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Aboveground Biomass and Carbon Sequestration Potential of Tea and Shade Trees in Miang Tea Gardens, an Agroforestry System in Northern Thailand

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ABSTRACT

In the mountainous areas of northern Thailand, a tea agroforestry system referred to as the “miang tea garden” has been maintained by smallholders for more than a hundred years. To discuss the ecological advantages of the miang tea garden system, we determined the spatial distribution patterns of these gardens and the relationship between shade trees and tea trees, emphasizing their aboveground biomass. We developed an allometric model for estimating the aboveground biomass of the stool-shaped tea trees. The area utilized for tea tree cultivation was approximately 72% of the total study area, and the remaining 28% was classified as forest patches or abandoned gardens. In miang tea gardens, trees other than tea trees were used by farmers to moderate the amount of sunlight reaching the tea leaves. Additionally, these trees ensured an alternative source of income for the farmers. However, we suggest that the canopy openness should be maintained at more than 25% to prevent tea leaf growth inhibition. The carbon content in the miang tea garden system was 45.51 ± 21.68 Mg C ha⁻¹, considerably higher than that in other types of upland agriculture. The miang tea garden could represent an efficient land-use system supporting sustainable economic activities in areas with geographical limitations for the cultivation of other crops.

Key words: agroforestry, aboveground biomass, carbon sequestration, miang tea garden, tea cultivation

INTRODUCTION

Agroforestry, the practice of growing trees and crops in interacting combinations, is recognized worldwide as an integrated approach to sustainable land use. It has been estimated that agroforestry is practiced on more than 1 billion hectares (ha) of land in developing countries, and to a lesser extent, in industrialized countries (Nair et al. 2010). The mechanisms by which agroforestry provides ecological services and contributes to biodiversity have been explored by many researchers (Schroth et al. 2004; McNeely 2004; Harvey et al. 2006; McNeely and Schroth 2006; Jose 2009).

Tea agroforestry can combine efficient land-use with sustainable livelihoods for local smallholders, especially in developing countries. The exact definition of a tea smallholder varies by country, but a general description would be a small-scale tea cultivator who manages areas varying from less than 1 ha to 20 ha, mainly using family labor (Committee on Commodity Problem 2011). Although most tea is produced on large-scale plantations, 25% is still produced by smallholders (Kalita et al. 2019). Small-scale tea production is important in developing countries such as India, Kenya, Sri Lanka, and Vietnam as it provides a leading export product and livelihood for a large proportion of the population (Onduru et al. 2012; Kalita et al. 2019).

Most small-scale tea plantations are regarded as agroforestry systems because smallholders frequently keep previously grown trees or plant new trees, other than tea trees, in their gardens as shade for their crops (Beer 1987; Hajiboland 2017). The previously grown or planted trees in the tea gardens help stabilize the soil, protect it from heavy rainfall, and stop moisture evaporating in extreme heat (Reay 2019). The diffused canopies provide shade for tea trees, reduce damage by heavy rain, improve the crop, suppress weeds, and reduce evapotranspiration of the shaded crops (Purseglove 1968; Beer 1987). Besides providing forest products, including fruit, fuel, and fodder, these trees also provide organic nutrition, genetic materials, water retention, and pest control (Beer 1987; Nair 1979; Reay 2019).
Compared to monocultures or pasture systems, agroforestry systems are believed to have a higher potential to sequester carbon (Montagnini and Nair 2004; Sharrow and Ismail 2004; Nair et al. 2009; Nair et al. 2010; Jose and Bardhan 2012). Agroforestry with tree crops such as tea, cacao, and coffee is more efficient than agroforestry with annual crops because of its greater ability to conserve carbon in the biomass of both the shade trees and the tree crops (Kalita et al. 2019). In addition to contributing to the stability of local livelihoods, the tea agroforestry system has the potential to store and sequester carbon, thus contributing to climate change mitigation (Kalita et al. 2016).

In mountainous areas of northern Thailand, tea agroforestry has been maintained by smallholders for more than a hundred years. The tea agroforestry system in this region is called "pa miang" (tea forest) or "suwan miang" (tea garden) by the local people. "Miang" is a local tea product used for chewing or eating. It is a traditional fermented food in the region and is also widely used as an offering in Buddhist rituals (Reichart and Philipsen 1996). Hereafter, in this paper, the tea agroforestry system in northern Thailand will be referred to as "miang tea garden."

In northern Thailand, the tea tree, Camellia sinensis var. assamica, originally grew in the lower layer of evergreen and fallow forests of the swidden agricultural system practiced by the Karen or Lua people. About a hundred years ago, the Khon muang people settled in the abandoned fallow forests to cultivate tea trees and produce miang (Kunstadter and Chapman 1978). The Khon muang constitute the largest population in northern Thailand (Kutanan et al. 2011). They are Thai people who identify themselves as the "lowland Thai of northern part" and are not included in hill tribes (Offringa 2015). They retained trees other than tea trees in their tea gardens to reduce the labor force required to clear the land (Keen 1978). The tea tree was the only cash crop they were able to cultivate in the area because the customary rules of miang-producing communities generally prohibit the cultivation of rice and vegetables on large plots (Sasaki 2008). The people are also prohibited from using fertilizers or pesticides for tea cultivation (Sasaki 2008; Tanaka et al. 2010), but occasionally, cattle are allowed to graze within the miang tea gardens (Watanabe et al. 1990; Preechapanya 2001).

Previous studies on the miang tea gardens have mainly focused on socioeconomic aspects, such as analysis of the long-term adaptation of miang farmers to social change (Sasaki et al. 2007; Sasaki 2008) or the evaluation of miang farmers’ indigenous knowledge about nature and agriculture (Preechapanya 2001; Santasombat 2003; Choocharoen et al. 2014). Few studies have discussed the structure and stability of miang tea gardens (Watanabe et al. 1990). However, within the context of providing both local and global sustainability, the tea agroforestry system should be evaluated from the viewpoint of ecological and ecosystem services (Kalita et al. 2016; Ahmed et al. 2017; Kalita et al. 2019).

To discuss the ecological advantages of the miang tea garden system, this study aimed to investigate why and how the structure of miang tea gardens is maintained and managed by miang farmers in the mountain of northern Thailand. Our main objectives were to (1) examine the spatial distribution patterns of miang tea gardens; (2) determine the relationship between shade trees and tea trees, focusing on their aboveground biomass; and (3) clarify why villagers preserve other trees in their tea gardens and how they utilize them. Finally, we assessed the significance of land-use practices in this agroforestry system for both farmers’ livelihoods and climate change mitigation in the mountainous areas of northern Thailand.

**MATERIALS AND METHODS**

**Study site**

The study was conducted in the main community region of the P village, Chiang Dao District, Chiang Mai Province in northern Thailand (Fig. 1). The P village is inhabited by the Khon muang (lowland Thai) community and is located approximately 60 km northwest of Chiang Mai city, in a mountainous area between 900 and 1200 m a.s.l. The vegetation in this area comprises montane evergreen forests. According to the documents obtained from the temple in the P village, the village was founded in 1931 by settlers who moved into the area to cultivate tea.

Previously, we created a land-use map of the village (Fig. 2, cited from Sasaki et al. 2007). As the harvest depends on the number of tea trees in each miang tea garden, the boundaries of each garden are strictly demarcated and recognized by all the villagers who manage the gardens (Keen 1972). As of 2002, 85 of the 99 miang tea gardens in the village accounted for 137 ha of land, with an average of 1.6 ha garden⁻¹. In the present study, this map was used as the basis for establishing the number of gardens and estimating their respective areas.

The sampling of the tea trees and the measurement of each plant component to develop the allometric model were conducted from August to September 2001. Ecological surveys and interviews of villagers were conducted from
Fig. 1. Study site in P village, Chiang Dao district, Chiang Mai province, Thailand.

Fig. 2. Land use map of P village. The shaded area on the map are the study sites in the *miang* tea gardens. (Quoted from Sasaki et al. 2007)
February to November 2002.

Allometric model for estimating the aboveground biomass of tea trees

One of the allometric models for estimating the aboveground biomass of trees using the diameter at breast height \((DBH, \text{cm})\) and tree height \((H, \text{m})\) is:

\[
w = A (DBH^2 H)^h
\]

where \(w \text{ (kg)}\) is the total dry weight of aboveground tree parts, and \(A\) and \(h\) are the parameters for the regression line \((\text{Chave et al. 2014})\). Here we used parameter values of \(A\) and \(h\) reported by Ogawa and Saito \((1965)\) in a study on the allometry of evergreen oak forest trees, as shown below.

\[
w_S = 0.0396 (DBH^2 H)^{0.9329}
\]

\[
w_B = 0.00602 (DBH^2 H)^{1.027}
\]

where \(w_S\) and \(w_B\) referred stem weight and branch weight in kg. They reported the best-fit model of leaf biomass, \(w_L\), as below.

\[
1/w_L = 26/(w_S + w_B) + 0.02
\]

Because the tea trees for miang production were pruned frequently and showed unique shapes (Fig. 3), we developed an allometric model for estimating the aboveground biomass of stool-shaped tea trees. The aboveground biomass of a tea tree can be expressed as a function of the stem’s diameter at 30 cm above ground level \((D_{30}, \text{cm})\) and tree height \((H, \text{m})\):

\[
w = A (D_{30}^2 H)^h
\]

For the development of this allometric model, the parameters \(A\) and \(h\) of the tea trees were evaluated. Sampled tea trees were collected in the M miang-producing village, located in the same watershed as the P village \((\text{Fig. 1})\). Twenty-one tea trees, with different tree heights, were logged from six miang tea gardens. After separating the leaves, stem, and branches, the fresh weight of each component was measured. Each component was placed in an aluminum drying rack and dried using an electric heater \((70 \text{ to } 80 \, ^\circ \text{C})\) for more than 24 hours to get final constant weight. The total dry weight of each plant component from each tea tree was measured. For larger tea trees, only a part of each component was sampled and dried, and the total dry weight was estimated from the sampled part.

Distribution of tea trees and other trees

While tracing the gardens’ boundaries, different distribution patterns of tea trees and shade trees were observed. We described the patterns used in the gardens and estimated the area and the number of each pattern in P village.

All miang tea gardens in P village were located on steep hillsides. The canopy coverage of both tea and shade trees at 5 m intervals was recorded by walking down the center of each garden, from the ridge to the lower side. Coverage was estimated using the five-level scale by Braun-Blanquet \((\text{Braun-Blanquet 1932})\). A total of 85 miang tea gardens were categorized into five types, according to the distribution and coverage of tea and shade trees \((\text{Table 1})\). Gardens that had densely planted tea trees and an open canopy of shade trees were categorized as type A. Gardens that had a closed canopy with fewer tea trees were categorized as type E. Types B, C, and D had similar cover estimates for both tea and shade trees, but different
distribution patterns of shade trees. The areas of each garden type and tea cultivation or forest patch were estimated using GIS software (ArcView 3.1).

**Tree censuses in the miang tea gardens**

The tree census survey was conducted in the sampled miang tea gardens in areas where the distribution patterns of tea and shade trees were different. To determine the relationship between tea trees and shade trees, we selected nine plots with differences in canopy openness in the central part of the garden. The degree of canopy openness was calculated with an open-source software CanopOn 2 (http://takenaka-akio.org/etc/canopon2/), based on the results of the analysis of hemispheric canopy photographs. The photographs were taken with a fish-eye lens camera, placed 1 m above the ground on a tripod. The plots were numbered in accordance with canopy openness (Table 2).

Two concentric subplots were located within each plot. The inner circle, with a radius of 10 m, was used for the tea tree census, while the larger circle, with a radius of 20 m, was used for the census of other trees. Owing to topographical limitations, the inner circle radius in plots 1 and 6 was 7 m, and the outer circle radius in plots 2 and 6 was 15 m. Trees other than tea trees, with DBH ≥ 10 cm, were identified, and their DBH (cm) and height (H, m) were measured. Banana plants and bamboos were also included in the tree census since these plants were utilized by the villagers of P village for their livelihood and miang production.

All tea trees in the inner circle were measured. As stated earlier, most tea trees were pruned to 70 cm to 1 m height every 2 or 3 years to develop the new shoots. Therefore, the tea trees were shaped like a "stool", a living stump with two or more branches (Fig. 3). Hereafter, the living stumps of the tea trees will be referred to as "stools." We measured the tree height and the stem diameter of stools at 30 cm above ground level (D₁₀) and the size of all branches, i.e., base diameter and length directly developed from the stool stem.
Interviews with miang tea farmers

Households with the right to use miang tea gardens were interviewed using open questions to ascertain the reasons for allowing trees other than tea trees to remain within their gardens. They were also questioned about the utilization pattern of trees observed in the village.

RESULTS

Allometric models for estimating the aboveground biomass of tea trees

Parameters $A$ and $h$ for the regression line of tea trees were evaluated. The coefficient of determination between $D_{30}^2$ (cm$^2$) × $H$ (m) and stem and branch biomass ($w_s + w_b$ kg) and between $D_{30}^2$ (cm$^2$) × $H$ (m) and leaf biomass ($w_l$ kg) of the tea trees showed 0.980 and, 0.983 respectively (Fig. 4). Based on these results, we used the following allometric equations:

\[
w_s + w_b = 0.03912(D_{30}^2 H)^{0.9342}
\]

\[
w_l = 0.01814(D_{30}^2 H)^{0.7633}
\]

where $w_s + w_b$ as well as $w_l$ is measured in kg. The aboveground biomass of each tea tree was estimated using the total of $w_s + w_b + w_l$.

Distribution of tea trees and other trees

As stated earlier, the boundaries of each garden are strictly demarcated and recognized by all villagers in P village. Miang tea gardens are usually located on steep hillsides, and the upper and lower parts of their gardens are demarcated by topographic landmarks, such as ridges and streams. To determine side boundaries, farmers utilize several landmarks, such as big trees, rocks, or trails. Tea trees are mainly planted near the center of the gardens on steep hillsides, whereas few or no tea trees are present near the boundaries. Trees other than tea trees near the ridges and streams are not logged and grow into dense stands. The area utilized for tea tree cultivation covered approximately 72% of the total study area (98 ha of 137 ha), whereas the remaining 28% (39 ha) comprised dense forest patches,
Table 3. The number and size of miang tea gardens categorized into five types according to the distribution and coverage of tea and shade trees.

| Type | Number of gardens (%) | Total area (ha) (%) | Average area (ha garden⁻¹) |
|------|-----------------------|---------------------|-----------------------------|
| A    | 9 11                  | 17 12               | 1.9                         |
| B    | 15 18                 | 30 22               | 2.0                         |
| C    | 30 35                 | 42 31               | 1.4                         |
| D    | 23 27                 | 35 25               | 1.5                         |
| E    | 8 9                   | 13 10               | 1.7                         |

Source: Field survey by the authors.

According to the GIS analysis.

As shown in Table 3, the number and area of gardens categorized as type C occupied more than 30% of the total number and covered over 30% of the total area of gardens. Gardens categorized as type B and D were relatively larger than those of type A and E. Both the area and the number of gardens categorized as type B, C, or D covered approximately 80% of the studied area.

Nearly 10% of both the total number and the total area of gardens was categorized as type E. Eight gardens (9%) were managed by six households. All the six households managed several gardens, and the average number of gardens was 3.7 (maximum nine gardens). The villagers had temporarily abandoned one or two of their gardens owing to labor shortage or engagement in additional work, such as gathering forest products. They also stated that it was a frequent practice to resume the care of miang tea gardens after seasonal work or migrant work.

Dominant species of shade trees

All tree species identified in the survey were indigenous to the area (Table 4). The total number of species recorded in the 9 plots was 75. Fifty species (67%) had a frequency of 11%, implying that all these species were present in a single plot. Table 4 shows the species of shade trees that constituted more than 1% of the total biomass in the nine plots.

Schima wallichii (Theaceae) had the highest aboveground biomass (12.9 Mg ha⁻¹), highest basal area (22.3 m² ha⁻¹), and highest frequency (67%). The average aboveground biomass of S. wallichii was twice as much as that of Erythrina stricta (Fabaceae), which had the second-highest biomass (9.4 Mg ha⁻¹). Musa acuminate (Musaceae), a non-tree crop, appeared only in Plot 2, where 17 plants of this species were recorded. In the garden where Plot 2 was set, the farmer planted M. acuminate to harvest the fruits and flowers for daily consumption and the stems for feeding pigs. This was the only instance of a farmer who planted a crop species other than the tea tree in his garden. Except for this case, other farmers showed little interest in managing any particular species identified in the tree censuses.

Fukushima et al. (2008) listed the dominant species that constituted more than 1% of the total biomass, in both uncultivated forests and secondary forests abandoned after upland rice or poppy cultivation, in the lower montane forest in northern Thailand. While comparing the results of the present study with those of Fukushima et al. (2008), it was observed that among the 24 species (13%) in the uncultivated forests, three were common shade trees in the miang tea gardens in our study, and, on average, 27% of the species were common to both the secondary forest in their study and the miang tea gardens in our study.

Aboveground biomass of shade trees

Table 5 shows the number of species, stem density, basal area, and average aboveground biomass of the shade trees from the miang tea garden plots. A comparison of the five types of miang tea gardens showed that the aboveground biomass of Plots 1, 2, and 4 was significantly lower than that of other plot types. These plots occurred in type A miang tea gardens. By contrast, Plot 9, which belonged to type D, had the highest aboveground biomass and basal area of shade trees. Except for Plot 9, the aboveground biomass varied significantly between types B, C, D, and E plots. The aboveground biomass of shade trees tended to increase with decreasing canopy openness (Fig. 5).

These results were compared with those of Fukushima et al. (2008), who investigated the aboveground biomass of uncultivated lower montane forests at the same elevation as our study and found it to be 185–260 Mg ha⁻¹. In the present study, the average aboveground biomass of type B, C, and D miang tea garden plots was 88.6 ± 43.12 Mg ha⁻¹, which was equivalent to 48%–34% of the biomass of the uncultivated forests investigated by Fukushima et al. (2008).

Aboveground biomass of tea trees

The aboveground biomass of tea trees did not have a clear relationship either with canopy openness or aboveground biomass of shade trees. However, the aboveground biomass of tea trees in Plots 1 and 6 was
The tea trees in Plot 1 had the largest basal area of both stools and branches, and many branches (Table 6). This structure indicated that the farmer had recently pruned the stems to encourage the growth of new shoots. While Plot 6 had many stools and branches, the stools had the smallest basal area among the plants from all the nine sampled plots. The mean and standard deviation values of the basal area of stools also indicated that most tea trees in Plot 6 were small (Table 7). According to the interview, this was because the farmer had planted more than 10000 tea tree seedlings in Plot 6 in 2002. The mean height of the tea trees in Plots 1 and 6 was relatively lower than in the other sample plots (Table 7).

Except for Plots 1 and 6, tea trees in all the investigated miang tea gardens had varying diameters and heights.

The farmers’ reasons for keeping trees other than tea trees in their gardens

According to 66 % of the miang farmers interviewed, the reason for keeping trees other than tea trees was for shade (Table 8). In addition, 16 respondents (43 %) explained that other trees were needed to prevent the color of the leaves changing from green to yellow as a consequence of direct sunlight since the price of miang made with yellow leaves
Table 5. Number of species, stem density, basal area, and average aboveground biomass of shade trees in *miang* tea garden plots.

| Plot No. | Number of species (n ha⁻¹) | Stem density (Ind ha⁻¹) | BA (cm² ha⁻¹) | Aboveground biomass (Mg ha⁻¹) | Category type |
|----------|----------------------------|------------------------|--------------|-------------------------------|---------------|
| 1        | 1                          | 8                      | 4            | 0.0*                          | A             |
| 2        | 4                          | 538                    | 16325        | 1.9                           | A             |
| 3        | 14                         | 366                    | 98415        | 55.4                          | D             |
| 4        | 10                         | 342                    | 7574         | 4.0                           | A             |
| 5        | 20                         | 454                    | 140229       | 84.1                          | E             |
| 6        | 7                          | 198                    | 115199       | 47.9                          | C             |
| 7        | 6                          | 88                     | 88431        | 73.4                          | C             |
| 8        | 40                         | 549                    | 175772       | 98.8                          | B             |
| 9        | 19                         | 223                    | 249381       | 167.4                         | D             |

*BA = basal area.*

*Aboveground biomass of shade trees in Plot 1 was 0.0004 Mg ha⁻¹.*

Source: Field survey by the authors.

Table 6. Number of stools, basal area and average aboveground biomass of tea trees in *miang* tea garden plots.

| Plot No. | Number of stools (n ha⁻¹) | BA of stools (cm² ha⁻¹) | Number of branches (n ha⁻¹) | BA of branches (cm² ha⁻¹) | Biomass of leaves (Mg ha⁻¹) | Biomass of stools and branches (Mg ha⁻¹) | Aboveground biomass (Mg ha⁻¹) | Category type |
|----------|---------------------------|------------------------|-----------------------------|---------------------------|----------------------------|------------------------------------------|-------------------------------|---------------|
| 1        | 1755                      | 68749                  | 35617                       | 7419                      | 0.2                        | 0.4                                      | 0.6                           | A             |
| 2        | 541                       | 17917                  | 4363                        | 34581                     | 0.7                        | 3.2                                      | 3.9                           | A             |
| 3        | 1433                      | 26278                  | 5955                        | 29064                     | 0.6                        | 2.7                                      | 3.3                           | D             |
| 4        | 2229                      | 40758                  | 6943                        | 55724                     | 1.4                        | 6.2                                      | 7.6                           | A             |
| 5        | 1529                      | 44330                  | 3280                        | 58896                     | 1.3                        | 6.3                                      | 7.6                           | E             |
| 6        | 11374                     | 11061                  | 15599                       | 12392                     | 0.3                        | 0.7                                      | 1.0                           | C             |
| 7        | 1338                      | 20044                  | 3408                        | 24988                     | 0.4                        | 1.6                                      | 2.0                           | C             |
| 8        | 1401                      | 44056                  | 4968                        | 26409                     | 0.6                        | 3.0                                      | 3.6                           | B             |
| 9        | 1401                      | 26423                  | 4905                        | 23037                     | 0.2                        | 2.3                                      | 2.5                           | D             |

*BA = basal area.* Diameter for calculating basal area of stools and branches were measured at 30 cm above ground level and near the fork, respectively.

Source: Field survey by the authors.
was less than that made with green leaves.

Of the other respondents, seven (22%) stated the importance of trees for the retention of water in the soil. According to them, the tea trees growing on steep slopes could easily lose soil water without the presence of other trees. The respondents also shared their experience regarding deforestation on the hilltops. They said that deforestation by hill tribes up above caused a massive flood that killed several people and many livestock several decades ago, resulting in huge damage in the nearby villages. The villagers of the P village were mostly told this story by their parents or the elderly.

Three farmers (9%) stated the necessity to keep the trees for fuel for steaming tea leaves and cooking, and one farmer (3%) said that the law, or community rules, prohibited tree logging in the village without permission. According to the head villager, the village’s customary rules allowed farmers to cut one tree per year in the forest patches of their gardens to obtain fuel for steaming tea leaves or cooking food. Farmers often cut trees in their forest patches on ridges to allow easy access to the road. Although cutting trees around tea trees on a slope was prohibited, the use of parts of fallen trees was allowed.

### Forest resource utilization by farmers

According to the interviews and participants’ observations, 13 tree species and 2 plants were frequently used by farmers (Table 9). Among the 15 species, 6 (40%) were recorded in the tree census. Bamboo was the most frequently used forest resource for producing materials such as belts for tying tea leaves, baskets, and building materials. Gathering of bamboo shoots was a frequent activity of the villagers from April to June. *Schima wallichii* was widely used in the area as a source of fuel. *Tectona grandis* (teak) was cited as a useful species. However, as of 2002, teak trees were found only near the boundary with the neighboring village. The young red leaves of *Ficus virens* are used as traditional food in northern Thailand, and the fruits of 10 other species were also eaten. Farmers often gathered forest products in both *miang* tea gardens and forest patches in the village.

### DISCUSSION

#### Why do farmers maintain other trees in *miang* tea gardens?

Among the five types of *miang* tea gardens, 35% of the total number and 31% of the total area was categorized as type C. Nearly 25% of the total number and total area was categorized as type D. The interviewed farmers also

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**Table 7. Mean and standard deviation values of basal area and height of tea trees in *miang* tea garden plots.**

| Plot No. | Number of stools (n ha⁻¹) | BA of stools (cm² ha⁻¹) | Mean BA (cm²) | Standard deviation | Minimum BA (cm²) | Maximum BA (cm²) | Mean height (cm) | Standard deviation | Minimum height (cm) | Maximum height (cm) | Category type |
|---------|--------------------------|------------------------|---------------|-------------------|-----------------|-----------------|-----------------|-------------------|-----------------|---------------------|---------------|
| 1       | 1755                     | 68749                  | 39.2          | 52.2              | 4.84             | 227             | 92.3            | 29.9              | 12              | 240                 | A             |
| 2       | 541                      | 17917                  | 33.1          | 33.6              | 0.20             | 134             | 155.0           | 82.7              | 28              | 370                 | A             |
| 3       | 1433                     | 26278                  | 18.3          | 26.7              | 0.01             | 137             | 154.8           | 77.7              | 17              | 453                 | D             |
| 4       | 2229                     | 40758                  | 18.3          | 24.0              | 2.32             | 120             | 225.6           | 100.1             | 35              | 465                 | A             |
| 5       | 1529                     | 44330                  | 29.0          | 30.6              | 1.68             | 111             | 251.1           | 95.2              | 80              | 481                 | E             |
| 6       | 11374                    | 11061                  | 1.0           | 0.8               | 0.07             | 4               | 96.3            | 36.2              | 8               | 232                 | C             |
| 7       | 1338                     | 20044                  | 15.0          | 23.1              | 0.20             | 103             | 131.6           | 61.7              | 45              | 322                 | C             |
| 8       | 1401                     | 44056                  | 31.4          | 102.4             | 0.03             | 669             | 159.5           | 91.1              | 40              | 541                 | B             |
| 9       | 1401                     | 26423                  | 18.9          | 14.4              | 0.20             | 70              | 163.9           | 135.5             | 20              | 693                 | D             |

BA = basal area. Diameter for calculating basal area of stools was measured at 30 cm above ground level.

Source: Field survey by the authors.

**Table 8. Responses to the interview using open question, "What are the reasons for keeping other trees in *miang* tea gardens?"**

| Answer                              | Number of respondents (people) | (%) |
|-------------------------------------|---------------------------------|-----|
| For shading tea trees               | 21                              | 66  |
| For maintaining soil moisture       | 7                               | 22  |
| For wood fuel                       | 3                               | 9   |
| To abide by community rules         | 1                               | 3   |

Source: Field survey by the authors.
recognized forested landscape as the proper environment for tea cultivation and specified the importance of shade for moderating the amount of sunlight reaching tea leaves.

The dominant species recorded in the tree census were similar to those found in secondary forests abandoned after swidden cultivation in the lower montane forest of northern Thailand (Fukushima et al. 2008). This suggested that the shade trees in miang tea gardens were not newly planted but were left by the farmers when they converted abandoned fallow forests to miang tea gardens. Apart from this, no clear preference for specific tree species in the gardens was observed in this study.

Kunstadter and Chapman (1978) reported that the miang-producing communities usually comprised people who had moved out of the lowlands about a hundred years ago, mostly because of limited irrigable land and shortage of wage work opportunities in the lowlands. By utilizing naturally growing tea trees and minimizing the logging of trees in the post-swidden cultivation secondary forests, the immigrants were able to develop tea gardens with less labor. Thus, the forested landscape of miang tea gardens we see today originated from the time when the immigrants attempted to convert secondary forests into tea gardens with a minimum labor force.

In addition to their environmental significance, trees other than tea trees are also important as sources of both timber and non-timber forest products. The miang farmers require a large quantity of fuel for steaming the tea leaves. Miang farmers also started to sell several components of trees or plants harvested in their gardens when the miang market was declining (Sasaki et al. 2007). It can be said that the trees and forest patches ensured an alternative source of income for the farmers to cope with dramatic socioeconomic changes outside or in their villages. Additionally, the villagers of P village, like those in other miang-producing villages, do not use chemical fertilizers or pesticides (Sasaki 2008; Tanaka et al. 2010). These farmers utilize the benefits of trees in agricultural fields.

Choocharoen et al. (2014) also suggested that miang farmers consider soil fertility and water management when cultivating tea trees. Furthermore, integrating local knowledge into scientific analysis could help develop sustainable highland agro-ecosystems (Choocharoen et al. 2014). Besides this, the maintenance of miang tea gardens substantially contributes to preserving local forests and maintaining biodiversity in the area (Santasombat 2003).

Do shade trees have negative effects on tea trees?

The tea trees in Plots 1 and 6 had lower aboveground biomass, but a higher number of stools than the trees in other plots (Table 6). This finding may be because in 2002, following the rapid expansion of the “green tea” market in 2001, two households managing the gardens where Plots 1 and 6 are situated began to harvest and ship the fresh leaves.

Table 9. List of trees, other than tea trees, frequently utilized by farmers in miang tea gardens in P village, northern Thailand.

| Species | Family       | Local name | Use                      |
|---------|--------------|------------|--------------------------|
| Schima wallichii | Theaceae | Mai Talo | Stem/Branch (fuel)        |
| Dimocarpus longan | Sapindaceae | Lam Yai | Fruit/Stem/Flower (for food and forage) |
| Musa acuminate | Musaceae | Kluewi | Fruit                      |
| Citrus maxima | Rutaceae | Mu O (Som O) | Fruit                      |
| Baccaraea ramiflora | Euphorbiaceae | Ma Fai | Fruit                      |
| Lichi chinensis | Sapindaceae | Linchi | Fruit                      |
| Artocarpus heterophyllus | Moraceae | Khanun | Fruit                      |
| Bamboo (unidentified) | Poaceae | Mai Phai | Shoot (food)/ Stem (tool) |
| Ficus genculata | Moraceae | Mai Ho | Fruit                      |
| Ficus virens | Moraceae | Phak Luat | Leaf (food)               |
| Ficus arborea? | Lamiaceae | Ton Teang Khao | Stem (tool for steaming tea leaf) |
| Mangifera indica | Anacardiaceae | Ma Muwang | Fruit                      |
| Nephelium pappaceum | Sapindaceae | Ngo | Fruit                      |
| Phyllanthus emblica | Pyllanthaceae | Ma Kham Pom | Fruit                      |
| Tectona grandis | Lamiaceae | Mai Sak | Stem (timber)              |

Species with numbers indicated next to them were identified in tree censuses.

Source: Field survey by the authors.
for drinking tea production, instead of miang production (Sasaki et al. 2007). When the tea trees were harvested for green tea production, the farmers cut back their tea trees stems to a height of 30–40 cm to stimulate the growth of new shoots and young leaves. We observed that the number of stools and branches varied greatly among the investigated plots, and depended on management practices such as seedling planting and stem pruning. Therefore, the aboveground biomass of tea trees was not directly dependent on canopy openness or on the aboveground biomass of trees other than tea.

A thick canopy environment potentially inhibited the growth of the tea leaves. However, the average ratio of tea leaf biomass to total aboveground biomass in Plot 9, where canopy openness was lowest, was 9.8 %. The average ratios of tea leaf to total aboveground biomass in other plots was 21.7 % (Fig. 5). This suggested that the miang farmers generally utilized naturally growing shade trees to maintain a proper tea cultivation environment except when the dense canopy of shade trees adversely affected the tea leaf growth. This could explain why various types of miang tea gardens were observed in P village.

Regarding the productivity of tea leaves, large-scale tea plantation has an advantage over the miang tea garden system. Based on the investigation by Li et al. (2011), the total aboveground biomass for large-scale tea plantation in the western part of China was estimated to be 77.9 Mg ha$^{-1}$. The biomass of harvested leaf and pruned branchlet and leaf in large-scale tea plantations were 1.1 Mg ha$^{-1}$ and 15.1 Mg ha$^{-1}$, which were equivalent to 1.4 % and 15.1 % of the total aboveground biomass, respectively (Li et al. 2011). The mean densities of the tea trees of a miang tea garden and a large-scale tea plantation were 2556 tree ha$^{-1}$ and 36750 trees ha$^{-1}$, respectively. In the present study, the largest aboveground biomass of a tea tree was 7.6 Mg ha$^{-1}$ in Plots 4 and 5, equivalent to 9.8 % of a large-scale tea plantation in China. In addition, the biomass of tea leaf in a miang tea garden was equivalent to 21.2 % of the biomass of harvested leaf and pruned branchlet and leaf in a large-scale tea plantation (Li et al. 2011). As mentioned above, miang farmers in P village usually keep the height of the tea trees relatively higher than those in tea plantations. The mean height of a tea tree in this study ranged from 92.3 cm to 251.1 cm, higher than in large-scale plantations where tea trees range from 60 cm to 110 cm (Li et al. 2011). This observation indicates that miang farmers ensure a higher tea leaf yield by allowing the tea trees to grow taller.

**Can miang tea gardens contribute to carbon sequestration?**

The average aboveground biomass of shade trees in types B, C, and D of the miang tea gardens was 88.6 ± 43.12 Mg ha$^{-1}$. We then estimated the aboveground carbon amount of shade trees in miang tea garden as 44.28 ± 21.56 Mg C ha$^{-1}$ by applying the conversion rate of plant mass to carbon (Brown and Lugo 1982; Dixon et al. 1994). It has been reported that tea trees maintain high aboveground woody biomass, and the carbon content is 49 % in stems and branches and 50 % in leaves (Horiuchi et al. 2011). In the average aboveground biomass of tea trees in


Table 10. Comparison of aboveground carbon stocks in different land covers of northern Thailand.

| Land cover                        | Aboveground carbon (Mg C ha⁻¹) | Province  | Detailed information                                      | Source                      |
|-----------------------------------|---------------------------------|-----------|-----------------------------------------------------------|-----------------------------|
| *Miang* tea garden                | 45.51 ± 21.68                   | Chiang mai| This study                                                |                             |
| Shade tree                        | 44.28 ± 21.56                   |           |                                                           |                             |
| Tea tree                          | 1.23 ± 0.46                     |           |                                                           |                             |
| Lower montane forest              | 93–130                          | Chiang mai| Uncultivated forest in *Karen* village                    | Fukushima et al. (2008)     |
| Dry evergreen forest              | 133                             | Chiang mai|                                                           | Ogawa et al. (1965)         |
| Hill evergreen and mixed deciduous forests | 135.87 ± 22.57               | Nan       | National park reserves                                    | Pibumrung et al. (2008)     |
| Agriculture fields                | 6.10 ± 0.83                     |           | Fallow land, orchard, paddy field, corn fields           |                             |

types B, C, and D of the *miang* tea gardens, the total aboveground carbon stored in tea trees was estimated to be 1.23 ± 0.46 Mg C ha⁻¹. The total aboveground carbon of the *miang* tea gardens was calculated as 45.51 ± 21.68 Mg C ha⁻¹.

Compared with other studies in northern Thailand, the aboveground carbon storage in the *miang* tea gardens was relatively lower than that in natural forests (Table 10). However, the amount of carbon stored in *miang* tea gardens was equivalent to 35%–72% of natural forests in northern Thailand, and was considerably higher than that stored in upland agriculture. *Miang* tea gardens have potential as an important carbon pool while functioning as agricultural fields for smallholders in northern Thailand. To evaluate the stability of the *miang* tea garden system as a carbon pool, it would be necessary to conduct continuous research on the transformation of the *miang* tea garden system and *miang* production in P village following socioeconomic changes.

**CONCLUSION**

This study’s objective was to report on the advantages of tea agroforestry practices by northern Thailand smallholders. *Miang* farmers managed the tea gardens to maintain the quality and quantity of tea leaf production with no adverse effect on the tea trees. Forest products in the *miang* tea gardens also provided *miang* farmers with a potential income source to support them in times of poor harvest or labor shortage. The *miang* tea garden system can be evaluated as an efficient land-use practice supporting a stable economy in areas with geographical limitations for cultivating other crops. We also developed an allometric model to accurately estimate carbon stocks in stool-shaped tea trees to evaluate the function of the *miang* tea garden system as a carbon pool. Compared with other upland agricultural systems, *miang* tea garden systems also store relatively large amounts of carbon. Thus, *miang* tea gardens can potentially contribute to climate change mitigation in the mountainous areas of northern Thailand.

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