L., *Nephelium hypoleucum* Kurz, *Adenanthera pavonina* L., and *Garuga pinnata* Roxb. were examples of TAF trees. *Lansium domesticum* Corrêa, *Aglaia dookkoo* Griff., *Durio zibethinus* L., and *Tetrameles nudiflora* R.Br. were examples of AAF trees. *Durio zibethinus* L., *Bombax ceiba* L., *Lansium domesticum* Corrêa, and *Albizia odoratissima* (L.f.) Benth. were examples of DAF trees.

According to the Community Land Allocation Project, the agroforestry system in Chiang Mai Province has 243 plant species, of which 144 are woody perennial tree species and 99 are cultivars of agricultural crops (Pongpichai *et al.* 2019). TAF methods revealed the presence of the East Kalimantan natives langsat (*Lansium domesticum* Corrêa) and durian (*Durio zibethinus* L.) in Kampung Birang and Kampung Merabu, respectively (Hartoyo *et al.* 2016).

Aboveground and Belowground Biomass in Types of Agrosilviculture Agroforestry in Practice

The carbon stock of parkland agroforestry methods differed significantly between agroecological regions, as biomass was influenced by stand age, tree species and structure, management approaches, diversity, and composition (Chave *et al.* 2004). The proportion of above- and belowground carbon stocks in agrosilviculture agroforestry of varying practice types is shown in Table 2.

Agrosilviculture agroforestry systems in Uttaradit Province, northern Thailand, stored the most carbon in DAF at 101.58 Mg C/ha, followed by 79 Mg C/ha in TAF and 58.76 Mg

C/ha in AAF. The carbon content of total tree organic carbon in DAF, TAF, and AAF was 96.27 Mg C/ha, 71.74 Mg C/ha, and 52.54 Mg C/ha, respectively. Biomass and carbon stock estimation showed 192.99 Mg C/ha in aboveground biomass and 96.50 Mg C/ha carbon stock in trees, herbs, and shrubs in the Nambor Wildlife Sanctuary in Assam's Golaghat and Karbi Anglong districts (Krishna *et al.* 2019). In this study, TAF had the highest total carbon stock in the undergrowth at 3.54 Mg C/ha, whereas AAF had the lowest at 3.14 Mg C/ha.

Forestry sector GHG inventories require accurate estimations of leaf litter and dead debris carbon (IPCC 2006). TAF had the largest carbon stock in litter at 3.72 Mg C/ha, followed by AAF at 3.08 Mg C/ha and DAF at 2.76 Mg C/ha (Table 2). While preservation of pasture/grassland after slash-and-burn cultivation resulted in a progressive reduction in total system carbon stocks, agroforestry systems, such as bush fallows and agroforests, accumulate approximately 60% of initial forest carbon stocks in approximately 30 years (Patrick *et al.* 2005).

Although each line of trees can create a significant quantity of litterfall and root biomass, hedgerows or windbreaks may not contribute much to the buildup of soil carbon at the field level due to the comparatively small fraction of area covered by trees. According to Rao *et al.* (1998), boundary tree plantings have a maximum effect of 10 meters on both sides of the boundary. When applied to this scenario, a 50% increase in carbon stocks along a 100-meter tree line results in a 10% increase in carbon per acre. On the other hand, boundary plantings can help enhance soil conditions and, therefore, promote carbon sequestration by enhancing crop yield and minimizing soil loss due to erosion.

Table 2 Carbon stocks (Mg C/ha) above- and below ground in agrosilviculture agroforestry

Type	CS	CB	CL	CR	TTC	UGC	LC	FFC	ABGC	TFFC
TAF	39.42	8.07	6.01	18.24	71.74	3.54	3.72	7.26	60.76	79
AAF	28.18	5.62	4.81	13.93	52.54	3.14	3.08	6.22	44.83	58.76
DAF	53.57	11.14	7.59	23.98	96.27	2.55	2.76	5.31	77.61	101.58

Notes: CS = stem carbon; CB = branch carbon; CL = leaf carbon; CR = root carbon; TTC = total tree organic carbon (CS + CB + CL + CR); UGC = carbon stock of undergrowth, seedlings, and saplings combined; LC = carbon in litter; FFC = forest floor carbon (UGC + LC); ABGC = aboveground carbon (CS + CB + CL + FFC); TFFC = total aboveground carbon stock; TAF = traditional agroforestry; AAF = applied agroforestry; DAF = developed agroforestry.

Soil Organic Carbon Stock

Agroecosystems contribute significantly to the global carbon cycle, accounting for roughly 12% of all terrestrial carbon (Smith et al. 1993; Dixon et al. 1994; Dixon 1995). Soil degradation associated with land use change is a significant source of carbon loss and CO₂ accumulation in the atmosphere. Shifting cultivation, pasture management through paddy culture, nitrogen fertilization, and animal production are all agroforestry activities that contribute to GHG emissions (Dixon 1995; Le Mer & Roger 2001).

As soil depth increases, the percentage of soil organic carbon tends to decrease. At a depth of 0-15 cm, the highest average soil organic carbon was 2.32% in DAF, 2.20% in TAF, and 2.09% in AAF, with soil organic carbon percentages ranging from 1.23% to 2.64%. At a depth of 15-30 cm, the highest average soil organic carbon was 2.21% in DAF, 1.94% in TAF, and 1.78% in AAF, with soil organic carbon percentages ranging from 1.62% to 2.65%. At a depth of 30-60 cm, the highest average soil organic carbon was 2.09% in DAF, 1.71% in AAF, and 1.65% in TAF, with soil organic carbon percentages ranging from 1.45% to 2.37% (Figure 2).

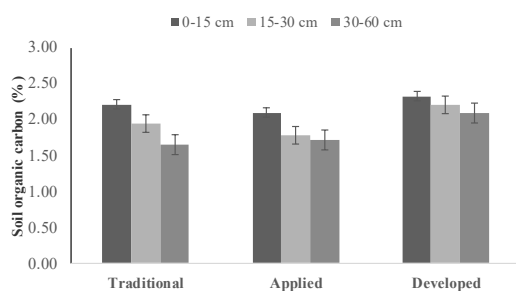


Figure 2 Soil carbon stock in agrosilviculture agroforestry systems categorized by practice type

This biomass carbon is decomposed by microbial population into leaf litter and SOC (Ramachandran et al. 2007). In many tropical locations, regular pruning and root turnover have resulted in the accumulation of soil organic matter and nutrient stocks in the soil (Lehmann et al. 1998; Rao et al. 1998; Kumar et al. 2001). In a 12-year hedgerow intercropping trial on Nigerian Alfisols, *G. sepium* with *Leucaena leucocephala* increased surface SOC by 15% (2.38 Mg C/ha) compared to solitary crops (Kang et al. 1999). A 12% increase in SOC (0.23 Mg C/ha) was also seen after five years of hedgerow intercropping with *Inga edulis* in Typic Paleudult soils in Peru (Alegre & Rao 1996).

The average soil pH of AAF, TAF, and DAF was 7.06±0.07, 6.88±0.05, and 6.95±0.05, respectively. The average soil electrical conductivity (EC) of TAF, AAF, and DAF was 38.45±1.56 µS, 37.26±1.33 µS, and 37.12±2.08 µS, respectively. The average soil bulk density (BD) of AAF, TAF, and DAF was 1.14±0.09%, 1.10±0.05%, and 1.08±0.04%, respectively. The SOC content of DAF, TAF and AAF was 2.20±0.12, 1.93±0.28, and 1.86±0.20, respectively. DAF had the highest average soil carbon stock, at 145.51±0.55 Mg C/ha, whereas TAF and AAF had 127.29±0.96 Mg C/ha and 122.89±0.84 Mg C/ha, respectively (Table 3).

Soil pH in the Chao Phraya Basin, Thailand, was in the range of 5.9 to 6.5 compared to that in the traditional home garden agroforestry system. The majority of the soil phosphorus content is in soluble forms that are available to plants within this range. This indicated that the fertility and pH conditions of home garden soils were good for agricultural purposes.

Table 3 Soil properties and soil organic carbon in agrosilviculture agroforestry systems

Type	pH	EC (µS)	BD (%)	SOC (%)	SOC (Mg C/ha)
TAF	6.88±0.05	38.45±1.56	1.10±0.05	1.93±0.28	127.29±0.96
AAF	7.06±0.07	37.26±1.33	1.14±0.09	1.86±0.20	122.89±0.84
DAF	6.95±0.05	37.12±2.08	1.08±0.04	2.20±0.12	145.51±0.55

Notes: Mean ± standard error; EC = electrical conductivity; BD = soil bulk density; SOC = soil organic carbon; TAF = traditional agroforestry; AAF = applied agroforestry; DAF = developed agroforestry.

Fruits, leaves, young shoots, bark, flowers, and other non-timber goods were some of the products of the traditional home garden agroforestry system. The traditional home garden agroforestry system is not completely harvested, which guarantees that the system's nutrient export is kept to a minimum (Gajaseni & Gajaseni 1999).

Total carbon stock and sequestration

The total carbon stock (ABGC + TFFC + SOC) was 267.05 Mg C/ha in TAF, 226.48 Mg C/ha in AAF, and 324.70 Mg C/ha in DAF. The contribution of SOC to the total carbon stock was 47.64% in TAF, 54.26% in AAF, and 44.81% in DAF. ABGC contributed 22.75%, 19.79%, and 23.90% to the total carbon stock in TAF, AAF, and DAF, respectively (Table 4; Figs. 3 & 4). CO₂ adsorption was 1,190.6 Mg CO₂/ha in DAF, 979.27 Mg CO₂/ha in TAF, and 830.50 Mg CO₂/ha in AAF (Fig. 3).

Table 4 Total carbon stock and soil organic carbon (Mg C/ha) in agrosilviculture agroforestry systems

Type	ABGC	TFFC	SOC	TC
TAF	60.76	79	127.29	267.05
AAF	44.83	58.76	122.89	226.48
DAF	77.61	101.58	145.51	324.70

Notes: ABGC = aboveground carbon; TFFC = total aboveground carbon stock; SOC = soil organic carbon; TC = total carbon; TAF = traditional agroforestry; AAF = applied agroforestry; DAF = developed agroforestry.

The results showed that ABGC, BGC, SOC, and total carbon were all positive. In Minjar Shenkora, the average carbon stock of parkland was 59.65 Mg C/ha (Reta *et al.* 2021). In the Teak Smallholder Compensation Scheme implemented by Inpang Agroforestry, which was started by the Inpang Registered Teak Carbon Bank Activity, covering about 300 hectares, the baseline C determined for registered land is 44,801 Mg CO₂ (Samek *et al.* 2011), with each hectare storing about 149 Mg CO₂. The amount of carbon sequestered is mostly determined by the agroforestry system in situ, which forms and functions are influenced by environmental and socioeconomic factors.

Tree species and system management are elements that also influence carbon storage in agroforestry systems. The carbon storage capacity of agroforestry systems in Southeast Asia is estimated to be 39-195 Mg C/ha in dry lowlands and 12-228 C/ha in humid tropical areas (Alain & Serigne 2003).

If croplands and pastures were rehabilitated by converting to tree-based systems, net ABGC sequestration would likely occur, as well as an increase in belowground carbon in the case of farmland conversions. Over a 25-year period, carbon sequestration could range from 10 to 70 Mg C/ha in vegetation and 5 to 15 Mg C/ha in the soil (Murdiyarso *et al.* 2000; Palm *et al.* 2000; Hairiah *et al.* 2001).

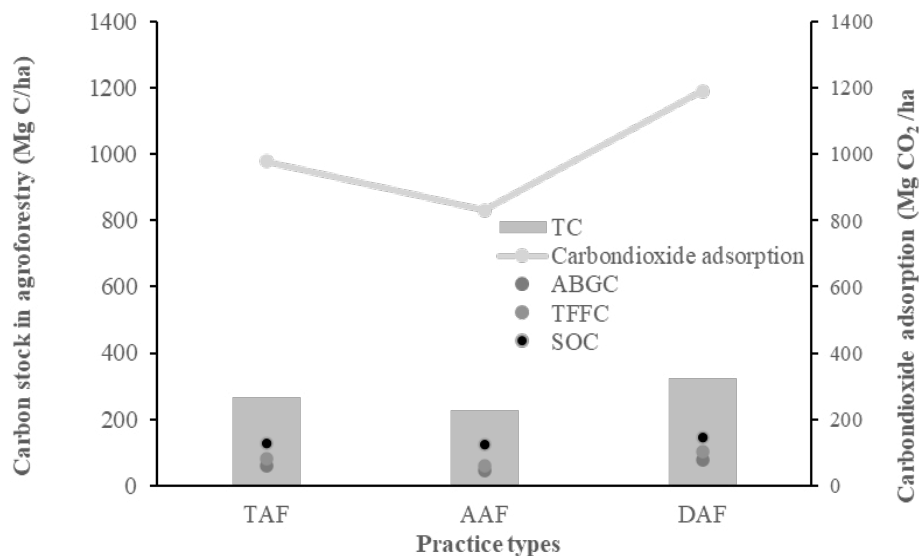


Figure 3 The proportion of carbon stock and carbondioxide adsorption in agrosilviculture agroforestry categorized by practice type

Notes: TAF = traditional agroforestry; AAF = applied agroforestry; DAF = developed agroforestry.

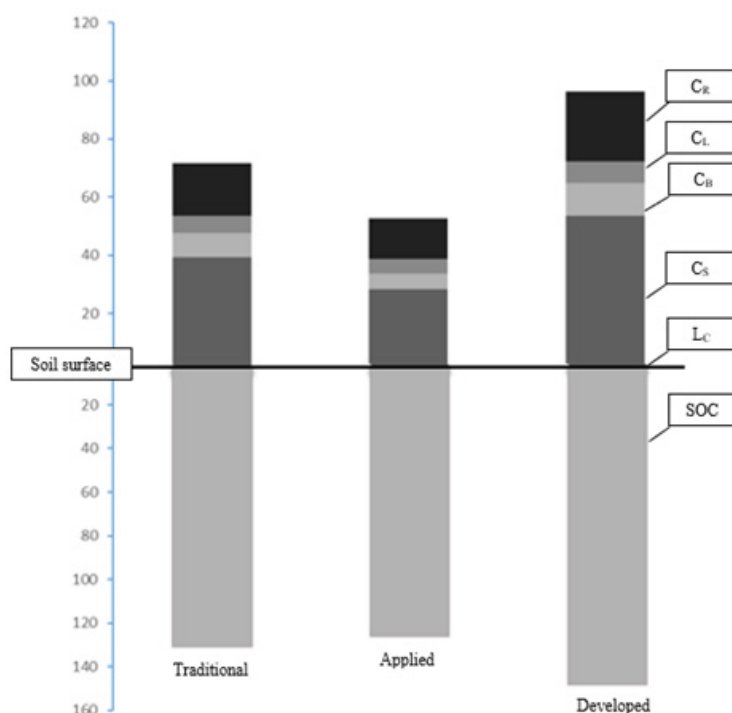


Figure 4 Carbon stock in agrosilviculture agroforestry, classified by practice type agroforestry categorized by practice type

Notes: CS = stem carbon; CB = branch carbon; CL = leaf carbon; CR = root carbon; LC = carbon in litter; SOC = soil organic carbon.

The potential for rapid carbon sequestration in the humid tropics is predominantly in the vegetation, and to a lesser extent in the topsoil, based on the observed magnitude of changes in carbon stocks. However, less is known about the possible changes in carbon stocks in soil at greater depths. Most estimates of changes in carbon stocks have failed to account for root biomass of trees in forests or agroforestry systems, owing to the technical difficulty of precise measurement.

Agroforestry systems have the ability to sequester some carbon in the root system. In the upper 0-50 cm level of soil, roots in agroforestry systems have been shown to have a time-averaged carbon stock ranging from around 6 Mg C/ha for shifting

cultivation to about 20 Mg C/ha for tree fallows (Woomer & Palm 1998). Rubber agroforests and secondary vegetation also show higher emissions, implying that agroforestry systems may not always minimize soil CO₂ emissions. In order to measure the net C balance of these systems, emissions must be clearly compared to belowground carbon allocation (Patrick *et al.* 2005).

Correlation analysis and matrix plot of ABGC, total aboveground carbon stock (TFFC), SOC, total carbon, density, and basal area showed that ABGC was positively correlated with density ($R = 0.975$, $P < 0.05$), SOC ($R = 0.948$, $P < 0.05$), and TFFC ($R = 0.895$, $P < 0.05$) (Table 5; Fig. 5).

Table 5 Pearson correlation matrix of aboveground carbon (ABGC), total aboveground carbon stock (TFFC), soil organic carbon (SOC), total carbon (TC), density, and basal area

	ABGC	TFFC	SOC	Density	Basal area
ABGC	1				
TFFC	0.895	1			
SOC	0.948	0.953	1		
Density	0.975**	0.971	0.853	1	
Basal area	-0.070	-0.054	0.250	-0.291	1

Note: ** P value < 0.05.

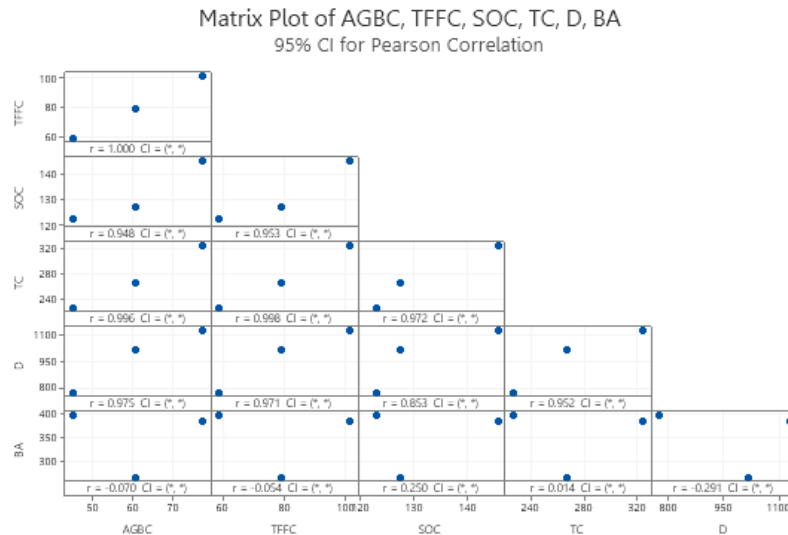


Figure 5 Pearson correlation matrix of aboveground carbon (AGBC), total aboveground carbon stock (TFFC), soil organic carbon (SOC), total carbon (TC), density, and basal area

Sequestration is ultimately determined by the fate of the carbon stockpiles that have been increasing over time. Carbon sequestration in agroforestry systems is a dynamic process that can be broken down into stages. Many systems in a facility are likely to be emitters of GHGs (due to loss of carbon and nitrogen from vegetation and soil). In the next stages, tonnes of carbon are stored in the soil as well as in tree boles, stems, and roots within an extremely short amount of time.

A portion of the carbon will return to the atmosphere when the trees are harvested and the land is returned to cultivation (sequential systems) (Dixon 1995). If the initial store of carbon has a positive net carbon balance after several decades, then effective sequestration can be evaluated (Feller *et al.* 2001). Perennial agroforestry systems (perennial-crop combinations, agroforests, and windbreaks) that allow full tree growth and where the woody component represents a significant portion of total biomass are the only systems that allow carbon storage in plant biomass. In these systems, sequestration can continue even after the wood is harvested. If boles, stems, or branches are transformed into long-lasting items, their carbon storage life can be extended significantly (Roy 1999).

CONCLUSION

Agrosilviculture agroforestry practices in Uttaradit Province, northern Thailand, have resulted in a wide range of carbon sequestration rates; that is, the potential for sequestering carbon and other nutrients in DAF is high, while the potential for sequestering these nutrients in TAF and AAF is much lower. According to these findings, carbon loss in northern Thailand's agroforests is linked to the removal of aboveground biomass, the organic matter in the soil, and even fine root carbon. Ratios such as these, are the commonest in advanced forms of forestry; on the other hand, the ratios for TAF and AAF are much lower. As a result, if a switch is made from TAF to modern agroforestry, the carbon loss from aboveground biomass would outweigh the loss from other carbon pools. Similarly, in agroforestry practices, top soil (0-15 cm) has the highest potential for carbon sequestration in SOC content. It is clear that agroforestry plays an important role in terrestrial ecosystems as carbon sinks. Although understanding the potential of carbon sequestration in different CO₂ pools is important, it is also crucial to compare agroforestry practices to other land use types because the information gained would be significant for carbon mitigation and the implementation of the "Land Use, Land Use Change, and Forestry (LULUCF)" concept for CO₂ sinks.

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