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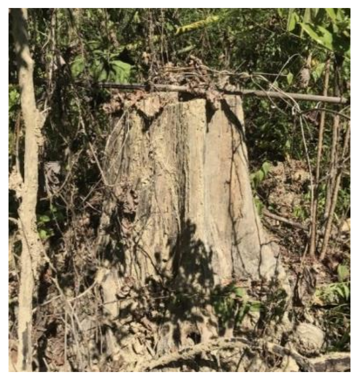
The Role of Coarse Woody Debris in the Logged Forest Carbon Stock





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နေမျိုးဝင်း၊ ဦးစီးအရာရှိ၊ စီမံကိန်းနှင့်စာရင်းအင်းဌာန
နှင့်
N. Mizoue, T. Ota, S. Yoshida
စိုက်ပျိုးရေးဆိုင်ရာမဟာဌာန၊ ကျူးရှူးတက္ကသိုလ်၊ ဖုကူအိုကာမြို့၊ ဂျပန်နိုင်ငံ

စာတမ်းအကျဉ်း

သက်မဲ့သစ်သားဇီဝဒြပ်ထုသည် အပူပိုင်းမိုးသစ်တောများ၏ ကာဗွန်သိုလှောင်မှုတွင် အရေးပါသော်လည်း ယခင် လေ့လာမှုများသည် သစ်ပင်များ၏ကာဗွန်သိုလှောင်နိုင်မှုနှင့် သစ်ထုတ်ခြင်း ၏ ဒါဏ်သက်ရောက်မှုမရှိသော သစ်တောများတွင်သာ အလေးပေး ဆောင်ရွက်ထားခြင်း၊ သစ်ထုတ်ပြီးအပူပိုင်းမိုးသစ်တောများ၏ ကာဗွန်သိုလှောင်မှုတွင် သက်မဲ့ သစ်သားဇီဝဒြပ်ထု၏ အထောက်အကူပြုနိုင်မှုကို မှတ်တမ်းတင်ထားနိုင်မှုမှာလည်း ယနေ့အထိ အားနည်းနေဆဲဖြစ်သောကြောင့် ယင်း၏အရေးပါမှုကို မြန်မာနိုင်ငံ၏ သစ်ထုတ်ပြီးတောများ၏ ကာဗွန်သိုလှောင်မှု တွင် လေ့လာရန် ဤသုတေသနကို ဆောင်ရွက် ခြင်းဖြစ်ပါသည်။ သုတေသနကို ပဲခူးခရိုင်နှင့် ကသာခရိုင်တို့ရှိ ထုတ်လုပ်ရေး သစ်တောများတွင် ဆောင်ရွက်ခဲ့ပြီး သက်မဲ့သစ်သား ဇီဝဒြပ်ထုများကို တစ်ဟက်တာ နမူနာကွက်(၆)ကွက်တွင် အပင်လဲ၊ မတ်ရပ်သေပင်နှင့် သစ်ငုတ်များခွဲခြားပြီး စာရင်းကောက်ယူခဲ့ပါသည်။ နမူနာကွက်များအား သစ်ထုတ်ပြီး(၁)နှစ် အကြာသစ်တော၊ သစ်ထုတ် ပြီး(၅)နှစ်အကြာ သစ်တော၊ သစ်မထုတ်သည့်တောဟူ၍ ခွဲခြားကာ လေ့လာဆန်းစစ်ခြင်း ဆောင်ရွက်ခဲ့ပါသည်။

တွေ့ရှိချက်အရ သက်မဲ့သစ်သား ဇီဝဒြပ်ထုများ၏ ကာဗွန်သိုလှောင်နိုင်မှုသည် သစ်ထုတ်ပြီးတောများနှင့် သစ်မထုတ်သည့်တောများတွင် များစွာမကွာခြားသော်လည်း၊ သက်မဲ့သစ်သား ဇီဝဒြပ်ထုများ၏ မြေဆီလွှာအပေါ်ယံ ကာဗွန်သိုလှောင်မှုအား အထောက်အကူပြုမှုသည် သစ်ထုတ်လုပ်ခဲ့သည့် အကြောင်းအရာပေါ်မူတည်၍ ကွဲပြားခြားနားမှုရှိပါသည်။ သက်မဲ့သစ်သား ဇီဝဒြပ်ထု ကာဗွန်အား မြေဆီလွှာအပေါ်ယံ ကာဗွန်နှင့် နှိုင်းယှဉ် လေ့လာရာတွင် သစ်ထုတ်ပြီး(၁)နှစ်အကြာတောတွင် မြေဆီလွှာအပေါ်ယံ ကာဗွန်၏ ၃၆(±၃၁)%၊ သစ်ထုတ်ပြီး (၅)နှစ်အကြာတောတွင် ၁၉.၈(±၁၉) %၊ သစ်မထုတ်သည့် တောတွင် ၂၂.၁(±၁၆) % အသီးသီးဖြစ်ကြောင်း တွေ့ရပါသည်။ သစ်ထုတ်ခြင်းသည် သက်မဲ့ သစ်သားဇီဝဒြပ်ထုကာဗွန်နှင့် မြေဆီလွှာအပေါ်ယံ ကာဗွန်အချိုးကို မြင့်တက်စေသောကြောင့် သစ်ထုတ်ထားသောတောများ အထူးသဖြင့် မြေဆီလွှာအပေါ်ယံ ကာဗွန်နည်းသော သစ်တောများတွင် သက်မဲ့သစ်သားဇီဝဒြပ်ထုကာဗွန် သိုလှောင်မှုအား ဂရုပြုတိုင်းတာ သင့်ပါသည်။ ဤလေ့လာမှုမှ မြန်မာနိုင်ငံအမျိုးသား ကာဗွန်စာရင်းကောက်ယူခြင်းအနေဖြင့် သက်မဲ့ သစ်သားဇီဝဒြပ်ထုကာဗွန် ပုံသေတန်ဘိုးအဖြစ် သစ်ထုတ်ပြီးစတောတွင် တစ်ဟက်တာ ၁၅ မီဂါဂရမ်၊ သစ်ထုတ်ပြီး (၅)နှစ် အကြာတောနှင့် သစ်မထုတ်သည့်တောများတွင် တစ်ဟက်တာ ၁၂ မီဂါဂရမ် အသုံးပြုသင့်ကြောင်း အကြံပြုပါသည်။ သက်မဲ့သစ်သား ဇီဝဒြပ်ထုမတိုင်းတာဘဲ အပေါ်ယံ မြေဆီလွှာကာဗွန်မှတဆင့် ခန့်မှန်း ခြင်းအတွက် သစ်ထုတ်ပြီးစတောတွင် အပေါ်ယံ မြေဆီလွှာ

ကာဗွန်၏ ၃၆%၊ သစ်ထုတ်ပြီး (၅)နှစ်အကြာတောနှင့် သစ်မထုတ်သည့်တောများတွင် အပေါ်ယံ မြေဆီလွှာကာဗွန်၏ ၂၀% အဖြစ်ထည့်သွင်းတွက်ချက်သင့်ပါသည်။

The Role of Coarse Woody Debris (CWD) in the Logged Forest Carbon Stock

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Abstract

Coarse woody debris (CWD: defined as sound and rotting logs, snags, stumps, and large branches above the soil ≥10 cm diameter) is an important component of tropical forest carbon stock. The disturbance events usually cause large changes in CWD stocks whereas logging events additionally accelerate the formation of CWD. However, previous studies mainly focused on live tree carbon or the forests which were unaffected by logging. To date, the contribution of CWD to carbon stocks in logged tropical forests remains poorly documented. We quantified the CWD by classifying five decay classes that ranged from recently fallen to highly rotten material in the four logged sites of Bago district and Katha district of Myanmar which is a timber-producing country with long history of selective logging. We also accounted above ground carbon (AGC) to make the ratio of CWD/AGC. We compare the CWD carbon potentials of forests with different logging histories in terms of 1-year post logged; 5-year post logged and unlogged sites. The study indicated that the average (±SD) CWD carbon stocks in 1-year post logged, 5-year post logged and unlogged sites are 14.7 (±13.0), 11.6 (±10.0) and 12.4 (±9.1) Mg C ha^{-1} respectively. In 1-year post logged site, CWD contributed 36 (±31.0) % to the AGC whereas CWD of 5-year post logged site and unlogged site contributed 19.8 (±19.0) % and 22.1 (±16.0) %. We conclude that the potential of CWD carbon in Myanmar logged forests is 20% to 36 % of above ground carbon stock. Even though CWD stocks are not significantly different among the forests with different logging histories, their contribution rates to AGC are significantly different. Loggings increase the CWD/AGC ratio and that CWD/AGC ratio is gradually descended at post-5-year logged and become similar to that of unlogged forest.

Keywords: Decay class, Ratio of CWD to above ground carbon, 1-year post logged site, 5-year post logged site, Unlogged site

The Role of Coarse Woody Debris (CWD) in the Logged Forest Carbon Stock

1. Introduction

One of the environmental issues of global concern today is the increase of carbon dioxide in the atmosphere and its potential effect on climate (Ekoungoulou et al., 2015). Forests play multiple roles in climate change mitigation because of their ability to absorb and store large quantities of atmospheric carbon through the process of photosynthesis. In contrast, forests return an almost equal amount to the atmosphere by auto- and heterotrophic respiration (Ekoungoulou et al., 2015) and especially carbon emissions occur when deforested or degraded. Tropical forests represent 44% of global forests (Keenan et al., 2015) and they store up to 59% of the carbon in global forest vegetation (Dixon et al., 1994). Forest carbon pools can be categorized into 5 groups: the above and below ground biomass of trees, dead woods, litter on the forest floor, soils and harvested wood products (Pearson and Brown et al., 2005). Live tree (Assefa et al., 2013) and dead wood (Pfeifer et al., 2015) carbon stocks respond more rapidly and significantly as a result of land-use change and forest disturbances than other carbon pools. Of these 5 carbon pools, AGB is the most visible, most easily measured and most published (e.g., Brown & Gaston, 1996; Saatchi et al., 2011; Baccini et al., 2012). However, most estimates of tropical forest carbon exclude coarse woody debris (Saatchi et al., 2011; Baccini et al., 2012), or assume it as a constant proportion of AGB (Houghton et al., 2001; Malhi et al., 2006; Saatchi et al., 2007; Lewis et al., 2009) by (Carlson et al., 2017).

Coarse woody debris (CWD), is defined by the Long Term Ecological Research Network as sound and rotting logs, snags, stumps, and large branches (located above the soil), which must be larger than 10 cm at the widest point (Harmon and Sexton., 1996). In undisturbed forests, CWD may account roughly for 10% of total carbon storage (Pregitzer and Euskirchen, 2004), and can constitute up to 33% of above ground biomass across tropical forests (Clark et al., 2002; Rice et al., 2004). However, the ratio of CWD to live biomass (CWD/AGB) varies from 2% in the undisturbed forest to 300% in the heavily disturbed forest (Palace et al., 2012).

About 20% of global tropical forests are designated as commercial logging concessions (Blaser et al., 2011) and logging events accelerate the CWD formation because timber harvesting focuses on high-value species and remove large trees with high biomass. Besides, its infrastructures and operations cause collateral damage which can dominate carbon emission in logged forest (Pearson et al., 2014). However, most of previous carbon stock studies have either focused exclusively on live standing biomass or have been carried out in the forests that are unaffected by logging (Pfeifer et al., 2015). To date, the contributions of CWD to carbon stocks in logged tropical forests remains poorly documented (Clark et al., 2002; Baker et al., 2007).

Myanmar has large forest covers in mainland Southeast Asia – 42.9% (FRA, 2015) of the total land area is forested. Myanmar is a timber producing country with over hundred-year experience and selective logging is the widespread practice in mixed deciduous forests which is 38% of the national forested area. The potential of CWD carbon stock in Myanmar logged forests might vary widely with logging histories. Despite CWD which is an important component of tropical forest carbon (Chamber et al., 2000), information about CWD stock potential in logged forests remain unstudied. The lack of CWD stock information of logged forests may lead uncertainty in calculation of carbon stock in Myanmar forests. It is therefore important to improve understanding of CWD and their roles in carbon stock of logged forests with different logging histories. That will contribute the adjustment of Myanmar forest carbon inventory which is the critical measure of country's performance on emission reduction. The present study aims to estimate the potential of CWD carbon stock of Myanmar logged forest studying in two typical timber production areas, Bago and Katha districts. The specific objectives are (1) to quantify CWD carbon stocks and their contributions to total above ground carbon stocks in logged forests with different logging histories and (2) To determine the influences of forest structure and logging disturbance on the CWD carbon stock.

2. Materials and Methods

2.1 Study site

The study was conducted in the timber production forests of Myanmar which are moist deciduous forest type. We worked in four study sites which are compartment 196 of Kaingshe RF (24º 02.44´N 95º 07.12´E), compartment 46 of Pyinde RF (23º 53.33´N 95º 58.39´E) in Katha district, upper part of Myanmar, compartment 93 (17º 50.85´N 96º 07.26´E) and compartment 54 (17º 50.98´N 96º 11.74´E) of S. Zamaryi RF, in Bago district, lower part of Myanmar (Figure 1). The average temperatures of the study sites are relatively constant over the year and with a mean of (27°C), a high of 31°C between April and May, and a low of 23°C between December and January. Mean annual rainfall of Katha and Bago districts are (1788 mm) and (3390 mm) respectively. Rainy season occurs between June and October in the study sites.

As their logging histories, dipterocarpus species 1087 trees (about 1874 hoppus ton) were extracted in Compartment 196 of Kaingshe RF in 2010 and 2011. Recently timber harvesting re-entered to that site in 2017 and teak (*Tectona grandis*) 1403 trees and commercial hardwood species 3208 trees, totally 2557 trees (about 5208 ton) were extracted (MTE, Kawlin). In compartment 93 of S. Zamaryi RF, commercial hardwood 1291 trees (about 1291 hoppus ton) were harvested in compartment 93 of S. Zamari RF in 2012-2013 (Khai et al.,2016). In Compartment 54 of S. Zamari RF, teak and commercial hardwood trees were harvested in 1997, 2007 and 2012 on which cumulative harvesting were 3027 trees (about 5265 hoppus ton) (Thein, 2014). The study plot from compartment (46) of Pynide RF did not involve in the logged area even though timber harvesting was conducted in that Compartment. The study sites can be classified as Kaingshe RF site is 1-year post logged site while S. Zamaryi RF and Pyinde RF sites are 5-year post logged site unlogged site respectively according to their logging histories.

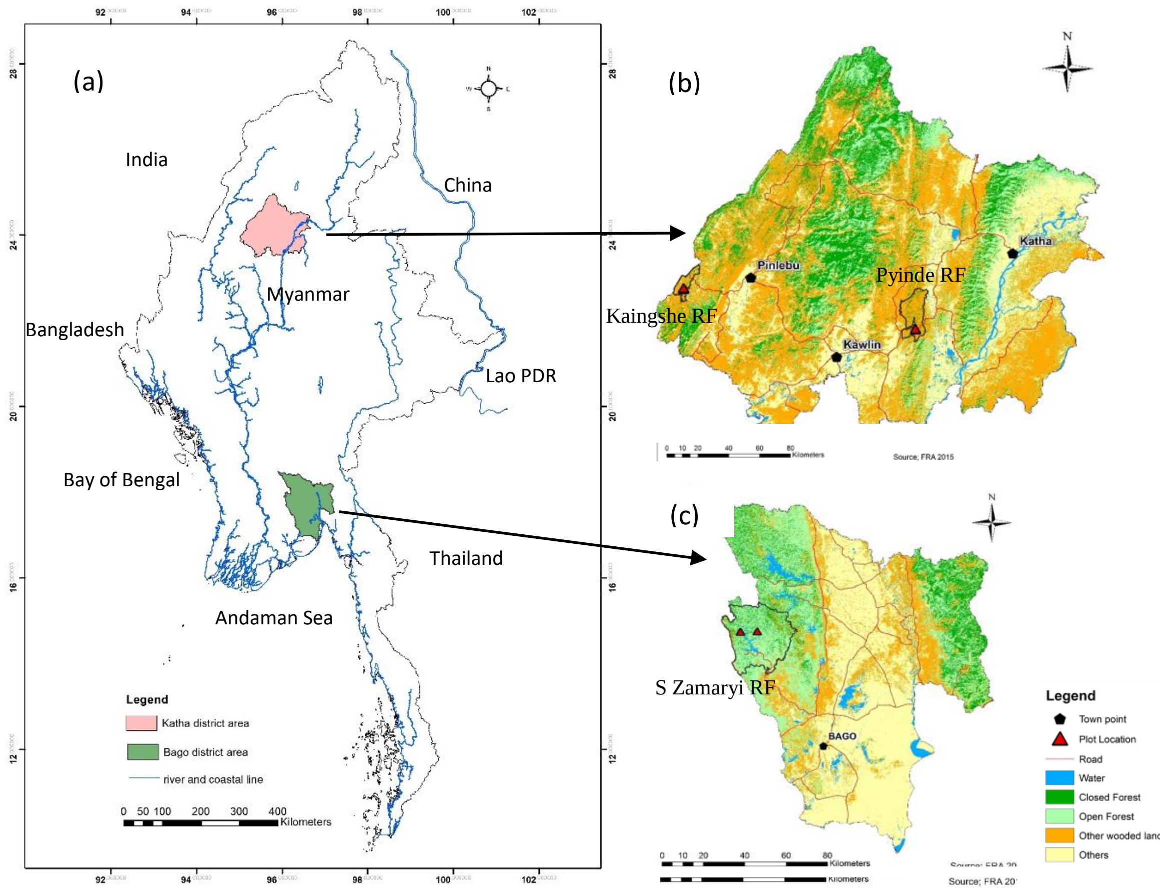

Figure 1 (a) Location Katha district and Bago district, (b) locations of compartment 196, Kaingshe reserved forest and compartment 46, Pyinde reserved forest and (c) locations of compartment 54 and 93, S. Zamaryi reserved forest

2.2 Field measurement

Data collection was conducted in 2018, January. CWD were measured in six 1-ha permanent sample plots (PSPs) from which 2 plots located in Kaingshe RF, 3 plots in S. Zamaryi RF and 1 plot in Pyinde RF. All PSP are 1 ha (10000 m^2) area with quadrative (100×100 m) design. These PSPs were established by (Khai et al., 2016) except the plot from Compartment 54, S. Zamari RF which was set up by (Thein, 2014). Each sample plot was divided into 0.04 ha (400 m^2) 25 sub plots to account the CWD.

In each PSP, CWDs ≥10 cm was measured with categorizing fallen logs, stumps and standing dead trees. Two diameters were measured at the right angles to one another at both ends of each fallen log. When a fallen log tapered to below 10 cm diameter, its length was taken only to that point. Similarly, where a fallen wood protruded outside a plot, its length was taken only to that point and its diameter was measured at that point. For standing dead trees, the diameters were taken at one end (D_1) as DBH measurement and heights were estimated using 5 m bamboo stick. Diameters at the upper end ($D_{upper} = D_2$) were calculated using taper function (Chambers et al., 2000). Standing dead trees ≤ 1.37 m height were recorded as stumps. Orthogonal two diameter measurements were made in the cutting end of each stump and height of stumps were recorded and stump species as well. While data collecting, CWD pieces were identified into five decay classes (Table 1) (Baker and Chao, 2009).

Table 1 Five decomposition classes of CWD

Decay Class	Descriptions from Baker and Chao, 2009
1	Solid wood, recently fallen, with intact bark and fine branches still attached
1.5	Solid wood, but with no fine branches, and bark starting to fall off.
2	Non-solid wood, in poorer condition, but where it is still difficult to push a nail into the wood by hand.
2.5	Soft, rotten wood, where a nail can be pushed into the wood easily
3	Soft, rotten wood, which collapses easily when stepped on

Living trees and bamboos were also measured in each PSP to calculate the total AGB. All trees ≥ 10 cm DBH were measured at 1.3 m height identifying tree species. Harvested trees and species were also recorded according to the stump marked by MTE. The tree heights were recorded by Laser True Pulse (360). However, tree heights from the compartment 93 and 54 of S. Zamaryi RF (5-year post logged site) were estimated using the following DBH-Height relationship equation derived from on the 2012 measurement in compartment 93, (H = 9.4375 ln (DBH) -13.058; r^2 = 0.6215) and 2016 measurement in compartment 54, (H = 1.9479 x0.6416; r^2 = 0.6363)

The diameters of maximum and minimum culms were measured for each bamboo clump. The number of bamboo culms from clumps was also counted. In the whole measurement, recorded tree and bamboo species were identified with the assistance of local foresters and local people and then checked with "A checklist of trees, Shrubs, Herbs and Climbers of Myanmar" (Kress et al.,2003).

2.3 Carbon stock estimation

CWD volume: the volume of fallen logs and standing dead trees (m^3) were calculated by using Smalian's formula (Baker et al., 2007), $V = L\left[\frac{\pi(D1/2)^2 + \pi(D2/2)^2}{2}\right]$; where L is the length or height of CWD and D_1 and D_2 are two diameter measurements at right angles to one another at both end of each fallen dead wood. In the standing dead trees (snags), taller than 1.37 m, we used the dbh of the stem as D_1. To estimate D_2 (diameter at the upper end), we used the tree height estimated with 5 m bamboo stick and applied a taper function from (Chambers et al., 2000); $D_{upper} = 1.59\ d_b\ (h^{-0.091})$. For stump volume, we used (Harmon and Sexton, 1996) formula; V= A× L; where A is an area of cutting end of the stump, L is the height of stump.

Wood density and Biomass calculation: the mass of CWD was computed as the product of volume per decay class and wood density for that class (Pfeifer et al., 2015). Site-specific measurement of CWD decay class density (g cm^{-3}) was not done and the decay class densities were estimated by using (Chao et al., 2008) models.

$P_{d=1} = 1.17\,(\rho) - 0.21$ and $P_{d=2} = 1.17\,(\rho) - 0.31$

where $P_{d=1}$ and $P_{d=2}$ are CWD densities in decay class 1 and 2 and ρ is the plot level average wood density of living tree. Since decay class 3 is not related to living wood density, default value, 0.29 g cm^{-3} was used for that class (Chao et al., 2008). We aggregated the five decay class system to a three decay class system for statistical analysis using the method suggested by (Baker and Chao, 2009). Thus, we combined decay class 1and 1.5 to $P_{d=1}$ and decay class 2 and 2.5 to $P_{d=2}$ for calculating decay class density.

Live tree biomass was calculated using the model, AGB = 0.0673 × $(pD^2H)^{0.976}$ (Chave et al., 2014) ; where D = DBH of tree, H = height of the tree and ρ= wood density (g cm^3). Wood densities for specific tree species were taken from global wood density database (Chave et al., 2009; Zanne et al. 2009) and genus level average densities were used where the species-specific density were not available. If the species could not be identified, mean wood density for Asian tropical forests, (0.57 g cm^{-3}) (Brown, 1997) was used. For bamboo biomass calculation, the model (Chan et al., 2013) was used for *B. polymorpha* whereas (Descloux et al., 2011) model was used for other bamboo species. CWD mass and biomass of live tree and bamboo were converted to carbon value by assuming 47% of dry biomass value (Pearson et al., 2014).

2.4 Data analysis

The volume of individual CWD items and total above ground biomass (live tree + bamboo) were calculated and summed into sub plot level. Then CWD mass of sub plot level was accounted according to their wood density by decay classes. After that biomass of CWD and AGB (Mg ha^{-1}) were calculated and converted to the carbon stock value (Mg C ha^{-1}). Mean values of CWD volume, mass, carbon and the ratio of CWD/AGC were used not to change the inference of statistics. We used ANOVA and multiple comparison test (Tukey HSD) to evaluate statistical differences in mean CWD carbon and ratio of CWD to total above ground carbon stock of three different logging histories. To determine the influences of forest structures and logging disturbances on CWD stock, we performed linear regression of each variable on CWD and the ratio of CWD/AGC.

3. Results

3.1 General forest structures of study sites

Among the six study plots, the highest standing tree density 183 stems ha^{-1} and highest species composition 46 species ha^{-1} were found in unlogged site (Kawlin) whereas the lowest stem density 53 stem ha^{-1} and lowest species composition 22 species ha^{-1} were in 1-year post logged site (Pin B) (Table 2). The standing tree density and species composition in other 4 plots are similiar ranging 127-146 standing tree ha^{-1} and 27-38 species ha^{-1} respectively. But the highest basal area 12.3 m^2 ha^{-1} was found in Pin B plot. The high bamboo clump density 246 clump ha^{-1} and 253 clump ha^{-1} were found in Bago A plot and Bago B plot respectively.

Table 2 Forest structures of study sites

Sample plot	Standing tree density	species composition	Mean DBH	Mean height	Tree basal area	Bamboo clump	Harvested Tree volume(m3)
	stem ha^{-1}	species ha^{-1}	cm	m	m^2 ha^{-1}	clump ha^{-1}	m^3
Pin A	135	33	28.5	13.4	11.1(±7.8)	23	37.8
Pin B	53	22	40.3	14.9	12.3(±27.1)	99	100.1
Bago A	146	38	26.7	16.2	7.9 (±5.0)	246	40.0
Bago B	127	34	30.6	18.4	11.1(±9.0)	253	15.4
Bago54	141	27	24.3	12.7	8.6(±7.8)	51	35-40
Kawlin	183	46	28.2	15.3	13.8(±8.7)	16	0
Average	130±42.8	33.3±8.4	29.8±5.6	15.2±2	10.8±2.2	114.7±108	

The harvested tree volume for each site was estimated from the harvested stump measurements for 1-year post logged plots and from the prior harvesting data for 5-year post logged plots by using model (Leech et al., 1986) which was developed for timber production forests of Bago and Katha districts. The harvested tree volume for Bago plot 54 was estimated from stump measurements of 2018 and cumulative harvested tree number which was reported by (Thein, 2014). The highest harvested tree volume (100.1 m^3 ha^{-1}) was found in Pin B plot and lowest (15.4 m^3 ha^{-1}) was in Bago B plot. Not quite different harvested tree volumes were found in Pin A (37.8 m^3 ha^{-1}), Bago A (40 m^3 ha^{-1}) and Bago 54 (35-40 $m^3 ha^{-1}$).

3.2 Disturbance index in different study sites

Disturbance index of each plot was determined as Disturbance = number of stumps/ (number of stumps+ number of live trees) (Pfeifer et al., 2015). The stumps found in the study sites were left by official and illegal loggings. The average (±SD) highest disturbance index, 0.29 (±0.27) was found in Pin B plot. Despite unlogged site, Kawlin plot resulted as the second highest 0.24 (±0.21) which is not quite different with the disturbance of Pin A plot, 1-year post-logged site 0.23 (±0.21). The disturbance index of Bago 54, Bago B and Bago A plots (5-year post-logged sites) are similar 0.21(±0.21), 0.2 (±0.19) and 0.19 (±0.23) respectively. Even though no disturbances were found in 25% of the area of the 1-year post logged site (Pin A, Pin B) and 5-year post logged site (Bago A, Bago 54), high disturbances were found in their 75% of the area (Figure 2). The disturbance index of Bago B plot (5-year post logged site) and Kawlin plot (unlogged site) were more consistent than that of other study plots.

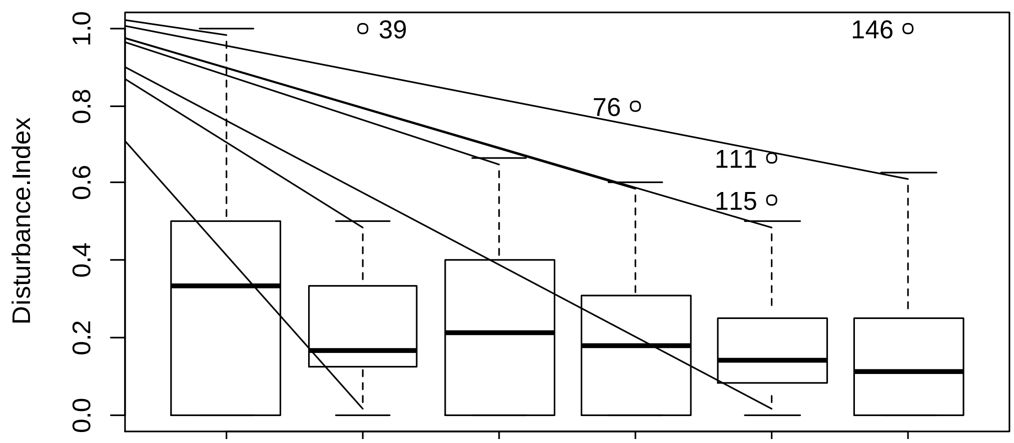

Figure 2 Disturbance index of different study sites

3.3 CWD volume and decay class proportion

In all plots, we measured 1183 CWD pieces totally; 947 fallen logs, 194 stumps and 42 standing dead trees. The highest CWD (±SD) volume 99.5 (±70) m^3 ha^{-1} was found in Pin B plot and second lowest volume, 73.6 (±58) m^3 ha^{-1} was in Bago B plot. The lowest CWD volume 25.8 (±22) m^3 ha^{-1} resulted in Bago 54 plot whereas Pin A and Bago A were not quite different CWD volume, 42.7 (±37) m^3 ha^{-1} and 49.9 (±49) m^3 ha^{-1} respectively. Despite the unlogged site, the third highest volume 57.1 (±40) m^3 ha^{-1} was accounted in Kawlin plot (Figure 3).

The highest amount of CWD volume (decay class 1 + 1.5) which were 41% and 51.4% of total CWD were found in Pin A and Pin B plots, 1-year post logged site. Even though the amount of CWD (decay class 1 + 1.5) were constituting up 24.5% in Bago B, 16.3% Bago A and 24.1% in Kawlin, both decay class 1 and 1.5 were not found in Bago 54 plot. The decay class 2 were highly found in 5-year post logged plots 70.6% in Bago 54, 53.8% in Bago B and 74.6% in Bago A respectively. The amount of CWD decay class 2.5 and 3 varied among the different sites. But a large amount of CWD (decay class 2.5 + 3), 44.9% of total CWD was found in the unlogged site, Kawlin plot.

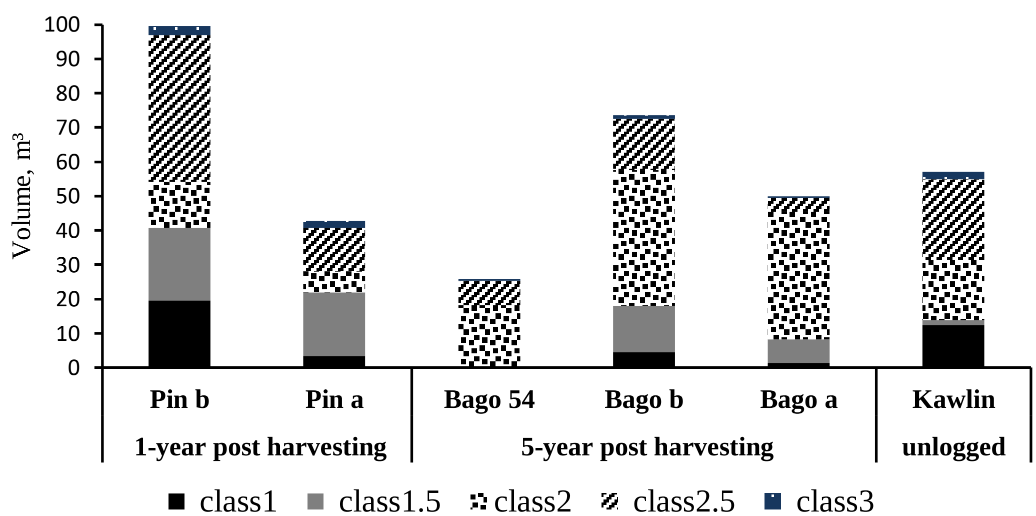

Figure 3 A stacked bar graph showing the proportions of CWD volume by decay class for diameter ≥10cm

3.4 CWD carbon stock in different study sites

The highest CWD carbon stock 20.3 (±14.6) Mg C ha^{-1} was found in Pin B plot while the second highest 13.7 (±12.3) Mg C ha^{-1} in Bago B plot (Figure 4). The third highest CWD carbon stock 12.4 (±9.1) Mg C ha^{-1} was existing in Kawlin plot, un-logged site. The lowest CWD carbon stock 5.9 (±6.7) Mg C ha^{-1} was resulted in Bago 54, 5-year post logged site. CWD stock of Pin A plot, 9.1 (±8.4) Mg C ha^{-1} and Bago A, 10.6 (±9.9) Mg C ha^{-1} were similiar. We found that the range of CWD carbon stock values are high in each study plot.

In each plot, fallen logs were found as the largest component of CWD carbon and standing CWD and stump were second highest and lowest respectively. As the mean value of all sites, fallen logs represented 74% whereas standing dead trees and stumps were constituting up 16% and10% of total CWD stock respectively.

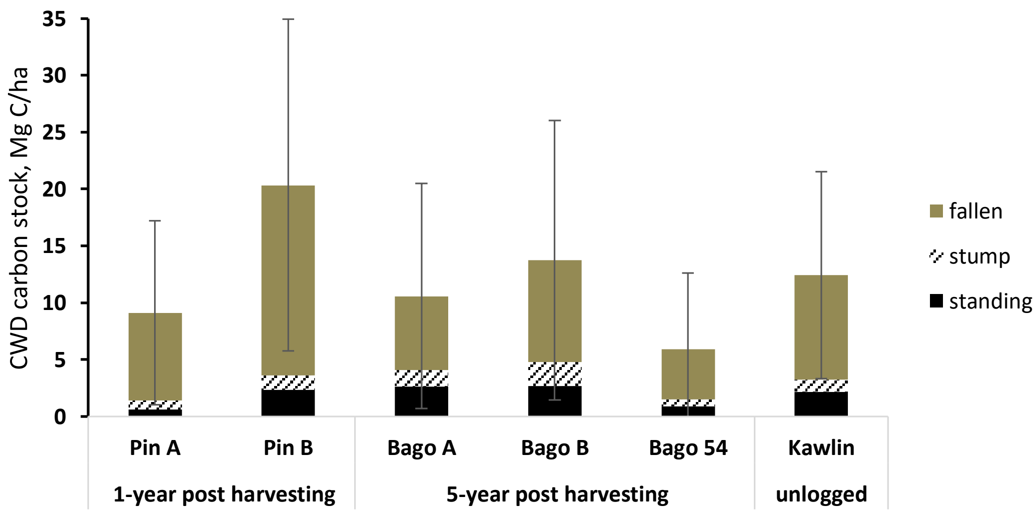

Figure 4 CWD carbon stock in six study plots

CWD carbon stock values of different study plots were grouped into the same recent logging histories in terms of 1-year post logged and 5-year post logged sites and they were compared with that of the unlogged site. Mean CWD carbon stock of 1-year post-logged site resulted as 14.7 (±13) Mg C ha^{-1} ranging 0.56 to 56.14 Mg C ha^{-1} (Figure 5). In 5-year post logged site and un-logged site, 11.6 (±10) Mg C ha^{-1} and 12.4 (±13) Mg C ha^{-1} were found respectively. According to ANOVA with the multiple comparison test (Tukey HSD), there were no significant differences among the mean CWD carbon stocks of different logging histories (1-year post logged - 5-year post logged site: P=0.299; 1-year post logged - unlogged sites: P=0.688; unlogged site - 5-year post logged site: P=0.951) (Table 3).

Figures CWD carbon stocks

Table 3 CWD carbon in different logging histories

Logging history	1-year post logged site (Mg C ha^{-1})	1-year post logged site (Mg C ha^{-1})	Unlogged site (Mg C ha^{-1})
Mean CWD carbon	14.7 ±13 [a]	11.6 ±10 [a]	12.4 ±13 [a]
Range	0.57 - 56.14	0 - 41.66	1.65 - 33.26
subplots	50	75	25

3.5 The contributions of CWD to above ground carbon stock

We combined the carbon stocks of live tree and bamboo as total above ground carbon stock (AGC). The highest total AGC, 65.6 (±53) Mg C ha^{-1} was existing in Bago B plot while the second highest, 56.2 (±39) Mg C ha^{-1} was stored in Kawlin plot (un-logged site). The total AGC of Pin A, Pin B, Bago A and Bago 54 plots were 37.8 (±25), 42.5 (±45), 46.2 (±17) and 37.8 (±34) Mg C ha^{-1} respectively and they were not much different from each other (Figure 6). Even though bamboo carbons are not highly found in Pin A, Bago 54 and Kawlin plots, they are constituting up 21.4%, 25.5% and 34.1% to their total AGCs of Pin B, Bago B and Bago A plots.

We calculated the ratios of CWD to the total AGC for each PSP. The highest and second highest ratios of CWD/AGC (±SD), 47.9 (±34) %, 24.1 (±21) % were found in Pin B plot and Pin A plot (1-year post logged site). The lowest ratio of CWD/AGC, 15.7 (±17) % was resulted in Bago 54 plot which is the 5-year post logged site. In Bago A, Bago B (5-year post logged site) and Kawlin (un-logged site) plots, their CWD ratios were similar, 22.9 (±22) %, 20.9 (±18) % and 22.1 (±16) % respectively.

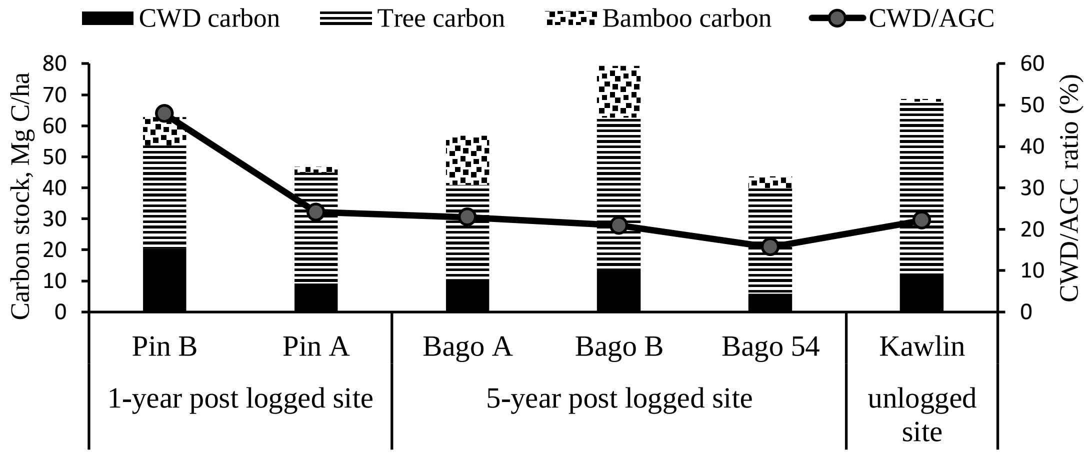

Figure 6 The comparison of CWD carbon and total above-ground carbon stock and ratios of CWD/AGC in different study plots

The different ratios of CWD/ AGC were grouped into the same logging histories in terms of 1-year post logged site, 5-year post logged site and they are compared with that found in the unlogged site. The mean ratio of CWD/AGC of the 1-year post-logged site resulted as 36 (±31) % (Table 4). The CWD ratios of the 5-year post-logged site and un-logged sites are 19.8 (±19) % and 22.1 (±16) % respectively. According to ANOVA with the multiple comparison test (Tukey HSD), the mean ratio of CWD/AGC of 1-year post logged site is significantly different with that of 5-year logged site and unlogged site (1-year post logged site - 5-year post logged site: P=0.001; 1-year post logged site – unlogged site: P=0.045) (Table 4). Between the mean ratio of CWD/AGC of 5-year logged site and un-logged site, there is no significant difference (5-year post logged site – unlogged site: P=0.907). The high variations of CWD/AGC ratio were found among the subplots of each logging history. The CWD ratio of 1-year post logged site varies much higher than that of 5-year logged site and un-logged site (Figure 7). In the otherwise, the CWD/AGC ratio of the unlogged site is more consistent than that of 1-year post logged and 5-year post logged sites.

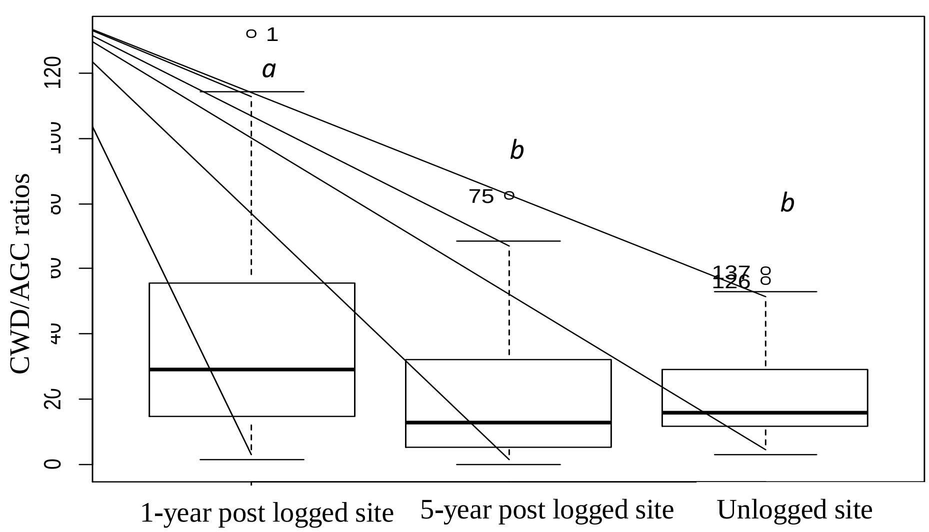

Figure 7 CWD/AGC ratios in different logging histories

Table 4 The ratios of CWD/AGC in different logging histories

Logging history	1-year post logged site	1-year post logged site	Unlogged site
Mean CWD/AGC ratio	36±31% [a]	19.8±31% [b]	22.1±16% [b]
Range	1.5% - 132%	0 – 82%	3% - 59%
subplots	50	75	25

3.6 Relationships of CWD carbon stock and ratios of CWD/AGC

Logging history, forest structure and disturbance index variables of study sites were calculated and determined their relationships with CWD carbon stock and CWD/AGC ratio. Harvested tree volume is significantly related to CWD carbon stock; r^2= 0.27, df =23, P =0.009 (Figure 8a and Table 5) and standing tree density is negatively related to CWD carbon stock; r^2= 0.2, df =23, P =0.029 (Figure 8 b and Table 5). The CWD carbon stock is not related to the disturbance index and live tree biomass as well (. But the significant relationship is found between the amount of CWD volume (decay class 1+1.5) and CWD carbon stock (r^2= 0.48, df =23, P =0.0003) (Figure 8 d and Table 5). That result suggested that the recent CWD formations to the site are highly influenced CWD carbon stock.

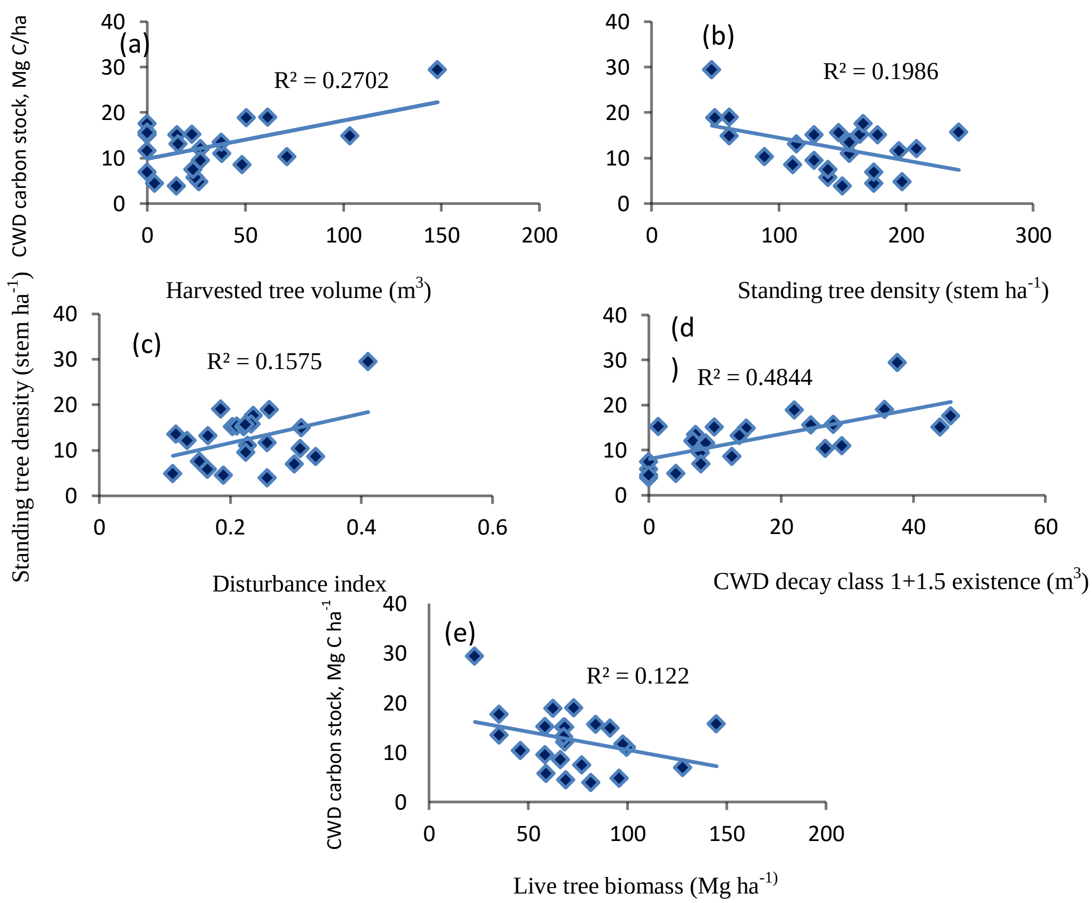

Figure 8 Relationship of CWD carbon stock to (a) harvested tree volume, (b) standing tree density, (c) disturbance index, (d) CWD decay class 1+1.5 existence and (e) live tree biomass

Table 5 Result of linear regression evaluating the relationship of CWD carbon

Variables	Estimate	SE	t	Pr(>|t|)	R^2
Harvested tree volume	0.08381	0.02936	2.854	0.00922 **	0.2702
Stem density ha-1	-0.0503	0.02156	-2.335	0.0291 *	0.1986
Disturbance index	0.00487	0.0024	2.028	0.0549	0.1575
CWD Decay class (1+1.5) existence	0.27796	0.06114	4.546	0.000159 ***	0.4844
Live tree biomass	-1.6604	0.9497	-1.748	0.0944	0.122

Harvested tree volume is significantly related to CWD/AGC ratio (r^2= 0.54, df =23, P =3.62e-05) and standing tree density is also negatively related to it (r^2= 0.33, df =23, P =0.003) (Figure 9 a, b and Table 6). Even though disturbance index is not related to CWD stock, it is related to CWD/AGC ratio (r^2= 0.2, df =23, P =0.03) (Figure 9 c and Table 6). Significant relationship is found between the amount of CWD volume (decay class 1+1.5) and CWD/AGC ratio (r^2= 0.31, df =23, P =0.005) (Figure 9 d and Table 6). There is no relationship between live tree biomass and CWD/ AGC ratio (Figure 9 e and Table 6).

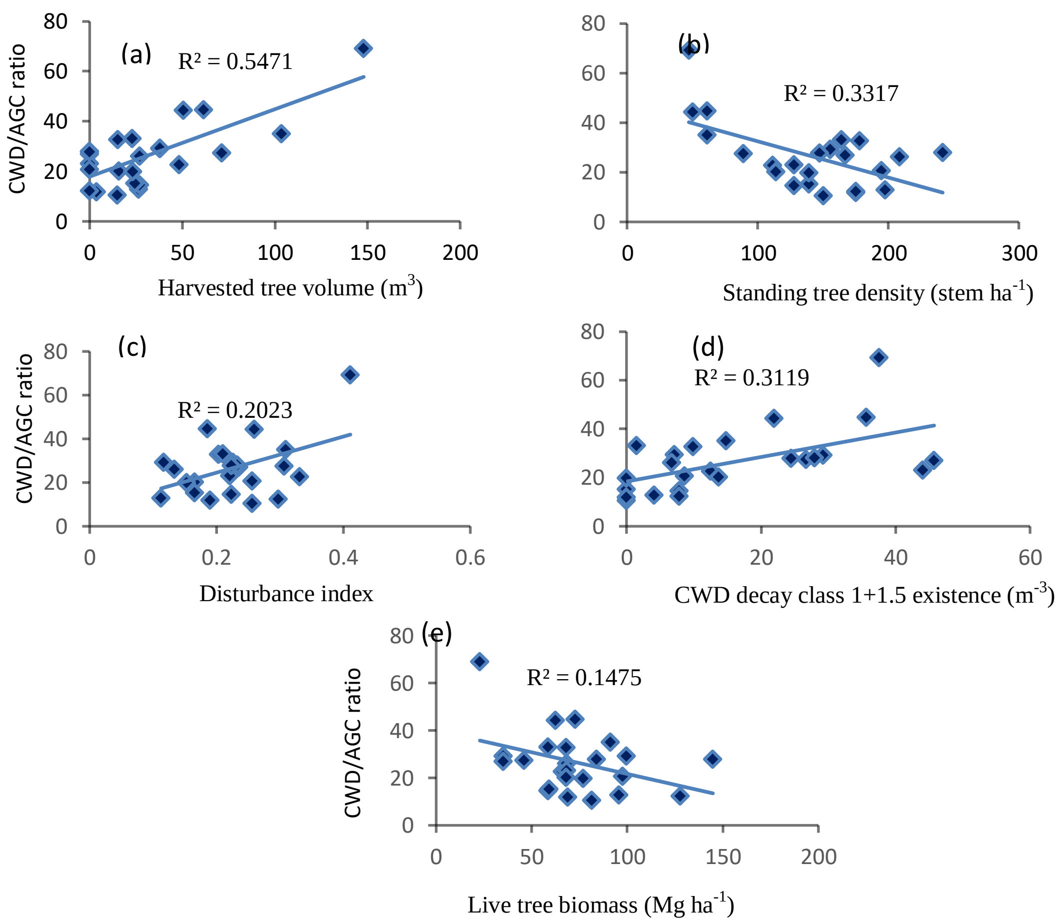

Figure 9 Relationship of CWD/AGC ratio to (a) harvested tree volume, (b) forest structure, (c) disturbance index, (d) the amount of CWD (decay class 1+1.5) and (e) live tree biomass

Table 6 Result of linear regression evaluating the relationship of CWD/AGC ratio

Variables	Estimate	SE	t	Pr(>|t|)	R^2
Harvested tree volume	0.2685	0.05208	5.155	3.62e-05 ***	0.5471
Stem density ha-1	-0.14645	0.04432	-3.305	0.00323 **	0.3317
Disturbance index	82.478	34.919	2.362	0.0274 *	0.2023
CWD Decay class (1+1.5) existence	0.5022	0.159	3.158	0.00456 **	0.3119
Live tree biomass	-0.8109	0.4156	-1.951	0.0639	0.1475

4. Discussion

The CWD carbon of 1-year post logged site 14.7 Mg C ha^{-1} is slightly higher than that of 5-year post logged site 11.6 Mg C ha^{-1}. However, the mean CWD carbon stocks are not significantly different among 1-year post logged, 5-year post logged and unlogged sites. This result deviates from Neotropic countries and Afrotropics (Gabon) in which CWD carbon found in logged forests are significantly higher than that of unlogged forest (Carlson et al., 2017). We compared the average (±SD) CWD carbon value of this study 12.8 (±11.7) Mg C ha^{-1} with that found in logged forests of the previous studies. This study is lower than that of Gabon, Cameroon, Indonesia and Malaysia (Table 7).

The average (±SD) total above ground carbon stock of this study 47.7 (±11.1) Mg C ha^{-1} lies within the range of that found in the mixed deciduous forest of Myanmar and Lao PDR (Table 8). However, this study is quite lower than Malaysia, Brazil and RO Congo. The reason of low above ground carbon stock of this study is likely to be due to the forest structures among different regions. The standing tree density and basal area of this study 130 (±42.8) stem ha^{-1} and 10.8 (±2.2) m^2 ha^{-1} are lower than that found in Indonesia 459 (±92) stem ha^{-1} and 20 (±5) m^2 ha^{-1} (Osone et al., 2016), Brazil 499 (±65) stem ha^{-1} and 28.1 (±3.3) m^2 ha^{-1} (Mazzei et al., 2010) and Gabon 452 (±34.8) stem ha^{-1} and 31.1 (±4.3) m^2 ha^{-1} (Medjibe et al., 2011). That comparisons of forest structures suggested that the timber production forests of Myanmar are not dense comparatively.

Table 7 Comparison of CWD from this study to previous studies

Country	Forest type	Measurement	CWD stock	Reference
Myanmar	Moist deciduous	CWD ≥10cm	12.8 ±11.7	This study
Gabon	Humid	CWD ≥10cm	43.5	Carlson, 2017
Cameroon	Moist	CWD ≥10cm	14.4	Djomo et al., 2011
Indonesia	Dipterocarp rain	CWD ≥10cm	18.0	Rozak, 2018
Malaysia	Humid (Light logged)	CWD ≥10cm	19.8	Pfeifer, 2015
Malaysia	Humid (Twice logged)	CWD ≥10cm	22.2 - 33.5	Pfeifer, 2015

The mean CWD/AGC ratio of 1-year post logged forests of this study 36 (±31) %) is higher than that found in logged forests of Borneo 13.5% (Hamuraby et al., 2018), Malaysia 25% (M Pfeifer et al 2015) and Gabon 30% (Carlson et al, 2017). However, the CWD ratio of 5-year post logged forest 19.8 (±19) % is lower than that found in the logged forest of Malaysia and Gabon whereas higher than that found in Borneo. Regarding with the CWD/AGC ratio of unlogged forest, this study, 22.1 (±16)% is higher than that found in Malaysia 10.5 (±4.6) % (Pfeifer et al., 2015), Hawaii 16.9% (Iwashita et al., 2013) and Gabon 18%.

Table 8 Comparison of above ground carbon stock to previous studies

Country	Forest type	Measurement	Above ground carbon stock (Mg C ha^{-1})	Reference
Myanmar	Moist deciduous	trees≥10cm	47.7 ±11.1 (37.6-65.6)	This study
Myanmar	Mixed deciduous	trees≥10cm	23-68	Brown et al., 1997
Lao PDR	Moist	trees≥10cm	42-74	Dexcloux et al., 2011
Malaysia	Dipterocarp rain	trees≥10cm	91.9 ±2.9	Saner et al., 2012
Brazil	Moist	trees≥10cm	269.0	Pearson et al., 2014
RO Congo	Moist	trees≥10cm	283.0	Pearson et al., 2014

Since the high densities of bamboo clump are constituting in the production forest of deciduous forests Myanmar, the contributions of CWD to above ground carbon were calculated by making the ratio of CWD to the total AGC (combination of tree and bamboo carbon) while the other studies make the ratio of CWD to only live tree carbon stock.

In 1-year post logged site, CWD formation increased due to residual logs and felling damages of recent logging. Simultaneously AGC was dropped due to harvested trees. That is why the CWD ratio immediately rose and resulted as 36%. In 5-year post logged site, CWD formation rate declined as well as CWD decompositions occurred in the post-5-year logged. At the same time, the above ground carbon recovered due to the growth of residual trees. Thus, CWD carbon ratio decreased to 19.8% in that site and it was lower than that of 1-year post logged site. In the unlogged site, illegal cutting entered and it accelerated the CWD formation rate that was higher than that found in the natural condition and AGC dropped due to illegally felled trees. That is why CWD ratio to AGC of that site took place 22.1% and it was slightly higher than that of 5-year post logged site.

A high amount of CWD decay class 1+1.5 volume (mean=46% of total CWD volume) was found in 1-year post logged sites because these CWD decay classes are generated by recent timber harvesting. No CWD decay class 1 and 1.5 were found in Bago 54 plot, 5-year post logged site and it suggested that illegal cutting which often followed official logging stopped and fresh CWD formation was interrupted at post-5-year logged. Highly CWD decay class 2 (mean=66% of total CWD volume) was found in 5-year post logged sites. According to the mean residence time of deadwood carbon= six to nine year (Chambers et al., 2001; Rice et al., 2004), these CWD (non-solid wood) were likely to be the CWDs generated by 5-year post logging or other human disturbances. In the unlogged site, the amount of CWD volume (decay class 2.5+3) was found as highest proportion and it was accounted 44.9 % of total CWD.

The significant relationship of CWD (decay class 1+1.5) volume and CWD carbon stock suggested that recent CWD formation due to 1- or 2-year post disturbances highly influences the

CWD stock. More long-term studies are needed for which period of CWD formation influenced the CWD stock of logged forests and the rate of CWD decomposition as well. We found that live tree biomass (AGB) is not related to CWD stock whereas it was highly correlated to CWD in Gabon (Carlson et al., 2017).

Even though the disturbance index is not related to CWD stock, it is significantly related to the ratio of CWD/AGC. Harvested tree volume and standing tree density are better predictors of the ratio of CWD/AGC in timber production forests.

4.1 Bias and uncertainties

CWD carbon estimation of this study was relatively lower than previous studies of logged forests and above ground carbon stock as well. The density of CWD pieces for five decay classes was not measured in this study. We used the model of humid forest from neo-tropical regions to calculate densities of CWD decay classes. Thus, CWD density estimation is likely to vary somewhat between neo-tropical and Asia tropical forests.

Similarly, densities of specific standing tree species from the study plots were not calculated for above ground biomass estimation. Using wood density from global wood density database is likely to have a bias on total above-ground carbon estimation. Moreover, different methodologies for biomass calculation may vary the forest carbon values among different regions.

5. Conclusion

Myanmar has been undertaking climate change action plan to reduce emissions over time according to the Paris Agreement which was ratified in 2017. Under this agreement, Reducing Emissions from Deforestation and Forest Degradation (REDD+) activity is the critical measure for national mitigation action plan (ECD's report, 2018). According to IPCC guidelines, accurate accounting for forest carbon pools is a key component for national greenhouse gas (GHG) inventories (Carlson et al., 2017). Since Myanmar is a timber producing country with over hundred-year experience, logged forests are taking place widespread in deciduous forests which are 38.2% of national forested area. Hence, it is important to account the CWD carbon which plays important role in tropical logged forest carbon stocks.

The results of this study imply that for logged forests, in previous studies, they may have underestimated CWD carbon stock and overestimated carbon storage in live trees. The study confirmed that the role of coarse woody debris has risen in the logged forest carbon stock. The potential of CWD carbon in Myanmar logged forest is 20 to 36% of total above ground carbon stock. Logging accelerated the CWD formation and increased the ratio of CWD/AGC up to 48% in 1-year post logged forests. However, that CWD/AGC ratio is gradually descended at post-5-year logged and similar with that of unlogged forests. The ratio of CWD/AGC of logged forest was influenced by the standing tree density, disturbance index and harvested tree volume of the site.

The significant ratios of CWD to their above ground carbon stock and their variations with different logging histories suggested that the attention should be paid for quantifying CWD carbon in logged forests, especially in the forests characterized by low above ground carbon stocks to enhance accurate carbon accounting. We therefore recommend that national carbon inventory of Myanmar to account selectively logged forests using default CWD values 15 Mg C ha^{-1} for 1-year post logged forest and 12 Mg C ha^{-1} for 5-year post logged and unlogged forest. For estimating CWD carbon from the total AGC, the different ratios; 36% for recently logged forests and 20% for 5-year post logged forests and unlogged forests should be used. Since about half of CWD found in recently logged sites were generated by logging operations, damages of selective logging should be reduced for emission reduction.

6. Acknowledgements

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