Carbon Sequestration by Mangrove Forest Planted Specifically for Charcoal Production in Yeesarn, Samut Songkram

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Abstract: In Yeesan, Samut Songkram Province, central Thailand, mangrove plantations (*R[full generic name]. apiculata*) have been run with the specific purpose of charcoal production for many years. In order to estimate carbon sequestration associated with such activities, field measurements of mangrove biomass and the amount of charcoal produced were carried out. The carbon emission reductions according to charcoal use was calculated based on the energy value of charcoal in replacing liquefied petroleum gas (LPG). At an age of 12 years old, when it was harvested for charcoal production, the total average above ground biomass of *R. apiculata* was 9.29kg/tree. The relationship between above ground biomass and diameter (DBH) and height (H) can be expressed as total biomass (ton dry matter) = $0.249x^{0.79}$, $R^2 = 0.97$, where *x* represents the product of ($DBH^2 \times H$). With an average plant density of 22,089 tree/ha and a carbon content of 47%, the carbon sequestration at an age of 12 years was 140.49 ton C/ha. For other ages, carbon sequestration can be estimated from the logistic growth curve, which is expressed as: Carbon stock (ton C/ha) = $141.56/(1+4.62\times10^3 e^{-1.11t})$, $R^2 = 0.99$, where *t* is the age (years) of *R. apiculata*. The total carbon sequestration associated with *R. apiculata* plantations in the whole Yeesarn area was estimated to be 51,106.72 ton C. Based on this biomass production and the charcoal conversion efficiency, about 36 ton/ha of charcoal was produced. In the scenario that this charcoal is used for energy to replace LPG, mangrove plantation and charcoal production in Yeesarn could substitute LPG of about 58TJ/year and 3,633 ton/year of CO_2 emissions could be avoided.

Keyword: Mangrove plantation, *A. apiculata*, charcoal production, CO_2 reduction, Fossil fuel substitution by charcoal.

1. Introduction

Climate change is regarded as one of the main threats to sustainable development [1]. In past decades, enormous research efforts have been made with the aim of finding ways for slowing down the climate change rate and subsequently alleviating its impacts. The technology and measures that lead to greenhouse gas (GHG) emission reductions are among those that have received considerable attention. Regarding this, forestry can make significant contributions to a low-cost global mitigation portfolio that provides synergies with adaptation and sustainable development [2].

Recently, the roles of mangrove forest as an important atmospheric CO_2 sink have been highlighted [3-8]. In Thailand, mangrove forests are found mainly along the coastlines. Along the coast of the Gulf of Thailand, some local communities have developed a sustainable mangrove planting system with the specific purpose of charcoal production [6]. Similar systems of mangrove-charcoal production are also found in many other Southeast Asian countries such as peninsular Malaysia, Vietnam, and on the east coast of Sumatra in Indonesia [9]. Although charcoal has traditionally been used for daily cooking by coastal villagers and rural households, in recent years it has been exploited as a commercial product particularly in Thailand. Mangrove charcoal is of high quality, characterized by a high percentage of fixed carbon, low ash content, low moisture content with a high specific gravity [6]. It is highly preferred because of its special qualities that ordinary charcoal often does not possess, in particular the absence of fire bursting during use, strong burning over a long period and its handling convenience. High quality charcoal is produced from the mangrove species *R. horaapiculata* and *R. mucronata*. Other species like *Bruguiera spp.* and *Ceriops spp.* are also used for charcoal production [10]. In Thailand, mangrove for charcoal production through private ventures can be found in the Yeesarn Sub-district (Tambol) of Samut Songkarm Province where *R. apiculata* plantations and charcoal making systems have traditionally been practiced for more than 50 years [6, 11-13]. Since an equal area of mangrove is replanted once it is cut for charcoal production, charcoal production from mangrove does not result in a net loss of mangrove forest. The produced charcoal is thus considered a renewable resource and can reduce the emissions of greenhouse gas when it is used to substitute the use of fossil fuels. However, the carbon sequestration achieved by such household scale plantation and charcoal production has not been evaluated. Such information is important to understand the roles of mangrove ecosystems and local communities to greenhouse gas emissions mitigation and to the sustainable adaptation to climate change.

The objective of this study is to estimate: 1) the carbon sequestration potential of mangrove forest plantation by the local community of Yeesarn, and 2) carbon emission off-set when charcoal produced from the planted mangrove is used to replace LPG as a cooking fuel.

2. Experimental

2.1 Study site

This study was carried out in mangrove plantation plots of the Yeesarn Community (13°25N 100°E/13°42N 100°E), Amphoe Ampawa, Samut Songkarm Province, central Thailand. Samut Songkram is one of the Provinces in Thailand with pristine mangrove forests dating back to before 1957. The local residents were dependent on these forests for goods and services such as fisheries and charcoal production. Mangrove plantations of *R. apiculata* and *Nypa* palm plantation were once common. The mangrove forest areas of this Province were approximately 10,934 ha in 1961 and decreased to 8,240 ha by 1975. From 1975, the majority of mangrove areas have been degraded due to intensive shrimp farming [13]. In 2004, only 1,276 ha of mangrove remained [14], and most of these were under intensive management specifically for charcoal production. The mangrove areas have slightly increased recently due to the failure of shrimp farming and some locals turning to mangrove plantation as a source of income. Generally, the owners of the plantations are responsible for the management and utilization of the mangrove resources. Several field surveys were made in 2009-2010 to collect data on cultivation practices, biomass measurements and charcoal production characteristics in the Yeesarn area.

2.2 Mangrove biomass measurements

In order to measure biomass that was subsequently available for charcoal production, a field study on tree age, height and dry weight was carried out. Six belt transects of 10 m wide was established. Along these transects, a total of 15 plots of 10 m × 10 m were marked. Duplicate plots for each age of mangrove plantation (1-year, 3-year, 6-year, 9-year, and 12-year-old) were made. For each plot, 3 trees (6 trees for each age class) were randomly selected in the study plots and harvested at ground level using handsaws. Stem diameter at 130 cm (diameter at breast height, DBH) of all harvested trees were measured. The above ground parts were separated into stem (trunk), branch and leaf. The fresh weight of each component was measured in the field, and representative sub-samples were oven-dried to constant weight at 85°C in order to calculate the wet-dry weight ratio. Tree height was measured using an altimeter (HagaGmbh, Nuremberg, Germany). The allometric relationship between DBH, height and dry weight of biomass (stem, branch and leave) was then derived. For tree density, from our surveys for the trees at age 8-10 years, the average was 22,089 trees/ha. This was consistent with the information acquired directly from farmers (20,000-30,000 trees/ha) at age 1 year when the mangrove was initially planted. The survival rate was thus around 88%. We used this tree density to estimate biomass content per area for all age classes.

2.3 Carbon content analysis of biomass sample

Mangrove biomass samples were dried and ground to powder for carbon content analysis using the CHONS analyzer (FlashEA 1112 series, Italy) with a thermal conductivity detector (TCD). The analytical conditions were as follows: Carrier gas; helium, carrier gas flow rate; 130 ml/min, combustion temperature; 900°C, column temperature; 50°C.

2.4 Charcoal production and characteristics, and calculation of CO_2 reduction potential

During the course of investigation, several field surveys were conducted. Data collection and interviews of mangrove plantation owners were the main objectives of such surveys. Charcoal samples from four out of eight charcoal producers in Yeesarn were taken and analyzed in the laboratory for their calorific values using the Bomb calorie method. These calorific values were used as the basis for estimating the amount of CO_2 reduction potential, based on the assumption that charcoal from mangrove forest is used to replace cooking fuel (LPG). The calorific values of LPG, and its associated CO_2 emission factor followed that of given by the IPCC [15].

3. Results and Discussion

3.1 Mangrove plantation for charcoal production in Yeesarn

Interviewing local residents and reviewing available literature revealed that mangrove plantations for charcoal production in the Yeesarn area have existed since 19th century [16]. This was when the technique for constructing brick kilns was imported from China. This activity has developed into the main source of income of the Yeesarn community. In 2010, 300 out of 716 households in Yeesarn were involved in mangrove plantations for charcoal production. The total plantation area was around 2,000 ha. The Yeesarn community itself is about 5 km away from the coast. However, the intensive cannel networks that bring in the seawater to submerge the plantation plots during high tide and draw the water out during low tide have provided ideal conditions for the growth of mangroves and its harvest for charcoal production.

R. apiculata, the mangrove species which is planted in Yeesarn area, is the most important species of commercial timber in the Asia-Pacific region [17]. Besides charcoal, it is also used for poles, fuel wood and wood chips. To plant mangroves, growers usually start to prepare the land in July or August each year. Planting usually begins in the following months (September-November). Before planting land clearing, including the removal of weeds, tree-branches and twigs leftover from the previous crop, are occasionally needed. In the past, on-site burning was the common practice. However, in recent years farmers planted the seedlings directly without removing them. The prepared mangrove seedlings were manually planted in the prepared areas. Approximately 18,750-30,000 seedlings/ha were usually used. Farmers either prepared these seedlings themselves or bought from those who have collected them from the mature mangrove forest nearby. After planting, replanting was usually required for the first three years to replace seeds which died. The survival rate was usually around 80%. After this period, mangrove seedlings were allowed to grow almost naturally and little care was needed. Usually fertilization, pest and disease control were not practiced. Mangrove trees were then manually harvested when their age reached 9-12 years. Only the stem was used for charcoal production. The rest of the biomass was left onsite and degraded naturally. After direct drying in the sun, the stems were transported out from the plots by boat to the kiln location near the grower's house. The appropriate harvest timing was judged by farmers themselves, mainly based on the availability of human labor, availability of the kiln, and tidal activity (high tide was necessary for transporting wood out from the harvested plot by boat), and market demand. Most of the charcoal was sold in Bangkok and provinces nearby. After repeated use of the land for several years, the land elevation could be increased due to sediment accumulation. In such cases, land was mechanically leveled to facilitate flooding.

3.2 Growth and carbon stock of *R. apiculata* plantation

There are various methods for estimating mangrove biomass. The main ones include the harvesting method, the mean-tree method and the allometric method. Among these, the allometric method is most popular due to its non-destructive nature and for being less tedious. It is used to estimate the whole or partial weight of a tree from measurable tree dimensions such as stem and height, using an allometric equation [5]. The basic concept of an allometric relationship is that the growth rate of one part of a tree is proportional to that of another. For example, it is well known that the stem diameter of a tree is highly correlated with stem weight.

Over the past decades, allometric equations have been developed for various tree species and forest types including mangroves. The main parameter that is usually used for defining the relationship is biomass weight and diameter at breast height (DBH). Sometimes, tree height (H) is included but obtaining accurate height data is difficult, especially when canopy and tree density are high. In this study, we obtained both DBH and height. Table 1 shows the results of above ground biomass measurements. On average, the mangrove tree at the harvest age (9-12 years) was usually about 10-11 meter in height, and the DBH was about 3-4 cm. On a dry weight basis at age 12 years, *R. apiculata* trees were about 9 kg, or about 16 kg/tree on a fresh weight-basis. Out of this, stem weight accounted for about

94% of the total weight. For younger ages, for example for 6 years old, the weight of the stem was only about 50% of the total dry weight. The carbon content was slightly increased from about 42% at age 1 year to around 47% at ages 9-12 years.

The allometric relationship between DBH, H and biomass dry weight was then derived (Fig. 1) and details are shown in Table 2. The allometric relationships for total and stem biomass were: total biomass = $0.249x^{0.79}$, R^2 = 0.97, and stem biomass = $0.140x^{0.84}$, R^2 = 0.99, when x represents $(DBH)^2 \times$ H. Comparing the values between those from direct measurement and from the allometric relationship, the error was within ±18%, and for the stem alone this was ±3%. Since the stem makes up the majority of biomass when a tree age approaches harvest and when biomass is at a maximum, the relationship obtained is thus quite accurate for estimating the stem biomass available for charcoal production. Estimating the amount of branches and leaves is more difficult than for the stem, probably due to the high plant density specially made for charcoal production, which aims mainly to have as much as possible in the stem fraction.

Since measurements of tree height in the field are quite difficult, especially when canopy and plant density are high, most of allometric relationship derived in the past have used only DBH [5, 17]. Our comparison, between the case which included the height and that which did not include it, in deriving the allometric equation, indicate that the relationship coefficient was higher when height was included than when it was not (Table 2). For more accuracy, it is thus recommended that height of mangrove should be measured when an allometric relationship is derived to estimate biomass.

Interviewing *R. apiculata* growers in Yeesarn area revealed that each year about 120 ha of *R. apiculata* was harvested for charcoal production. After harvest, new planting was usually undertaken [18]. Therefore, we can assume that the same land area (120 ha) is planted every year, and therefore the plantation area for each age of *R. apiculata* is also 120 ha. Using the tree density mentioned earlier (22,089 trees/ha) and the carbon content shown in Table 1, carbon stock on the aerial basis was estimated

Table 1. Dry matter of *R. apiculata* mangrove biomass and carbon content of stem at different ages. The values are mean±S.D of 6 samples.

Age (Year)	DBH (cm)	Height (m)	Dry weight (kg)			Total (kg)	Carbon content (%)
			Stem	Branch	Leave		
1	0.69±0.05	0.47±0.04	0.04±0.01	0.00±0.00	0.03±0.01	0.07±0.02	41.63±1.49
3	1.07±0.13	1.00±0.14	0.15±0.03	0.00±0.00	0.16±0.02	0.31±0.05	43.87±0.75
6	1.41±0.17	3.08±0.41	0.67±0.23	0.41±0.11	0.34±0.07	1.42±0.35	45.33±3.17
9	2.61±0.14	10.24±0.66	5.09±0.83	2.47±0.49	0.16±0.05	7.73±1.31	47.60±0.59
12	3.41±0.25	11.39±0.66	8.72±1.74	0.30±0.05	0.28±0.06	9.29±1.73	47.20±0.11

Table 2. Allometric relationship between dry weight of biomass and DBH or DBH2 of R. apiculata biomass aged between 1-12 years (n = 30). All relationships shown are statistically significant at p<0.05.

Biomass part	Allometric equation	
	Without tree height (x represents DBH)	With tree height (x represents (DBH^2×H)
Total above ground	$y = 0.275x^{3.19}$, R^2 = 0.95	$y = 0.249x^{0.79}$, R^2 = 0.97
Stem	$y = 0.155x^{3.43}$, R^2 = 0.98	$y = 0.140x^{0.84}$, R^2 = 0.99
Branch	$y = 0.160x^{2.79}$, R^2 = 0.93	$y = 0.109x^{0.73}$, R^2 = 0.93
Leaf	$y = 0.076x^{1.24}$, R^2 = 0.47	$y = 0.073x^{0.31}$, R^2 = 0.48

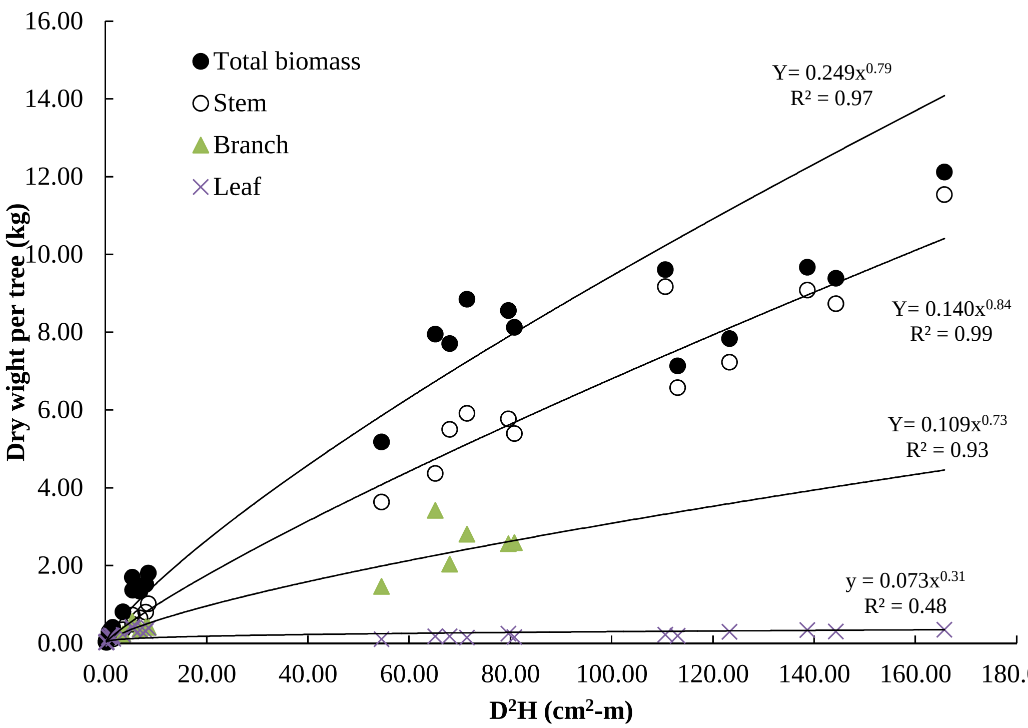

Figure 1. Allometric relationships between mangrove biomass (total, stem, branch and leaf) and diameter at breast height (D) and height (H).

(Fig. 2). It was found that at ages 1, 3, 6, 9 and 12 years old, the carbon stock in the above ground biomass was 0.09, 0.28, 20.46, 116.81, and 140.49 ton C/ha, respectively. If we include the below ground biomass which is around 20% of total biomass [17], the total above ground biomass of *R. apiculata* at the 12th year would be 169 ton C/ha. Yet, our estimate is still considered conservative, since the fraction of stilt root was not accounted for. This normally accounts for around 15-17% of above ground biomass [19]. Our results on above ground biomass were within the range found in other *R. apiculata* studies [5, 17]. However, the biomass content is different according to forest type (natural versus plantation), and with the objective of the forest plantation (conservation versus charcoal production, for example). Our estimates were in the upper ranges of the values found in the literature, possibly due to the high tree density specifically needed for stem harvest for charcoal production.

The relationship between carbon stock and age of *R. apiculata* is also useful for estimating carbon stock at different ages. We found that this relationship can be expressed as a logistic growth model as:

$$y = \frac{141.56}{1 + 4.62 \times 10^3 e^{-1.11t}}, R^2 = 0.9996$$

Where *y* represents the amount of carbon stock of *R. apiculata* (ton C/ha) at age of *t* years-old. The average growth rate of *R. apiculata* was approximately 12.76 ton C/ha/y. It is noted that the estimate described here was based on the same dataset of H and DBH used for the allometric relationship and the tree density as mentioned above. However, we also did the growth parameter measurements (H, DBH) of unknown mangrove samples for ages 6-10 years. It was found that the logistic growth curve shown in Fig. 2 could be used to estimate above ground biomass with an uncertainty range of 5-18%. From this relationship and with the area of *R. apiculata* for each age of 120 ha, we can estimate that the total amount of carbon stock for all age classes (1 to 12 years) associated with plantations having a specific purpose for charcoal production was 51,106.72 ton C.

3.3 Charcoal production in Yeesarn

From our surveys, brick beehive was the only type of kiln used for charcoal making in Yeesarn. The diameter of the kilns varied from 5 to 6 m and the height from about 2.5 to 3.5 m. The kilns were constructed with a single door 1 m wide by 1.25 m high to facilitate loading and unloading with a basal portion constructed for the firing port. There were four small chimneys placed equidistantly around the circumference. The kilns were constructed as a battery inside the shed, built with mangrove pole structures and a thatched roof from nipa palm. In the Yeesarn area, 8 charcoal makers were found and still active in 2010. But in total about 300 households out of the 716 households [in the Yassern area] were growing *R. apiculata*. They were the main suppliers of raw materials for these 8 charcoal makers. Each charcoal maker has 3 to 6 kilns in their possession, and a total of 41 kilns existed in 2010. Three sizes of kiln were found with volumes of 16.35, 28.26 and 32.97 m^3. The volume of all kilns combined, which indicates the charcoal production capacity for each cycle, was 2,138.44 m^3 (Table 3). The number of kilns has significantly decreased from 62 kilns in 1992 [6]. During the past decades, the Yeesarn area has experienced drastic land use change, especially the conversion of mangrove plantation to shrimp farming. This also reflects the decrease in the numbers of kilns and mangrove growers during that period.

After harvest, stems were cut into short pieces of around 130 cm long and the bark was then removed by hand. They were left a few days on site during which moisture was reduced to the appropriate level. They were then transported out from the plots and were immediately available for charcoal production. When doing so, the raw materials were piled up orderly inside the kilns until it become fully loaded. After igniting with firewood, the kiln was left to burn continuously and pyrolysis at a temperature of around 250-400°C was continued for about 10 days. Together with the cooling down period, each cycle of charcoal production usually took about 10-13 days, depending on wood moisture content. On average, charcoal is made 7 times (or cycles)/year. Based on the survey results, it was found that for each 30 m^3 of raw material used (about 26.7 ton dry matter), 5 ton charcoal was produced. With a carbon content of raw material of 47% (Table 1) and of charcoal of 60% (Table 4), it is therefore estimated that the productivity on the carbon basis is 23.9%. In 2010, the total wood that was used in Yeesarn for charcoal production was 13,322.48 ton dry matter. The charcoal yield in 2010 was, thus, 2,495.30 ton. On a real basis, this was about 36 ton charcoal produced/ha.

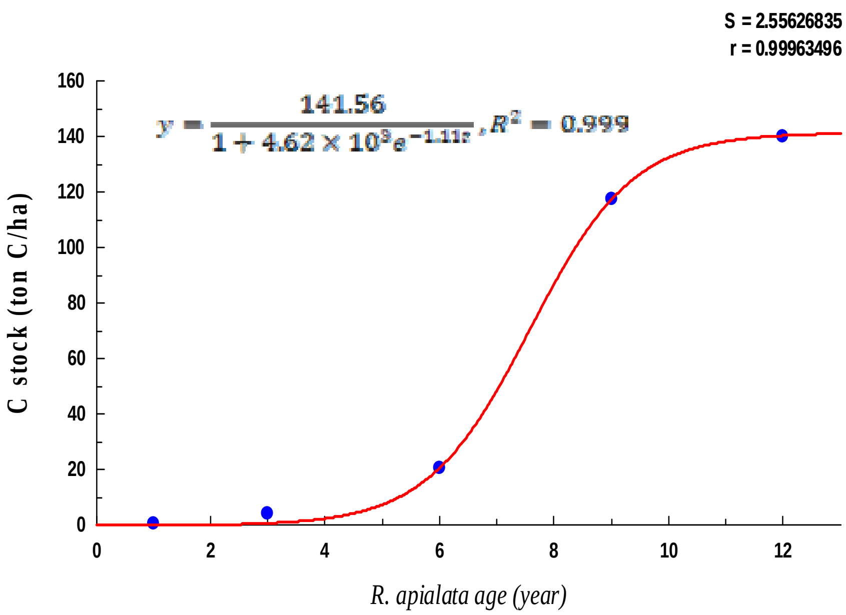

Figure 2. Logistic growth curve expressed in terms of carbon content/ha of *R. apiculata* at different ages (1- 12 years old).

Table 3. Summary of parameters used for calculating charcoal production from *A. apiculata* biomass in Yeesarn, Samut Songkram.

Parameters	Values
Raw materials	
Stem density	22089 tree/ha
Stem weight	8.72 kg/tree
Total amount of stem available	192.62 ton/ha
Kiln capacity	
Total number of kilns	41 klins
Total capacity	2138.44 m^3/cycle
Average number of cycle from 8 owners	7 cycles/year
Charcoal production	
Total raw material used	13322.48 ton dry matter/years
Total charcoal produced	2495.30 ton/year
Charcoal productivity	36 ton/ha

3.4 Charcoal characteristics

Charcoal samples taken from 4 out of 8 makers were analyzed for their carbon content and calorific values (Table 4). The average carbon content was around 60% (increased from 47% of that of the raw material). The calorific values varied from 4234 to 7011 calories/g charcoal, with an average of 5,494.41±1,207 Cal/g or an equivalent of 23.1±5.1 MJ/kg. We compared our values with those reported by Cheunwarin and Chantarasena [20] and found that both the carbon and calorific values were lower, although charcoal from both studies were made from *R. apiculata*. This indicates that the characteristics of charcoal is quite site specific, probably depending on the difference in moisture content and pyrolysis temperature.

However, the lower values of charcoal from Yeesarn suggest quality and productivity could be improved. More details study concerning pyrolysis and raw material analysis are needed regarding this.

3.5 Greenhouse gas emission reduction potential

Since the charcoal produced in Yeesarn was used solely for cooking, we assumed that if this was used in place of fossil fuel such as cooking gas, charcoal production activity in Yeesarn could contribute to greenhouse gas emission mitigation. This aspect is important since *A. apiculata* plantations in Yeesarn have been managed in a sustainable way for quite some time. We considered the case when there is a substitution of cooking fuel (LPG) with charcoal. Greenhouse gas emission during pyrolysis (e.g. CH_4 and N_2O) and transport of charcoal to the end use location were excluded since these data were not available. In the scenario that all of this charcoal is used to replace the use of cooking LPG, the amount of CO_2 emissions that are avoided could be then estimated. This is based on the energy value of both charcoal and LPG. As mentioned above, the energy value of charcoal produced from this area was approximately 0.023 TJ/ton. With the total charcoal production per year of 2495.30 ton (equivalent to 57.58 TJ/year), and from the energy value of LPG of 50.0 kJ/gram LPG, and the emission factor for LPG of 63.1 ton CO_2/TJ (IPCC, 2006), it was estimated that emissions of about 3,633 tons CO_2 per year could be avoided. However, there are some uncertainties associated with this calculation. Firstly, CO_2 emissions from fossil fuel use, such as during wood transport, land preparation, and charcoal transport to the users are not accounted for. Also, certain greenhouse gases such as N_2O and CH_4 may be also produced during the pyrolysis phase of charcoal production. If these are included, the amount of CO_2 emissions avoided could be reduced. Despite this, the results of this study reveal that forest management through repeated planting and harvesting for charcoal production do contribute to reducing greenhouse gas emissions. In addition, significate amounts of carbon can be stored in the soil and in other parts of the biomass, for about 12 years during the growth of mangrove trees. In future studies, these fractions of carbon should also be included in total C or CO_2 equivalent that could be avoided from mangrove plantation and utilization activities.

Charcoal production from mangrove plantations serves as the main income source and livelihood of farmers in the Yeesarn area. In this example, climate change mitigation (through mangrove plantation and charcoal utilization and soil carbon sequestration) and adaptation (through the incomes from charcoal production and from preventing damages from sea level rise and storm surge, for example) are interlinked and compatible, and policy approaches to address them can be mutually supportive. While acting as the media to buffer damages due to climate change impacts, mangrove forest ecosystem is also one of the highest carbon stock densities. Protecting mangrove forest thus helps mitigate CO_2 emissions while supporting livelihoods and their capacities to adapt to climate change.

4. Conclusions

In this study, we present the results of carbon sequestration potential by planting the mangrove *R. apiculata*, and by using it as raw material for charcoal production. Charcoal was then used for fossil fuel substitution. The carbon emission avoidance was calculated based on the energy value of charcoal in replacing LPG. The total average above ground biomass was 9.29 kg/stem and 7.73 kg/stem for mangrove plantations of 12 and 9 years old, respectively. The average above ground biomass for 12 and 9 years old was 172.94 ton/ha and 206.08 ton/ha, respectively. Based on the average biomass and charcoal conversion efficiency from field samplings and surveys, about 36 ton/ha of charcoal could be produced from this biomass. In the scenario that this charcoal is used for energy to replace LPG, charcoal produced from Yeesarn could substitute the use of LPG of about 58 TJ per year (1,152 ton LPG). Based on the IPCC CO_2 emission factor of 1 TJ = 63.1 ton CO_2 for LPG, mangrove plantation and charcoal utilization could help mitigate about 3,633 ton CO_2 per year. The results demonstrate that with mangrove plantations, additional benefits in terms of carbon sequestration in biomass and reducing CO_2 emissions from fossil fuel use could be achieved without additional investments. In addition rural life and coastal ecosystems could also be protected if proper management is implemented. According to the findings, together with additional investigation on economic gains, social aspects, and other environmental benefits, mangrove forest plantations for such purposes may help highlight the importance of mangrove plantations and their role in supporting sustainable communities along the coast.

Table 4. Some characteristics of charcoal produced from *R. apiculata*in Yeesarn.

Parameter	Cheunwarin and Chantarasena, [20]	This study
Moisture content (%)	5.1-5.4	5-10%
Carbon content (%)	69.71	60.0±4.01 (± S.D. of 20 samples)
Calorific values (Cal/g)	6684-47-7200.45	4235.91- 7011.07 (ave 5494.41)
Charcoal productivity (on carbon content basis, %)	29.91-33.0	23.9

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