Carbon sequestration by mangrove plantations and a natural regeneration stand in the Ayeyarwady Delta, Myanmar

Ya Min Thant1*, Mamoru Kanzaki1, Seiichi Ohta1 and Maung Maung Than2

ABSTRACT Above and below ground biomass was studied in six years old mangrove plantations of Avicenia marina (Am), Avicenia officinalis (Ao) and Sonneratia apetala (Sa) and a naturally regenerated stand under regeneration improving felling operation (NR consists of Ceriops decandra, Bruguiera sexangula, and Aegiceras corniculatum) protected for seven years since 2000. Common allometric equations were developed for biomass estimation by performing regressions between dry weights of trees as dependent variables and biometric parameters such as stem diameter, height and wood density as independent variables. The above and below ground biomass in NR (70 Mg ha⁻¹ and 104 Mg ha⁻¹) was the greatest (P < 0.001), and followed by Sa (69 Mg ha⁻¹ and 32 Mg ha⁻¹), Am (25 Mg ha⁻¹ and 27 Mg ha⁻¹) and Ao (21 Mg ha⁻¹ and 26 Mg ha⁻¹). The total carbon stock in biomass was 73 Mg C ha⁻¹ in NR, 43 Mg C ha⁻¹ in Sa, 21 Mg C ha⁻¹ in Am and 18 Mg C ha⁻¹ in Ao respectively. The averaged total soil carbon stock up to 1 m soil depth in plantation site was estimated to be 167 ± 58 Mg C ha⁻¹ which was nearly two times higher than that of current paddy fields 85 ± 17 Mg C ha⁻¹. These facts suggest the feasibility of mangrove plantations and natural regeneration as a carbon sequestration tool. The induced natural regeneration method showed high feasibility as a low cost management to enhance the rapid restoration of the mangrove ecosystem.

Key words: Ayeyarwady Delta, carbon stocks, common allometric equation, specific gravity

INTRODUCTION

At present, global warming is one of the most important issues concerning the international community. The issue focuses on the increasing accumulation of greenhouse gases, principally carbon dioxide, in the atmosphere due to emissions caused by industrial activities and deforestation (Althoff and Chandler 1999). However, forest ecosystem could help reduce greenhouse gas concentrations by absorbing carbon from the atmosphere through the process of photosynthesis and pool carbon in their ecosystem as biomass and soil organic matter. In this concept, mangrove forests have been expected to function as sinks of carbon dioxide and greenhouse gases than other forest types, by their carbon dioxide sequestration ability due to their high primary productivity (Lugo and Snedaker 1974, Mann 1988) and large quantities of roots and organic matter in their substrata (Komiyama et al. 2000, Fujimoto 2004). Therefore, the estimation of mangrove forest biomass becomes an important study in order to manage the degraded mangrove ecosystem. It is also an essential aspect for the study of the effects of deforestation and global carbon balance.

Mangrove communities are normally characterized by high productivity, high biomass and high litter production when compared to other terrestrial plant communities (Lugo and Snedaker 1974, Mann 1982). The biomass of mangrove forests have been studied by many researchers by using allometric relationships based on the data from harvested sample trees. It is minimal destructive method and preferred for all trees and the biomass estimation of a forest ecosystem. However, such conventional allometric equations differ between tree species and regions. It means they can be applicable for specific tree species in specific location. Komiyama et al. (2002) reported that trunk weight solely depends on the trunk volume and its specific gravity (ρ). They analyzed species specific allometric relationships based on (ρ), with the aim of establishing a common equation for estimating the stem weight of mangroves. They again established common allometric relationships for the weight of mangrove trees growing both in primary and secondary stands, based on the pipe model theory and
difference in wood density among the species. They successfully established a set of common allometric equation for trunk, leaf, above-ground part and root.

In the Ayeyarwady Delta, mangrove forests have been an important ecosystem which provides a variety of resources and environmental service to coastal communities. However, mangrove forests in the Delta is one of the most threatened ecosystems, and is rapidly disappearing as in many tropical countries where mangrove was once abundant. Sit Bo (1992) reported faster deforestation rate of 7,775 ha per year in Ayeyarwady Delta which was three times faster than the other terrestrial forests in Myanmar. Most of the Ayeyarwady Delta mangrove forests have been disappeared due to continuous production of charcoal for local consumption and supply for Yangon city since Second World War. Charcoal production was considered four times greater than the sustained capacity of the Ayeyarwady Delta forest (Lahiri 1996). Due to increasing population, the over logging areas were cleaned, burned and transformed into paddy fields, settlement, fish and shrimp ponds and salt production. Paddy production was good in the beginning of 6 to 7 years. However, the production finally goes down because of the salt and acid sulphate intrusion from below. When the production was not justified economically, they abandoned the area and then shifted to the new forest areas and repeated the same process. In the meantime, these abandoned paddy fields are transforming into unproductive wastelands with sedge and undesirable species. Therefore, the deforestation and degradation of mangrove forest in the Ayeyarwady Delta results in the shortage of wood resources and declining of environmental services that have been provided by the mangrove ecosystem. As the local demands of the fuel wood and local use timbers are increasing and also the demand of the mangrove as the disaster control is also increasing after the catastrophe by Nagris in 2008 (Ya Min Thant et al. 2010).

The estimation of mangrove forest biomass becomes an important study in order to manage the degraded mangrove ecosystem. It is also an essential aspect of study of the effects of deforestation and carbon stocks and carbon sequestration on the global carbon balance. The biomass of mangrove forests has been studied for the past 20 years (Clough and Scott 1989, Clough et al. 1997, Komiyama et al. 1988, 2000, 2002, 2005, Ong et al. 1995, 2004, Tamai et al. 1986) by using allometric relationships based on the data from harvested sample trees. It is minimal destructive method and preferred for all trees and the biomass estimation of a forest ecosystem. Moreover, it is also laborious to weigh a number of trees for establishing a series of allometric relationships for all tree species and locations. Therefore, it is necessary to identify a common allometric relationship which can be applicable for different tree species in a forest ecosystem. Komiyama et al. (2002) reported that trunk weight solely depends on the trunk volume and its wood density or specific gravity (ρ). They analyzed species specific allometric relationships based on SG, with the aim of establishing a common equation for estimating the stem weight of mangroves. They again established common allometric relationships for the weight of mangrove trees growing both in primary and secondary stands, based on the pipe model theory and difference in wood density among the species (2005). They successfully established a set of common allometric equation for trunk, leaf, above-ground part and root. Common allometric relationships were investigated to estimate the biomass from independent variables such as stem diameter (DBH) and tree height (H) which are measurable in the field.

Mangrove plantations have been established by Forest Department and NGO with the participation of local people. Establishment of mangrove plantations is urgently needed to restore the degraded mangrove ecosystem. Information to understand and predict changes in ecosystem structure and function after the plantation establishment is necessary for the rational management of the plantation establishment, but fundamental ecological information on biomass and productivity of mangrove forests are still quite limited in Myanmar. The study aims to challenge the problem and set three objectives shown below.

1. To provide an acceptable method for the estimation of the above- and below-ground biomass of the mangrove plantations in the delta,
2. To estimate the biomass increment and carbon sequestration rate in plantations and natural regeneration stand,
3. To discuss the role of the small scale reforestation program in the delta as a measure for the mitigation of climate change.

**STUDY AREA**

The Ayeyarwady Delta is located in the southern part of Myanmar, between latitudes 15° and 18° North, and between longitudes 94° and 96° East. The annual rainfall is over 3000 mm, the average minimum and maximum temperatures are about 22.6°C and 28.8°C (Meteorology
Department, Myanmar, 2000 to 2004 data). Generally, the soil is classified as clay and clay loam, except along the sandy ridges. The soil acidity increases in the soil of abandoned paddy field to pH 5.0 - 5.5 (Kogo 1991). The level of the land is very low and most of the areas are submerged at spring tide during the rains. However, equinoctial tide days are the only time some areas can be submerged in dry season. Semi-diurnal tide commonly occurs in the delta, it means the tide rise and fall two times a day.

Mangroves in Myanmar are of interest to the conservationists because of the unique life forms that live among them and the adaptation of the mangroves themselves. However, most of the extensive mangroves in the Ayeyarwady Delta are much degraded because of exploitation for fuel wood and charcoal production. It is the most essential to restore the mangrove forests to their original state before it is too late. In the meantime, these abandoned paddy fields are transforming into unproductive wastelands with sedge and undesirable species. Forest Department and NGO Projects have been established mangrove plantations in the abandoned paddy fields with the participation of the local people. Many areas are still remaining as abandoned land and seriously degraded forests near the study village and also existing in many places in the Ayeyarwady Delta. These waste lands have to be reclaimed and restored to get back to the original or near original stage. Then only, the mangrove ecosystem will be restored and the environment will be improved or developed sustainably.

The study site was located at Wakone village in Pyin Daie Reserve Forest in Bogalay Township (Fig. 1). In the study area, Action for Mangrove Reforestation (ACTMANG) has initiated to launch a 5 year (1999 to 2004) Mangrove Reforestation program jointly with Forest Resource Environment Development and Conservation Association (FREDA). This project aimed at the establishment of mangrove plantations based on Community Forestry.

**MATERIALS AND METHODS**

The study was conducted in three mangrove plantations established in 2001 and in a natural regeneration forest (NR) protected since 2000 under small scale local community plantation scheme. These local community plantation stands were established on abandoned paddy fields where natural mangrove forests once existed. The farmers abandoned the area around 1995 after unsuccessful agricultural development. Examined plantation species were *Avicenia officinalis* (Ao), *Avicenia marina* (Am) and *Sonneratia apetala* (Sa). A spacing of 1.8 m × 1.8 m was generally adopted in the afforestation

![Fig. 1. Location of study area (●) in Bogalay Township, Ayeyarwady Delta.](image)
program in the area. Five 9 m × 9 m plots (each plot contains 25 planted trees) were chosen randomly in each of three plantations. The NR stand had been under regeneration improvement felling operation (RIF), such as weed cleaning and thinning to enhance the regeneration of tree species since 2000. RIF operation successfully eliminated weed plants common in this area such as Acanthus ilicifolius (Local name; Kaya), Acrostichum aureum (Hngetgyidaung), Derris scandens (Migyaunghwe), and Phoenix paludosa (Thinbaung) and three mangrove species, Ceriops decandra (Cd), Bruguiera sexangula (Bs), and Aegiceras corniculatum (Ac), naturally regenerated. Five 5 m × 5 m plots were chosen from a NR stand. Diameter at breast height (DBH) and height (H) of all trees in these plots were measured and recorded.

**Biomass measurement**

Two sample trees for each plantation species and one sample tree per species in NR were harvested from the outside of the census plots to evaluate the applicability of Komiyama’s common allometry equations and if necessary to develop common allometry equations for our stands. The diameter (DBH) and stem height (H) were measured on the felled trees. The sample trees ranged from 1.7 cm to 12.1 cm in DBH and from 3.8 m to 9 m in height. Stratified clip technique was used for aboveground measurement and block sampling method (1.8 m × 1.8 m × 0.5 m) in plantations were used for below ground measurement. Roots were excavated to a depth of approximately 0.5 m in both plantations and natural regeneration stand. We gave up excavation of deeper part because of submergence of the pits. The excavated root materials were washed nearby creek to remove the adhering mud, a sieve being used to retain fine roots. Root materials were sorted as pneumatophores, cable, anchor roots and fine roots (diameter < 2 mm), and dead materials. The living roots were sorted and separated from dead roots and other materials by eye. The samples of each component of the harvested trees were oven dried in the field to reach to the constant weight. The dry weights of each organ were calculated by the ratio of dry weight to fresh weight of the samples.

The wood density (ρ) was measured for each mangrove species studied. ρ represents an oven dry weight divided by green volume (Mg m⁻³). Each wood samples were taken from the harvested trees at 1 m interval parts of height. For the other additional calculation of ρ for each species, three or four wood samples around 1 to 2 m height stem samples were cut out from the trees outside plots. All the harvesting took place at the end of February 2007. The sub samples of the plant organs were then oven dried again and after crushing into powder it was subjected to CN analysis using JM1000 CN (J-Science Group).

**Development of common allometric equation**

The common allometry of Komiyama et al. (2005) poorly predicted the aboveground weight of sample trees in this study; especially for trees over 20 kg weight (Fig. 2). It is possibly because Komiyama et al. (2005) based on sample trees in natural stand. Therefore, allometric equations were developed using nine sample trees in this study. The regression analyses were performed for allometric equations in the form of

\[
\ln W/(1000ρ) = \alpha + \beta \ln (DBFH),
\]

where W denotes the stem weight (Wₛ), branch weight (Wₐ), leaf weight (Wₗ), above-ground weight (Wₐₐ), or root weight (Wᵣᵣ) of the mangroves were determined as shown in (Figure 3). Dependent variable (lnW/1000 ρ) was predicted by (D’H) in our analysis and then the equation was transformed to the W=α’ D’H².

![Fig. 2. The relationship between actual above-ground weight of sample trees and the estimates by common allometric equation proposed by Komiyama et al. (2005).](image-url)
**Soil carbon measurement**

As mentioned earlier, a large amount of dense mangrove forests were converted to paddy cultivation in the Ayeyarwady Delta. In the study area, the paddy fields were abandoned since around 1995 before the plantations took place in 2001. Soil carbon accumulation after plantation establishment was estimated by comparing soil carbon in paddy field soil and plantation soil. Three soil pits were selected randomly in the plantations of Ao and Am and another three soil pits in paddy field located about 3 km from the plantation site. It was assumed that the soil carbon in paddy field is equivalent to the soil carbon in plantation site just before the planting trees. Three 100 cc soil samples were taken from 0-5 cm, 5-10 cm, 20 cm, 30 cm, 60 cm, 80 cm, and 100 cm soil depth in each pit. Soil samples were then separated from roots and other plant fragments and charcoal and then air dried and powdered before assay. The samples were sieved to < 2 mm, then homogenized and split into a smaller sub sample and handpicked carefully to remove fine roots. The sub samples of the soil samples were then oven dried again and after crushing into powder was subjected to CN analysis as the plant materials.

**RESULTS**

**Stand structure**

The stand density of three plantations was 2,938 ha\(^{-1}\) in Ao; 2,889 ha\(^{-1}\) in Am and 2,592 ha\(^{-1}\) in Sa respectively (Table 1). As initial plantation density was constant between three species (3086 ha\(^{-1}\)), the survival percentage (within six years) of Sa, 84.0%, was the lowest among three species. Sa had, however, the largest mean DBH in the three species (Table 1). Stand density in the NR stand was very high, 29,040 ha\(^{-1}\); which consisted of 11,120 ha\(^{-1}\) of Cd, 7,840 ha\(^{-1}\) of Bs and 10,080 ha\(^{-1}\) of Ac. Cd was found the most abundant among three species in the natural regeneration forest. The mean DBH of the three species were 3.2 cm in Ac, 2.1 cm in Bs and 2.3 cm in Cd, respectively.

**Common allometric equation**

The value of \(\rho\) was 0.515 ± 0.021 (× 10\(^{-3}\) kg m\(^{-3}\)) for *Avicenia officinalis*, 0.556 ± 0.015 for *Avicenia marina*, 0.474 ± 0.042 for Sonneratia apetala, 0.660 ± 0.011 for *Ceriops decandra*, 0.531 ± 0.010 for *Bruguiera sexangula* and 0.513 ± 0.011 for *Aegiceras corniculatum*, respectively.

The regression analysis for \(\ln W/1000\rho\) was satisfactory performed with high coefficient determination (Fig. 3). The regression constants (a and

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Table 1. Stand structure in the census plots. Data show the average and standard deviation for five plots in each stand type.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Stand age in 2007</th>
<th>Stand density (ha(^{-1}))</th>
<th>Tree basal area (m(^2)ha(^{-1}))</th>
<th>Mean DBH (cm)</th>
<th>Max. DBH (cm)</th>
<th>Mean H (m)</th>
<th>Max. H (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ao 6</td>
<td>(±135)</td>
<td>2938 (6.7)</td>
<td>3.6</td>
<td>9.3</td>
<td>4.2</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Am 6</td>
<td>(±270)</td>
<td>2889 (6.9)</td>
<td>3.9</td>
<td>8.3</td>
<td>4.7</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>Sa 6</td>
<td>(±290)</td>
<td>2592 (17.9)</td>
<td>8.8</td>
<td>14.0</td>
<td>9.0</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td>NR 7*</td>
<td>(±14521)</td>
<td>29040 (18.7)</td>
<td>3.3</td>
<td>12.3</td>
<td>3.9</td>
<td>8.7</td>
<td></td>
</tr>
</tbody>
</table>

Regeneration improvement felling was applied from 2000 and stand age was defined as 7 years old.
b), the correlation coefficient (r²), and the standard error of the biomass estimate (S.E.) for all components of each species are summarized in Table 2. By using allometric equations for \( W_s, W_b, W_l, W_{top} \) and \( W_{root} \), biomass of six mangrove species was estimated.

**Above and belowground biomass**

The above and belowground biomass in the plots are listed in (Table 3). The biomass in NR stand (70 and 104 Mg ha\(^{-1}\)) was the greatest (P < 0.001), and followed by Sa plantation (69 and 32 Mg ha\(^{-1}\)), Am plantation (25 and 27 Mg ha\(^{-1}\)) and Ao plantation (21 and 26 Mg ha\(^{-1}\)). Mean annual biomass increment (MABI) in the plantations was estimated by dividing the total biomass per hectare of each stand by its stand age (year). MABI was 16.83 Mg ha\(^{-1}\) yr\(^{-1}\) in Sa plantation, 8.71 Mg ha\(^{-1}\) yr\(^{-1}\) in Am plantation and 7.80 Mg ha\(^{-1}\) yr\(^{-1}\) in Ao plantation respectively. In the NR stand MABI was 24.89 Mg ha\(^{-1}\) yr\(^{-1}\).

Mangroves usually cope with the stresses of high water tables, salty soils (Havanond and Maxwell, 1996), and anoxic conditions. Moreover, the huge amount of root biomass could be attributable to the habit that mangroves grow on the swampy substratum. In order to hold themselves in such swampy condition, mangroves produce large amount of roots to a wider and deeper extent. It was observed that the top/root ratios in the studied plots were 0.8 for Avicennia officinalis (Ao), 0.9 for Avicennia marina (Am), 2.1 for Sonneratia apetala (Sa) and 0.7 for NR stand. Komiyama et al 1988 reported the top/root of Sonnetria is 4.4, 2.3 to 3.5 for Bruguiera, and 1.5 to 1.9 for Rhizophorea forests and 1.05 for Ceriops tagal forest respectively. The top/root ratios of Avicennia forest was 0.7 to 1 (Briggs 1997). The large amount of biomass was allocated in the underground root system of mangrove forests and they showed low top/root ratio than other type of forests. The top/root ratios of temperate forests ranged from 2.68 to 3.70 (Ovington 1957, Baskerville 1966, Yamada and Shidei 1972, Yamakura et al. 1972, Karizumi 1974). In the tropical inland forests, the top/root ratio ranged from 5.10 to 10.68 (Ogawa et al. 1965, Hozumi et al. 1969, Klinge 1973, Stark and Sprat 1977).

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**Table 2.** Results of regression analysis using a model, ln\( W/1000 = a + b \ln (DBH \cdot H) \) [kg, kg m\(^{-1}\), cm, m], where, \( W \) denoted weight of a organ (stem, branch, leaf, or root), and \( a \) and \( b \) denoted allometric constants. Header \( r^2 \), AR, and S.E. denoted correlation coefficient, adjusted \( r^2 \), and standard error of estimate, respectively. \( p<0.001 \).

<table>
<thead>
<tr>
<th>Component</th>
<th>( a )</th>
<th>( b )</th>
<th>( r^2 )</th>
<th>AR</th>
<th>S.E.</th>
<th>Allometric Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem</td>
<td>-3.94</td>
<td>0.85</td>
<td>0.98</td>
<td>0.98</td>
<td>0.08</td>
<td>( W_s = 0.12 \rho (DBH \cdot H)^{0.85} )</td>
</tr>
<tr>
<td>Branch</td>
<td>-4.36</td>
<td>0.87</td>
<td>0.90</td>
<td>0.89</td>
<td>0.19</td>
<td>( W_b = 0.044 \rho (DBH \cdot H)^{0.87} )</td>
</tr>
<tr>
<td>Leaf</td>
<td>-4.03</td>
<td>0.55</td>
<td>0.79</td>
<td>0.76</td>
<td>0.06</td>
<td>( W_l = 0.090 \rho (DBH \cdot H)^{0.83} )</td>
</tr>
<tr>
<td>Above ground</td>
<td>-3.66</td>
<td>0.82</td>
<td>0.99</td>
<td>0.99</td>
<td>0.08</td>
<td>( W_{top} = 0.22 \rho (DBH \cdot H)^{0.82} )</td>
</tr>
<tr>
<td>Below ground</td>
<td>-2.77</td>
<td>0.40</td>
<td>0.98</td>
<td>0.97</td>
<td>0.06</td>
<td>( W_{root} = 1.69 \rho (DBH \cdot H)^{0.88} )</td>
</tr>
</tbody>
</table>

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**Table 3.** Average and standard deviation of stand biomass. Aboveground biomass was obtained by summing up stem, branch and leaf biomass.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Stand age in 2007</th>
<th>Stem (Mg ha(^{-1}))</th>
<th>Branch (Mg ha(^{-1}))</th>
<th>Leaf (Mg ha(^{-1}))</th>
<th>Above ground (Mg ha(^{-1}))</th>
<th>Below ground (Mg ha(^{-1}))</th>
<th>Total (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ao</td>
<td>6</td>
<td>12.3 (± 4.1)</td>
<td>5.1 (± 1.7)</td>
<td>2.6 (± 0.6)</td>
<td>20.8 (± 6.7)</td>
<td>26.0 (± 4.9)</td>
<td>46.8 (± 11.6)</td>
</tr>
<tr>
<td>Am</td>
<td>6</td>
<td>15.1 (± 4.4)</td>
<td>6.3 (± 1.9)</td>
<td>2.9 (± 0.9)</td>
<td>25.2 (± 7.2)</td>
<td>27.1 (± 3.4)</td>
<td>52.3 (± 10.3)</td>
</tr>
<tr>
<td>Sa</td>
<td>6</td>
<td>43.8 (± 9.2)</td>
<td>19.4 (± 4.2)</td>
<td>4.6 (± 0.6)</td>
<td>69.3 (± 14.1)</td>
<td>41.4 (± 4.0)</td>
<td>101.0 (± 17.1)</td>
</tr>
<tr>
<td>NR</td>
<td>7</td>
<td>41.0 (± 11.5)</td>
<td>16.9 (± 5.0)</td>
<td>10.4 (± 2.5)</td>
<td>70.0 (± 18.4)</td>
<td>104.2 (± 23.7)</td>
<td>174.2 (± 30.0)</td>
</tr>
</tbody>
</table>
Carbon sequestration in vegetation

The carbon percentage in stem (including bark) is 45% ± 1.4, branch (including bark) is 44% ± 2.0, leaf is 46% ± 1.1 and root (including bark) is 38% ± 1.1. It was found that the carbon percentage in root was smaller than that of other organs. By using the carbon percentage of each organ, the amount of total carbon stock in the biomass of each organ was calculated. Table 4 shows the above and belowground carbon stock in the biomass of three plantations and a natural regeneration forest. The total carbon stock in biomass was 73 Mg C ha⁻¹ in NR stand, 43 Mg C ha⁻¹ in Sa plantation, 23 Mg C ha⁻¹ in Am plantation and 21 Mg C ha⁻¹ in Ao plantation respectively (Table 4).

Soil carbon

The average cumulative carbon up to 100 cm depth in plantation was found to be 167 ± 58 Mg C ha⁻¹ and in paddy field 85 ± 17 Mg C ha⁻¹ respectively (Fig. 4). Soil carbon in plantation was nearly two times higher than those of paddy field. Assuming that the start point of soil before plantation establishment was same level as in the current paddy field, soil carbon increased by 82 Mg C ha⁻¹ during 6 years. It corresponds to the mean annual soil carbon increment of 13.7 Mg ha⁻¹ yr⁻¹. Therefore, a large gain of soil carbon stock was observed from the conversion of paddy field to mangrove plantations.

DISCUSSION

Growth performance

This study successfully provided the reliable five common allometric equations for six mangrove species based on specific gravity of stem. It was observed that biomass in natural regeneration forest was higher than those in three plantations even tree size was smaller in the NR stand than in the other plantations. It can be one of the options of low cost management to enhance the rapid restoration of degraded mangrove ecosystem by the improvement felling operation. It was observed that Sonneratia apetala was growing faster in plantation sites compared with the other species. As the primary purpose of plantation establishment in the area was to provide firewood, wood for pole and post for local demand, fast growing species like Sonneratia apetala should be introduced. Sonneratia apetala is the feasible species in the study area. From the viewpoint of carbon sequestration, the examined stands can be effective carbon pool.

Biomass and primary production in tropical mangrove forests are large in comparison with those in many other plant communities (Golley et al. 1962, Golley et al. 1969, Miller 1976). Estimates of mangrove biomass are usually restricted to aboveground structures and in many cases, only include the timber that can be harvested.

### Table 4. Carbon stock in the biomass of the census plots. Data show the average and standard deviation for five plots.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Stand age in 2007</th>
<th>Stem (Mg ha⁻¹)</th>
<th>Branch (Mg ha⁻¹)</th>
<th>Leaf (Mg ha⁻¹)</th>
<th>Above ground (Mg ha⁻¹)</th>
<th>Below ground (Mg ha⁻¹)</th>
<th>Total (Mg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ao</td>
<td>6</td>
<td>5.8 (± 1.9)</td>
<td>2.4 (± 0.7)</td>
<td>1.2 (± 0.3)</td>
<td>8.9 (± 1.6)</td>
<td>9.5 (± 3.3)</td>
<td>21.1</td>
</tr>
<tr>
<td>Am</td>
<td>6</td>
<td>6.8 (± 2.0)</td>
<td>2.9 (± 0.9)</td>
<td>1.3 (± 0.2)</td>
<td>10.6 (± 0.6)</td>
<td>10.2 (± 2.6)</td>
<td>23.0</td>
</tr>
<tr>
<td>Sa</td>
<td>6</td>
<td>19.3 (± 4.0)</td>
<td>8.3 (± 1.8)</td>
<td>2.1 (± 0.3)</td>
<td>31.1 (± 0.8)</td>
<td>12.4 (± 3.9)</td>
<td>43.4</td>
</tr>
<tr>
<td>NR</td>
<td>7</td>
<td>18.0 (± 5.1)</td>
<td>6.9 (± 2.1)</td>
<td>4.7 (± 1.1)</td>
<td>32.0 (± 1.9)</td>
<td>41.3 (± 3.9)</td>
<td>73.2</td>
</tr>
</tbody>
</table>

Fig. 4. Soil carbon percentage and cumulative carbon up to the 1 m soil depth in plantations and paddy field.
from the forest. Twilley et al. (1992) stated that the distribution of biomass throughout the tropics indicates that higher values occur at lower latitudes. They presented that there is much variation of mangrove biomass at any latitude, particularly in the warmer tropics. However, the upper limits of mangrove biomass may occur at lower latitudes, there are local effects that may limit the potential for forest development at all latitudes. These local effects include topography and hydrology, including the effects of river and tides on soil characteristics. The biomass values of two geographically close mangrove forests could be very different. Lugo and Snedaker (1974) stated that the biomass of a mangrove forest is also related to the species composition, community structure, growth forms and the age of the plant community.

**Soil carbon**

This study investigated that the average total soil carbon stock up to 1 m soil depth in plantation site was estimated to be 167 ± 58 Mg C ha⁻¹ which is nearly two times higher than that of paddy field 85 ± 17 Mg C ha⁻¹. This suggests the soil carbon accumulation rate in the plantation soil might be quite high in mangrove forest. Soils in equilibrium with a natural forest ecosystem have high carbon density. The estimation of soil carbon amount was 169.3 Mg C ha⁻¹ in Rhizophora stylosa forest soil and 117.7 Mg C ha⁻¹ in Avicenia marina forest soil in Western Australia (Alongi 2002). Alongi (2002) reported again that soil carbon was 162.8 Mg C ha⁻¹, 189.4 Mg C ha⁻¹, 337.1 Mg C ha⁻¹ in 25, 5 and 3 years old Rhizophora apiculata forest in Thailand. As mentioned earlier, a large area of dense mangrove forests were converted to paddy land in the Ayeyarwady Delta. Such kind of land use change might reduce the soil carbon stock. Reforestation of abandoned or marginal agricultural lands can increase soil carbon stock (Akala and Lal, 2001).

Nguyen et al., 2004 investigated soil carbon accumulation rate in mangrove forest and the factors influencing it and concluded that the amount of soil carbon stock vary with difference amount of root biomass, stand age and frequency of tidal inundation. Carbon stock in the soil of plantations in this study was observed to be lower than their study. However, the age of the plantations in this study is still young and the forests are expected to increase their biomass and soil carbon stock along with aging of the trees. The observed rate of carbon sequestration to the soil was high as 13.7 Mg ha⁻¹yr⁻¹. It might be caused by the high productivity of root production and slow decomposition of organic matter in anaerobic condition of mangrove soil (Komiyama et al., 1988). This study also proofs that reforestation of agricultural land to forest plantations can enhance soil carbon stock; a large gain of soil organic carbon was observed in the conversion of paddy field to mangrove plantations. From the viewpoint of carbon sequestration, the examined stands can be effective carbon pool.

**CONCLUSION**

This study successfully provided the reliable five common allometric equations for stem, branch, leaf, above ground and below ground for six mangrove species based on specific gravity of stem. It was observed that biomass in natural regeneration forest was higher than those in three plantations even tree size was found smaller in the NR stand than three plantations. It is the most essential to restore the mangrove forests to their original state before it is too late. Many areas are still remaining as abandoned land and seriously degraded forests near the study village and also existing in many places in the Ayeyarwady Delta. Rehabilitation of mangrove forests enables local supply and conservation of mangrove vegetation, but at the same time has to fulfill the demands of the local people. Natural regeneration method is the most preferable and effective where conditions for regenerations by natural means are favorable. This study showed the total biomass of NR stand was higher and the growth increment was faster than the plantations even tree size was small. Therefore, it can be one of the options of low cost management to enhance the rapid restoration of degraded mangrove ecosystem in the Ayeyarwady Delta.

The selection of fast growing species can have a much higher productivity than slow growing species. It was observed that *Sonneratia apetala* was growing faster in plantation sites compared with other species. As the primary purpose of plantation establishment in the area was to supply fuel wood, pole and post for local demand, fast growing species should be introduced. Both the plantation and natural regeneration showed high feasibility as the ecosystem for carbon sequestration. Especially the soil carbon increment and root biomass increment are expected to be rapid and high amount of carbon could be fixed in the ecosystems. Thus the reforestation activities can contribute not only to the local society’s benefit but also to the global carbon management.
Depletion and deforestation in the Ayeyarwady Delta mangrove forests is due to socio-economic issues of the local communities. However, the social and economic conditions and environmental knowledge of the mangrove dwellers is very poor and they could not consider for conservation and sustainable use of these invaluable natural resources. So it should be educated to local people to take part in restoration activities since the knowledge of natural mangrove forest is essential for the restoration and conservation of mangrove forest. Conservation of the remaining natural forest and estimation of mangrove biomass as well as the carbon cycle. It is particularly important for the Ayeyarwady Delta of Myanmar as a shelterbelt against natural calamities. In order to secure sustained yield of mangrove resources a proper management system based upon ecological knowledge is required. The present study provides the estimation of mangrove biomass as well as the carbon sequestration potential of mangrove reforestation program in the Ayeyarwady Delta. Moreover, such kind of information will be necessary for the management of forest ecosystem and their contributions to the global carbon cycle.

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