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Above Ground Biomass-carbon Partitioning, Storage and Sequestration in a Rehabilitated Forest, Bintulu, Sarawak, Malaysia

(Pembahagian, Takungan, Sekuestrasi Biojisim-karbon Atas Tanah di Hutan Terpulih, Bintulu, Sarawak, Malaysia)

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ABSTRACT

Forest degradation and deforestation are some of the major global concerns as it can reduce forest carbon storage and sequestration capacity. Forest rehabilitation on degraded forest areas has the potential to improve carbon stock, hence mitigate greenhouse gases emission. However, the carbon storage and sequestration potential in a rehabilitated tropical forest remains unclear due to the lack of information. This paper reports an initiative to estimate biomass-carbon partitioning, storage and sequestration in a rehabilitated forest. The study site was at the UPM-Mitsubishi Corporation Forest Rehabilitation Project, UPM Bintulu Sarawak Campus, Bintulu, Sarawak. A plot of 20 × 20 m^2 was established each in site 1991 (Plot 1991), 1999 (Plot 1999) and 2008 (Plot 2008). An adjacent natural regenerating secondary forest plot (Plot NF) was also established for comparison purposes. The results showed that the contribution of tree component biomass/carbon to total biomass/carbon was in the order of main stem > branch > leaf. As most of the trees were concentrated in diameter size class ≤ 10 cm for younger rehabilitated forests, the total above ground biomass/carbon was from this class. These observations suggest that the forests are in the early successional stage. The total above ground biomass obtained for the rehabilitated forest ranged from 4.3 to 4,192.3 kg compared to natural regenerating secondary forest of 3,942.3 kg while total above ground carbon ranged from 1.9 to 1,927.9 kg and 1,820.4 kg, respectively. The mean total above ground biomass accumulated ranged from 1.3 × 10^{-2} to 20.5 kg/0.04 ha and mean total carbon storage ranged from 5.9 × 10^{-3} to 9.4 kg/0.04 ha. The total CO_2 sequestrated in rehabilitated forest ranged from 6.9 to 7,069.1 kg CO_2/0.04 ha. After 19 years, the rehabilitated forest had total above ground biomass and carbon storage comparable to the natural regeneration secondary forest. The rehabilitated forest activities have the potential to increase carbon stock through tree planting. Therefore, forest rehabilitation has shown the potential role as a carbon sink that helps to reduce emissions of greenhouse gases and mitigate climate change.

Keywords: Biomass partitioning; carbon sequestration; forest biomass; forest carbon; natural regenerating secondary forest; rehabilitated forest

ABSTRAK

Degradasi dan kehilangan hutan adalah antara keprihatian global yang utama kerana ia boleh mengurangkan takungan dan kapasiti sekuestrasi karbon hutan. Pemulihan hutan di kawasan hutan yang telah terdegradasi mempunyai potensi untuk meningkatkan stok karbon, maka ia boleh mengurangkan pelepasan gas rumah hijau. Walau bagaimanapun, takungan dan potensi sekuestrasi karbon di hutan tropika terpulih adalah kurang jelas kerana kekurangan maklumat. Kertas ini melaporkan satu inisiatif untuk membuat anggaran pembahagian, takungan dan sekuestrasi biojisim-karbon di hutan terpulih. Tapak kajian adalah di Projek Pemulihan Hutan UPM-Mitsubishi Corporation, UPM Kampus Bintulu Sarawak, Bintulu, Sarawak. Plot bersaiz 20 × 20 m^2 telah ditubuhkan setiap satu di tapak 1991 (Plot 1991), 1999 (Plot 1999) dan 2008 (Plot 2008). Satu plot di hutan sekunder beregenerasi secara semula jadi yang bersebelahan (Plot NF) ditubuhkan untuk tujuan perbandingan. Keputusan menunjukkan sumbangan biojisim/karbon di komponen pokok kepada jumlah biojisim/karbon dalam susunan batang utama > dahan > daun. Kebanyakan pokok tertumpu di saiz kelas diameter ≤ 10 cm untuk hutan terpulih yang muda, maka jumlah biojisim/karbon atas tanah adalah daripada kelas tersebut. Pemerhatian tersebut mencadangkan hutan tersebut adalah pada peringkat awal sesaran. Jumlah biojisim atas tanah untuk hutan terpulih berjulat daripada 4.3 ke 4,192.3 kg berbanding dengan hutan sekunder beregenerasi secara semula jadi dengan 3,942.3 kg manakala jumlah karbon atas tanah, masing-masing berjulat daripada 1.9 ke 1,927.9 kg dan 1,820.4 kg. Min jumlah pengumpulan biojisim atas tanah berjulat daripada 1.3 × 10^{-2} ke 20.5 kg/0.04 ha dan jumlah takungan karbon berjulat daripada 5.9 × 10^{-3} ke 9.4 kg/0.04 ha. Jumlah sekuestrasi CO_2 di hutan terpulih berjulat daripada 6.9 ke 7,069.1 kg CO_2/0.04 ha. Selepas 19 tahun, hutan terpulih mempunyai jumlah takungan biojisim dan karbon atas tanah yang setara dengan hutan sekunder beregenerasi secara semula jadi. Aktiviti pemulihan hutan menunjukkan potensi untuk meningkatkan stok karbon melalui penamanan pokok. Oleh yang demikian, hutan terpulih menunjukkan potensi dalam berperanan sebagai kawasan tadahan karbon yang boleh membantu dalam mengurangkan pelepasan gas rumah hijau dan mengurangkan perubahan iklim.

Kata kunci: Biojisim hutan; hutan sekunder beregenerasi secara semula jadi; hutan terpulih; karbon hutan; pembahagian biojisim; sekuestrasi karbon

Introduction

Forest degradation and deforestation are some of the major global concerns. This is because FAO reported that 13 million hectares of global forests were converted to other land uses or lost through natural causes between 2000 and 2010, while the remaining global forest accounted for 36% of primary forest, 57% of naturally regenerated forest and 7% of planted forest (FAO 2010). In Southeast Asia, it was reported that secondary forest accounted for 63% of the total forest cover in 2005 (Kettle 2010). Tropical forest has been known to play an important role in the carbon sequestration because of the high carbon storage (Lal & Augustin 2012). Hence, forest degradation and deforestation reduced the forest carbon storage and sequestration capacity. This leads to the increasing in emissions of greenhouse gases (CBD 2011; Gorte 2009).

With large area of forest being converted to other land uses and issues related to forest degradation, these elevate the role of the remaining various forest categories such as secondary, regenerating and rehabilitated forests in biodiversity conservation, carbon sequestration and also providing products and services to mankind. Regenerating forest has been reported to be increasingly important as global carbon storage (Kauffman et al. 2009; Kenzo et al. 2010; Van Bruegel et al. 2011). This is due to the recruitment and growth rate of trees in the logged-over forest are usually higher than that of primary forest trees (Swaine & Agyeman 2008; Whitmore 1984). As for the rehabilitated forest, above ground carbon has been reported to show rapid accumulation in the first 20 years of forest rehabilitation but slower rates at the subsequent 60 years old (Silver et al. 2000).

In the recent Copenhagen Climate Change Summit in 2009, developed nations renewed their commitment towards the Kyoto Protocol. It targeted developed nations to reduce their greenhouse gases emissions to at least 40% by 2020 (Netto 2009). Malaysia is reported to record the third highest carbon emitter in South East Asia with 187 million tonnes of carbon emission in 2006 or 7.2 t CO_2 per capita (Netto 2009). With that, Malaysia was reported to be committed in reducing carbon emission to 40% by 2020 with assistance from the developed nations (NRE 2009). Forest plays a prominent role in global carbon cycle and its relation to greenhouse effect is well known. The capability to sequester carbon dioxide in the atmosphere through the process of photosynthesis enables green plants/forest to play a significant role for the benefit of mankind. It has been reported that the forest stored about 4500 Gt of carbon (IUCN 2009).

Information on the biomass and carbon is important to calculate nations' carbon storage for the Reduction Emissions from Deforestation and Degradation in developing countries (REDD) scheme under the United Nations Framework Convention on Climate Change (UNFCCC 2008). Carbon inventory would assess the changes in carbon stocks. Therefore, monitoring on the above and below ground biomass, litter, dead wood and soil organic carbon are required. This will determine the sequestration potential and emissions in an area (Elizabeth & Norini 2010). The most common methods to determine above ground forest biomass are the combination of forest inventories with allometric tree biomass regression models and remote-sensing techniques (Brown 2002; Houghton et al. 2001; Houghton 2005). Hence, such data is important for managing forested area for reducing and mitigating CO_2 emission (Van Breugel et al. 2011).

Forest rehabilitation in the degraded areas could enhance forest carbon stock and provide biodiversity benefits (CBD 2011). It has been estimated that the rehabilitation of degraded lands could reduce 690 million tons CO_2 emission (Elizabeth & Norini 2010). Therefore, forest rehabilitation also has the potential to mitigate greenhouse gases emission. However, the carbon storage and sequestration potential in a rehabilitated tropical forest remains unclear due to the lack of information. Several researchers such as Kenzo et al. (2009(a), 2009(b), 2010) reported on the biomass/carbon storage for the early successional secondary forest in Sarawak, Malaysia while Van Breugel et al. (2011) reported for the secondary forest in Panama. The gap data limits the understanding on the role of rehabilitated tropical forest as sources and sinks of atmospheric carbon. This paper reports the initiative to estimate the above ground biomass-carbon partitioning, storage and sequestration in a rehabilitated forest. This information would provide a wider understanding on the effect of forest rehabilitation activities on carbon storage and sequestration.

Materials and Methods

Study Site

The study was conducted at the UPM-Mitsubishi Corporation Forest Rehabilitation Project in Universiti Putra Malaysia, Bintulu Sarawak Campus, Sarawak, Malaysia. It is located about 600 km Northeast of Kuching (latitude 03°12'N, longitude 113°02'E) and at 50 m above sea level. The annual rainfall recorded at the study site was 2490.00 mm while the average monthly relative humidity was 83.6%. The average monthly air temperature was 27.7°C.

The forest rehabilitation project began in the 1990 where the accelerating natural regeneration technique was applied. The technique was based on the concept of vegetation association and accelerating natural regeneration. High density of three-seedlings per meter was planted with indigenous species. The species selected are mainly from the Dipterocarpaceae and Non-Dipterocarpaceae (such as Anacardiaceae, Moraceae, Sapindaceae and Myrtaceae) family which was based on the field survey conducted in Southeast Asia forest in 1978 (Miyawaki 1999).

A research plot of 20 × 20 m^2 was established each at stand of 19-year-old (Plot 1991), 10-year-old (Plot 1999) and 1-year-old (Plot 2008). The assessments of the plots were conducted in 2009. The small plot size was due to the small annual planting area. A plot was established in a natural regenerating secondary forest at Bukit Nyabau (Plot NF) which is adjacent to the rehabilitated forest. Many tropical secondary forests show rapid rates of above ground biomass during the initial stage of succession (Kendawang et al. 2007; Silver et al. 2000). The selection of different ages at the rehabilitated forest could provide the trend of above ground biomass/carbon storage in the first 20 years of forest rehabilitation.

The site for Plots 1991 and 1999 were an ex-shifting cultivation area with grassland dominated by *Ischaemum magnum* and *Miscanthus floridulus* and woody species of *Trema orientalis*. Previously, Plot 2008 was a regenerating forest with mainly grassland species and some pioneer species like *Macaranga* spp. and *T. orientalis* (Yusof & Abas 1992). As for Plot NF, it was a logging site prior to the opening of the campus in 1987. Anthropogenic disturbances are deemed to cease. The forest is in the natural regenerating state (± 23-year-old) with the opening of the campus.

Stand analysis showed that most of the trees are small, which are within ≤ 10 cm diameter size class (Figure 1). The accelerating natural regeneration technique applied to rehabilitate degraded forest area has accelerated the structural characteristics performance compared to the adjacent natural regenerating secondary forest (Kueh et al. 2011(a)). In term of forest stand development, the forests at all the study plots are at early stage of development compared to mature forest. Information on the selected forest structural features is as in Table 1.

ESTIMATION OF ABOVE GROUND FOREST BIOMASS

The above ground forest biomass was estimated using the following model (Kueh et al. 2011(b)):

$$Y = 0.041 \times (\mathrm{Dbh} \times H)^{1.335},$$

where Y is biomass (kg), Dbh is diameter breast height (cm) and H is height (m).

ESTIMATION OF ABOVE GROUND FOREST CARBON

The above ground forest carbon (C) was determined by using dry-combustion method (Schumacher 2002). The samples from the biomass study were ground and were sieved using a 200 mm sieve. Sample of 2.0 ± 0.1 mg was placed in a silver capsule and analysed in a LECO CHNS TruSpec 600 Analyser. The average tree carbon value for the overall study plots was 45% of biomass. The following formula was used to estimate the tree carbon:

$$\text{Weight of tree carbon (kg)} = \text{Tree biomass (kg)} \times 0.45.$$

ESTIMATION OF CARBON DIOXIDE (CO_2) SEQUESTRATION BY FOREST

The measurement for CO_2 sequestration by forest was calculated using the value of the carbon and multiple by the atomic weight of the CO_2 (Lal & Augustin 2012). The atomic mass of each carbon dioxide (CO_2) molecule would be 12 + 2(16) = 44 (atomic mass unit; amu), of which only 12 are due to the carbon (C). Therefore, for each atom of carbon stored in a tree, 44 amu of CO_2 is removed from the

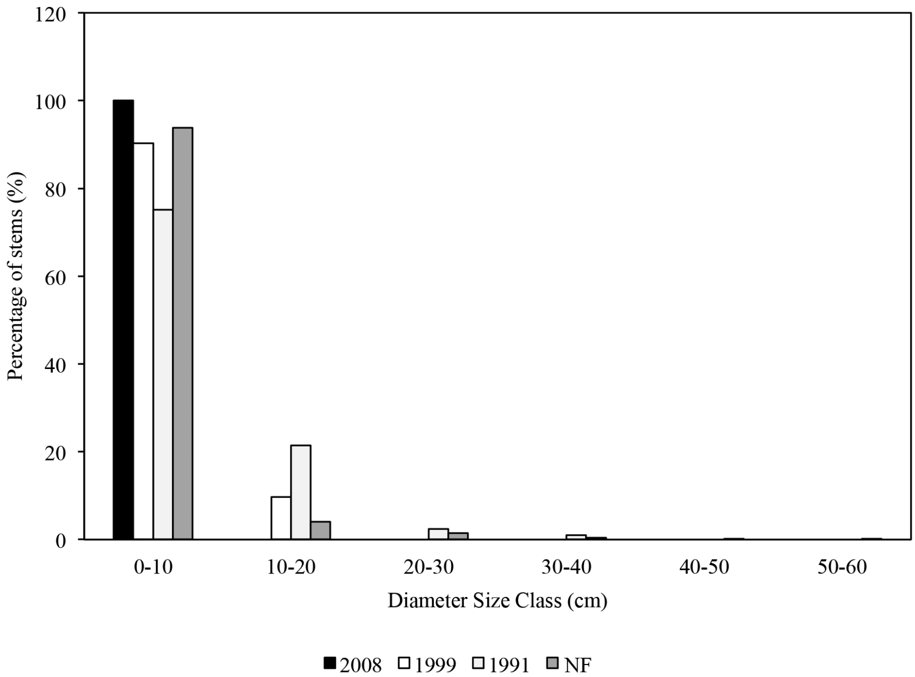


FIGURE 1. Distribution of the stands in the study plots (Adapted from Kueh et al. 2011(a))

TABLE 1. Selected key forest structural features of the study plots

	Plot 2008	Plot 1999	Plot 1991	Plot NF
Mean dbh (cm)*	0.76	6.00	8.16	3.24
Mean height (m)*	0.46	6.15	9.30	4.02
Basal area (m^2/0.04ha)*	0.02	0.80	1.56	1.64
No of trees	321	227	205	546
No of species	19	19	18	120
No of family	10	9	5	38
5 most common families	Dipterocarpaceae Meliaceae Clusiaceae Myrtaceae Sapotaceae	Dipterocarpaceae Anacardiaceae Fabaceae Lauraceae Mrytaceae	Dipterocarpaceae Sterculiaceae Bombacaeae Clusiaceae Myrtaceae	Dipterocarpaceae Anacardiaceae , Eupborbiaceae Sapotaceae Ixonanthaceae
Common species (%)	*Sandoricum borneense*	*Dryobalanops beccarii*	*Shorea dasyphylla*	*Parishia maingayi*
Importance Value (IV) Index	*Sandoricum borneense*	*Dryobalanops beccarii*	*Shorea dasyphylla*	*Teijsmanniodendron holophyllum*
Canopy openness (%)	78	19	8	3

Note: * indicates data adapted from Kueh et al. (2011a)

atmosphere. The following formula was used to estimate the weight of CO_2 sequestrated by a tree:

$$\text{Weight of } CO_2 \text{ sequestrated (kg/tree)} = \text{Tree biomass (kg)} \times 0.45 \times \frac{44 \text{ amu of } CO_2}{12 \text{ amu of C}}.$$

DATA ANALYSIS

The estimated mean total above ground biomass, carbon and CO_2 sequestrated were compared between the study plots using Analysis of Variance (ANOVA). All significant differences of means were grouped using Duncan's New Multiple Range Test (DNMRT). All statistical analyses were carried out using SAS Version 9.2 statistical package software.

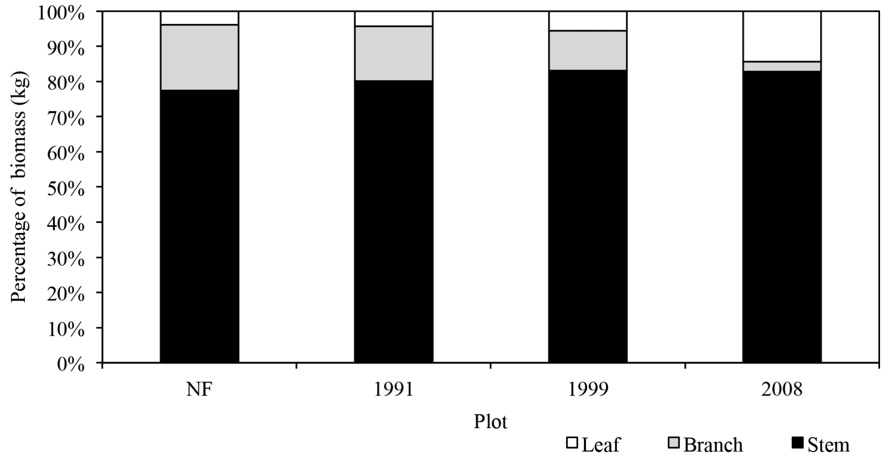
Results and Discussion

PARTITIONING OF BIOMASS AND CARBON

Biomass and carbon partitioning at each of the tree components in the study plots recorded wide variations. Generally, the carbon partitioning also showed similar pattern as to the biomass. The distribution of biomass and carbon partitioning at different tree components are as shown in Figure 2. The partitioning of tree component biomass/carbon to total biomass/carbon was in the order of main stem > branch > leaf. Wide differences were found in the branch biomass and leaf biomass which ranged from 0.12 to 784.50 kg and 0.63 to 161.89 kg, respectively. Therefore, the branch component recorded a range of 3-19% and leaf component of 4-14% of the total biomass and carbon, respectively. These high variations and differences resulted from the crown competition between adjacent trees causing suppression of the smaller trees especially in older rehabilitated and natural regenerating secondary forests. The rehabilitation technique which involves planting of three-seedlings per meter square introduced the competitive environment among the seedlings to survive. In natural regenerating secondary forest, the high density of smaller trees competing to regenerate and colonize the area. Competition within the plots may have affected the partitioning of biomass and carbon at different tree components. This leads to growth suppression and allocation more biomass on the main stem as a result of the struggle for adequate light (Bastien-Henri et al. 2010; Lim 1986).

Branch biomass partitioning depends on the stand density and the stage of growth. In this study, age is an important factor that affects the branch biomass partitioning. Older rehabilitated forests have branch biomass ranging from 11 to 16% of the total biomass while 19% was recorded for natural regenerating secondary forest. In contrast to 1-year-old rehabilitated forest which had branch biomass of 3% of the total biomass. The branch biomass proportion to the stem biomass changes with age and many studies in plantation also showed similar trend (Fang et al. 2007; Nirmal Kumar et al. 2011). Higher stand density as reported at 10-year-old rehabilitated forest with 227 trees/plot compared with the 19-year-old rehabilitated forest with 205 trees/plot. The 19-year-old rehabilitated forest recorded 16% of branch biomass proportion to total biomass compared with 11% at 10-year-old rehabilitated forest. Studies in forest plantation also showed that the tree density reduction through thinning activities has increased the biomass partitioning to the branch component (Munoz et al. 2008; Sabatia et al. 2010; Tadaki 1977).

(a)



(b)

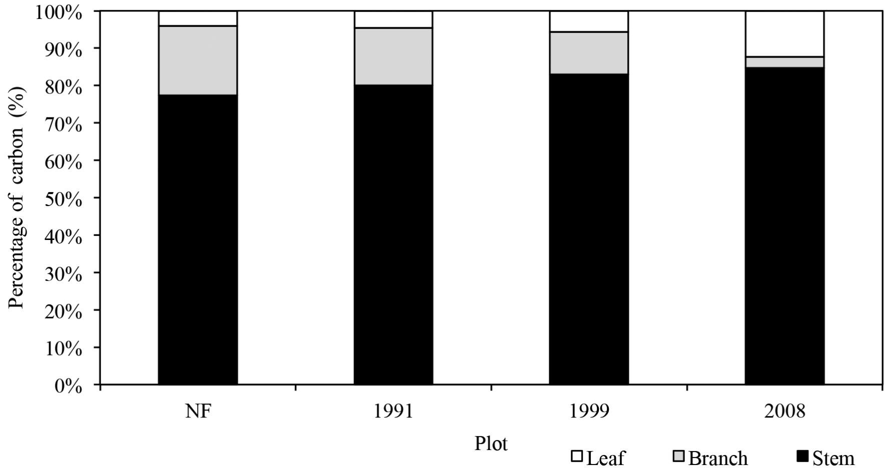


FIGURE 2. Proportion of (a) biomass and (b) carbon partitioning among tree components at the study plots

The 1-year-old rehabilitated forest consists of stand that is still small and short in size. Younger trees allocated more biomass on the leaf section or vegetative part to be competitive in the photosynthesizing activities. In addition, the rapid development of canopy at this early stage was due to available of space between trees compared with the older rehabilitated forest. The inverse and compensatory relationship between stem and canopy mass contributed to the lower leaf biomass. In a regenerating secondary forest as reported by Kenzo et al. (2009(a)), they found that leaf biomass to stem biomass decreased significantly with tree diameter in Sarawak, Malaysia.

Generally, older rehabilitated forests allocated more biomass on woody components (main stem and branch) which ranged from 95-96% of the total biomass compared with 85% in 1-year-old rehabilitated forest. In natural regenerating secondary forest, the allocation of biomass on woody components was 96%. Higher proportion of biomass recorded in the stem generally increases with tree size (Montagu et al. 2005) and age (Son et al. 2001). These reflect the variations of physical tree size in the study plots. As tree biomass increases over age, the main stem must have greater mechanical strength to support increasing weight. Increased mechanical strength in tree can be achieved through increased in stem diameter (King 1986) or wood density (Niklas 1994). However, increased in diameter is the main reason in the increase in strength (Niklas 1993).

The information on the trend of partitioning of biomass and carbon in tree is important to foresters as this would affect the biomass/carbon yield of various tree components. The allocation and cycling of forest carbon is an important component of the biospheric carbon cycle, but is particularly understudied within tropical forests (Litton et al. 2004; Malhi et al. 2009). Hence, the information would provide indication to the effect of stand management which would affect the overall woody biomass. As for forest stand managed for carbon sequestration, the effect of stand management affects their carbon credits. Furthermore, this information can be used in the greenhouse gases inventory report under the REDD+ initiatives.

DISTRIBUTION OF TOTAL ABOVE GROUND BIOMASS AND CARBON

In general, all study plots had more than 80% of trees concentrated in diameter size class 0-10 cm except for

19-year-old rehabilitated forest (75%). The distribution is right-skewed with the right tail is long and the mass of the distribution is concentrated on the left of the Figure 1. This suggests that all the study plots are in the early regenerating stage. The distribution of carbon in the diameter size classes showed similar pattern as in biomass (Figure 3).

In older rehabilitated forest like Plot 1991, the diameter size class 10-20 cm contributed 45% of the total biomass and carbon. About 21% of the total trees are concentrated in this diameter size class. For diameter size class over 20 cm dbh, about 3% of the total trees contributed to the 25% of the total biomass. In Plots 1999 and 2008, more than 80% of trees are concentrated in diameter size class 0-10 cm. Therefore, 69% and 100% of the total above ground biomass and carbon were contributed by trees in this size class, respectively. After 19 years of forest rehabilitation, tree sizes within 10-20 cm dbh plays an important role in the biomass and carbon storage while younger rehabilitated forests, trees below 10 cm dbh are the major contributor of the biomass and carbon storage. As the smaller diameter size class plays an important role in the biomass and carbon storage, this indicated that the rehabilitated forests are in the early stage of succession.

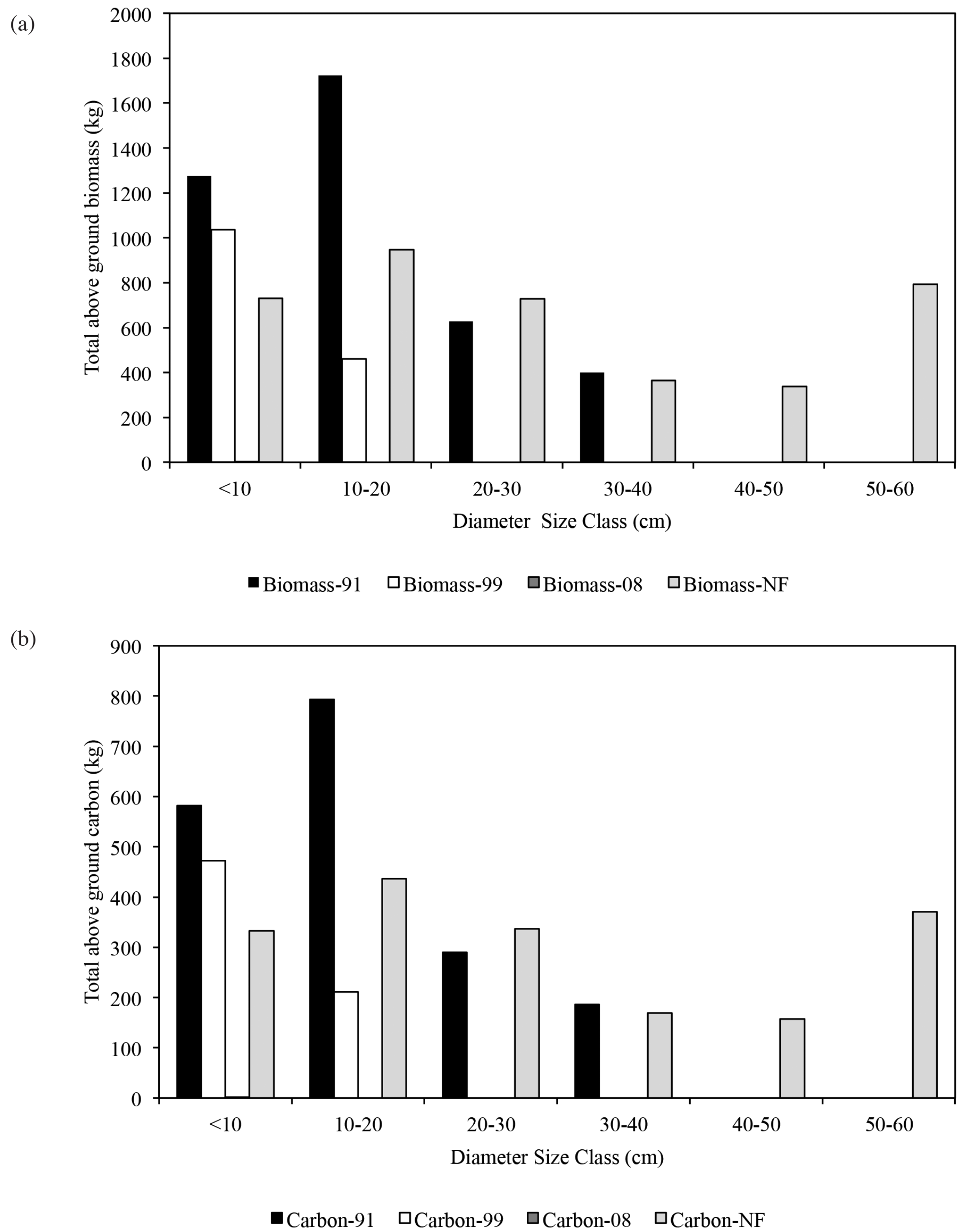


FIGURE 3. Distribution of (a) total above ground biomass and (b) total above ground carbon (kg) in the diameter size class among the study plots

In natural regenerating secondary forest (Plot NF), diameter size class 10-20 cm has 24% of the total biomass and carbon. This is contributed by 4% of the total trees. As for diameter over 50 cm, about 0.1% of the total trees contributed to 20% of the total biomass and carbon. Therefore, bigger diameter size tree in natural regenerating secondary forest has the potential to maintain larger biomass and carbon storage. The major contributor (81%) of the total biomass and carbon storage by tree size over 10 cm indicates the natural regenerating secondary forest is between building to late stage of succession.

Overall, all the study plots are in the process of recovery at different successional stage. Smaller size trees present in all the study plots is a reflection of a typical characteristic of secondary forest. The main characteristics of a secondary forest is having high stem density of < 10 cm dbh with low basal area and short trees with small diameters (Brown & Lugo 1990), hence lower biomass and carbon storage.

The total above ground biomass obtained for rehabilitated forests ranged from 4.3 to 4,192.3 kg compared to natural regenerating secondary forest of 3,942.3 kg. On the other hand, the total above ground carbon recorded a range of 1.9 to 1,927.9 kg and 1,820.4 kg, respectively (Figure 4). The mean biomass and carbon storage was in the order of Plot 1991 > Plot 1999, Plot NF > Plot 2008 (Table 2). Generally, 19-year-old rehabilitated forest has total above ground biomass and carbon storage that is comparable to the natural regeneration secondary forest. In addition, comparison of mean above ground biomass and carbon analysis showed that 19-year-old rehabilitated forest has significant higher ($p \leq 0.05$) biomass and carbon storage compared to the natural regenerating secondary forest. The lowest mean above ground biomass and carbon storage was in 1-year-old rehabilitated forest.

The high density planting applied in the forest rehabilitation technique created a stressful environment for securing resources such as light, water and nutrients. This stressful environment accelerated the regeneration, hence productivity. In a study by Sheriff (1996) on the effect of thinning and pruning in forest plantation on carbon storage suggested that at high stocking, productivity of individuals is small because of competition for resources, but site productivity is high. This could explain the higher overall site productivity as in 19-year-old rehabilitated forest compared with the natural regenerating secondary forest. The accelerated regeneration of the trees in the rehabilitated forest are reflected as higher mean diameter (8.2 cm) and height (9.3 m) in 19-year-old rehabilitated forest compared with the natural regenerating secondary forest (Table 1).

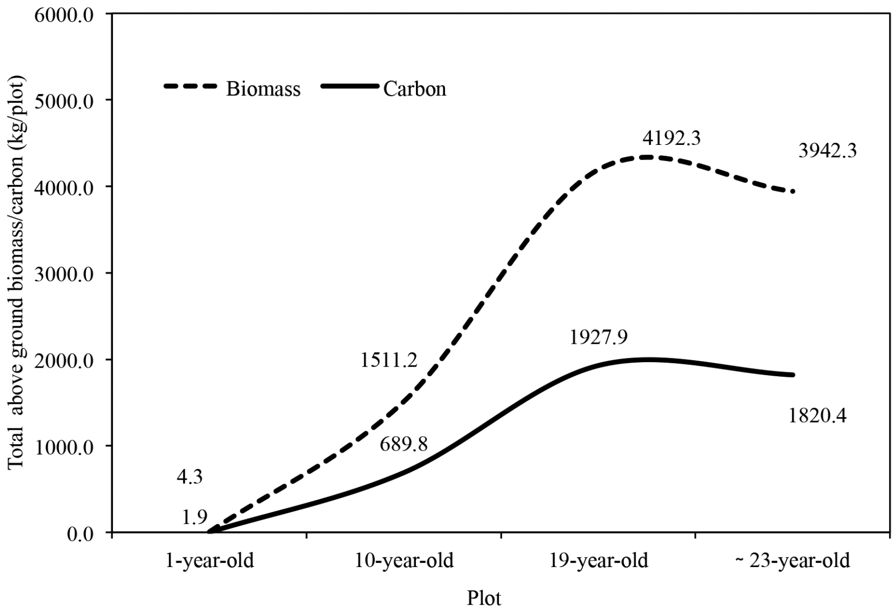


FIGURE 4. The distribution of total above ground biomass and carbon among the study plots

TABLE 2. Mean total above ground biomass and carbon (kg/plot) among the study plots

	Plot 2008	Plot 1999	Plot 1991	Plot NF
Mean total above ground biomass (kg/0.04 ha)	$1.3\times10^{-2\,c} \pm 0.86 \times 10^{-3}$	$6.7^{b} \pm 0.41$	$20.5^{a} \pm 2.14$	$7.2^{b} \pm 1.78$
Mean total above ground carbon (kg/0.04ha)	$5.9 \times10^{-3c} \pm 0.04 \times10^{-2}$	$3.0^{b} \pm 0.19$	$9.4^{a} \pm 0.99$	$3.3^{b} \pm 0.83$

Note: Mean with different alphabets indicate significant differences between study plots by Duncan's New Multiple Range Test at $p \leq 0.05$. Values are expressed as mean ± standard error

As the function of the allometric equation was based on the dbh and height, older rehabilitated forests would result in a higher total above ground biomass/carbon compared with the natural regenerating secondary forest. In contrast to the smaller and shorter tree in 1-year-old rehabilitated forest with mean diameter of 0.76 cm and height of 0.46 m, it recorded the lowest biomass and carbon storage when compared with other study plots.

In short, the forest rehabilitation technique applied in the degraded forest areas showed the potential to restore the total above ground biomass and carbon storage. Forest rehabilitation will generally sequester more carbon than those without forest covers (Gorte 2009). The total above ground biomass and carbon storage in 19-year-old rehabilitated forest was comparable with the ± 23-year-old natural regenerating secondary forest. This reflects the rapid biomass and carbon storage which was also reported by other researchers such as Brown and Lugo (1990) and Silver et al. (2000). They found the rapid trend occurred in the first 15-20 years of forest rehabilitation or natural regeneration. This study provided the baseline information to facilitate the understanding on the trend of above ground biomass and carbon storage beyond 20 years of forest rehabilitation.

CARBON DIOXIDE (CO_2) SEQUESTRATION BY FOREST

The total amount of carbon dioxide (CO_2) sequestrated by forest in the study plot was in the order of Plot 1991 > Plot NF > Plot 1999 > Plot 2008. Rehabilitated forests sequestrated 6.9 to 7,069.1 kg of CO_2 while in the natural regenerating secondary forest was amounted to 6,674.8 kg of CO_2. ANOVA analysis showed that 19-year-old rehabilitated forest sequestrated significantly higher ($p \leq 0.05$) amount of mean CO_2 compared with the natural regenerating secondary forest. Among the rehabilitated forest, the youngest rehabilitated forest recorded lowest mean amount of CO_2 sequestrated from the atmosphere (Table 3).

These values were extrapolated to a hectare. The rehabilitated forests have the sequestration potential to sequester 6.9×10^{-3} to 7.1 t CO_2/ha while in the natural regenerating secondary forest was 6.7 t CO_2/ha. This is the amount of CO_2 emission that could be avoided to the atmosphere. Forest rehabilitation activities have the potential to increase carbon stock through tree planting. The role of forest as carbon storage helps to reduce net emissions of greenhouse gases (Sohngen 2009) and facilitates in mitigating climate change. It can be summarized that rehabilitating degraded forest areas is important as forest rehabilitation has the potential in helping to reduce greenhouse gases emission.

CONCLUSION

It can be concluded that forest rehabilitation using the accelerating natural regeneration technique could facilitate in the above ground biomass and carbon recovery. The information on the partitioning of biomass and carbon at different tree components provided a better understanding on the effect of stand management on it's storage, hence their carbon credits. The study also revealed that the oldest rehabilitated forest had better recovery in terms of biomass and carbon storage compared with the natural regenerating secondary forest. The variations in the biomass and carbon storage also reflected the differences in the successional recovery stage and age. The high density of smaller size trees indicated that the rehabilitated forest is still at the early successional stage.

The comparable above ground biomass and carbon storage after 19 years of forest rehabilitation to the ± 23-year-old natural regenerating secondary forest reflects the rapid biomass and carbon storage. This information provided the baseline data to predict the forest responses on forest management and to understand the recovery trend of above ground biomass and carbon storage. The forest rehabilitation activities have the potential to increase carbon stock through tree planting. Therefore, rehabilitated forest has shown the potential role as carbon sink that helps to reduce emissions of greenhouse gases and mitigate climate change.

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TABLE 3. Mean and total CO_2 sequestrated (kg/plot) among the study plots

	Plot 2008	Plot 1999	Plot 1991	Plot NF
Total (kg/0.04ha)	6.9	2,529.1	7,069.1	6,674.8
Mean (kg/0.04ha)	$0.2 \times 10^{-1c} \pm 0.01 \times 10^{-1}$	$11.1^{b} \pm 0.68$	$34.5^{a} \pm 3.58$	$12.3^{b} \pm 3.00$

Note: Mean with different alphabets indicate significant differences between study plots by Duncan's New Multiple Range Test at $p \leq 0.05$. Values are expressed as mean ± standard error

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