AN ABSTRACT OF THE DISSERTATION OF

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Title: Carbon Dynamics in Response to Land Cover Change in Tropical Peatlands, Kalimantan, Indonesia.

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J. Boone Kauffman

This study focuses in providing the knowledge on carbon (C) stocks, emission and ecosystem productivity related to land use/land cover change in tropical peatlands. The field research activities were conducted for about 17 months between August 2013 to December 2015, at Pematang Gadung peat dome (peat depth up to 10.5 m), Ketapang Regency, West Kalimantan, Indonesia. The objectives of this study were: a). to quantify C stocks of tropical coastal peat swamp forest, and the potential impact of forest degradation due to draining and logging activities on the forest's carbon stocks; b). to examine the change in ecosystem C stocks and the potential C emissions in relation to land conversion from intact peat swamp forest (PSF) to logged peat forest (LPSF), early seral (ES) and oil palm plantation (OP); and c). to estimate net primary production (NPP) and net ecosystem production (NEP) in peat swamp forests, logged peat forest, early seral and smallholder - oil palm plantations.

The intact peat forest sites have higher total aboveground C stocks (125 Mg C $ha^{-1}$) than the logged peat forest sites (77 Mg C $ha^{-1}$). Mean depths of the LPSF was 725 cm and the PSF was 915 cm ($p= 0.06$). Mean peat carbon stocks at PSF was 4,243 Mg C $ha^{-1}$, higher than at LPSF that was 3,675 Mg C $ha^{-1}$. Logging and draining had reduced the biomass of trees and the peat carbon pools. My study demonstrated that tropical coastal PSF has the largest total carbon stocks among terrestrial ecosystems on earth. The large carbon stocks and high rates of PSF degradation, points to the relevance for inclusion of PSF in nationally appropriate climate change mitigation and adaptation strategies.

The mean ecosystem carbon stock for the PSF sites was 4,401 Mg C $ha^{-1}$. Ecosystem C stocks of LPSF, ES and OP was 3,768, 3,147, and 3,442 Mg C $ha^{-1}$, respectively. PSF stocks was significantly higher than the degraded land covers. At all sites, soils comprised > 96% of the mean ecosystem carbon stock. Using the estimation based on ecosystem carbon loss to total peat depths, the conversion of PSF to LPSF, ES and OP was estimated to result in a net loss of 1,982, 4,259 and 3,176 Mg C-$CO_2$ $ha^{-1}$, respectively. My results confirm that land cover change significantly impacted soil properties and reduced ecosystem carbon stocks. The tropical peatlands need urgent and significant efforts in conservation and restoration, to regain its function as a C sink and mitigate climate change.

I found that land use/land cover change resulted in large shifts in NPP and NEP. LPSF, ES and OP have significantly lower NPP (11.1 Mg C $ha^{-1}$ $yr^{-1}$, 10.8 Mg C $ha^{-1}$ $yr^{-1}$ and 3.7 Mg C $ha^{-1}$ $yr^{-1}$, respectively) than PSF (13.2 Mg C $ha^{-1}$ $yr^{-1}$). ES showed lower heterotrophic respiration (30.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) than PSF, LPSF and OP (37.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, 40.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, 38.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$**,** respectively)**.** LPSF and OP were net carbon sources; they have negative mean NEP values (-0.1 Mg $CO_2$-e $ha^{-1}$ $yr^{-1}$ and -25.1 Mg $CO_2$-e $ha^{-1}$ $yr^{-1}$, respectively). In contrast PSF and ES were net carbon sinks (10.8 Mg $CO_2$-e $ha^{-1}$ $yr^{-1}$ and 9.1 C-$CO_2$ $ha^{-1}$ $yr^{-1}$, respectively). PSF is among the most productive of terrestrial ecosystems, with an NPP exceeding that of many tropical rain forests and similar to the most productive mangrove ecosystems. I found that land use decreases productivity of the LPSF and OP sites. The ES had a similar NEP to the PSF, but frequent fires in this ecosystem likely offset carbon gains during the fire intervals.

Land use change and forest degradation have shifted tropical PSFs from net carbon sinks to net carbon sources. My study demonstrated that land conversion in tropical peat swamp forests should be halted and degraded peatlands need to be restored in order to mitigate climate change.

Carbon Dynamics in Response to Land Cover Change in Tropical Peatlands,

Kalimantan, Indonesia

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APPROVED:

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Head of the Department of Fisheries and Wildlife

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Imam Basuki, Author

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# CONTRIBUTION OF AUTHORS

Dr. J. Boone Kauffman was involved in the design, analysis, and writing of all chapters of this dissertation. Dr. Daniel Murdiyarso, Dr. Gusti Z. Anshari, Dr. James Peterson and Dr. David Myrold were involved in the review process of this dissertation.

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# Chapter I

# Introduction

**INTRODUCTION**

Wetlands as defined by the Ramsar Convention are: “all areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt” (Moore, 2006). Peatlands are a type of wetland and defined as terrestrial wetland ecosystems in which the production of organic matter exceeds its decomposition and a net accumulation results (Page *et al.*, 2007; Sulman *et al.*, 2012). Tropical peatlands are defined as those peatlands lying within latitudes 35 degrees North and South including those at high altitudes (Andriesse, 1988; Page et al., 2007).

Tropical peat swamp forests provide many important ecological services. They harbor unique communities of aquatic and terrestrial biodiversity (Rieley *et al.*, 2008). Peat forests regulate the water flow from terrestrial to aquatic ecosystems and slow the transmission of pollutants across this interface (Murdiyarso *et al.*, 2012). Among the most important values of peat forests is that of carbon (C) sequestration (Murdiyarso et al. 2009).

Tropical peatlands comprise about 10% (44 Mha) of the global peatland area (400 Mha), in which about 15 to 21 Mha are in Indonesia (Murdiyarso, Hergoualc’h, & Verchot, 2010) . The total sequestered C of tropical peatlands has been estimated to range from 81.7 to 91.9 Pg or about 15-19% of global peat carbon stock (610 Pg), in which Indonesia contains about 57 Pg (Verwer & Meer, 2010). Tropical peatland ecosystems have among the largest ecosystem C stocks on earth (Page *et al.*, 2011; Basuki *et al.*, 2016), The largest area of peatland in Indonesia are in Borneo, with about 6.8 Mha (Radjagukguk in Rieley & Page 1997; Murdiyarso et al. 2009). Unfortunately this valuable ecosystem has been threatened by deforestation and forest degradation in recent years (Koh *et al.*, 2011; Miettinen *et al.*, 2016). Deforestation is defined as the long term or permanent conversion of land from forested to non-forested, while degradation is defined as changes within the forest which negatively affect the structure or function of stand or site and thereby lower the capacity to supply products or services (Lepers *et al.*, 2005).

Global deforestation and land use change in forests have contributed significantly to the global greenhouse gas emissions from terrestrial ecosystems. Recent low estimate suggests that Indonesia’s forest loss is >1,000 $km^2$/year (Hansen *et al.*, 2013), and high estimate suggests at >5,000 $km^2$/year (BP-REDD+, 2015). Deforestation and forest degradation, including forest conversion to oil palm (*Elaeis guineensis)* plantations, are the main human disturbance to peat forest ecosystems (Hergoualc'h & Verchot, 2011). Conversion of peat swamp forests involves cutting trees, burning and/or developing drainage canals (Anshari *et al.*, 2010; Verwer & Meer, 2010). About three million ha of oil palm plantation and a million ha of abandoned peatlands had been developed in South East Asia's peatlands in the last three decades (Miettinen *et al.*, 2016). This created a fragmented mosaic of degraded forests, seral ecosystems and agricultural cover types in peatlands. Intact peat swamp forest is now less than 7% of all peatland areas in main Indonesia's islands (Miettinen *et al.*, 2016). Moreover, recent reports showed that tropical peatlands in Indonesia are now net sources of carbon (Dommain *et al.*, 2014), as there are much more degraded peatland ecosystems than the intact forest.

Conversion of tropical peat forest likely increases decomposition rates and C emissions (Murdiyarso *et al.*, 2010; Hergoualc'h & Verchot, 2011). Losing tropical peat forests means that we are losing the most effective ecosystem in sequestering $CO_2$ from the atmosphere. Yet, few studies have been conducted to estimate total ecosystem carbon stocks in peatlands (Murdiyarso *et al.*, 2009b; Suwarna *et al.*, 2012, Novita, 2016). Furthermore, there have been even fewer studies that estimate ecosystem carbon loss in response to land cover change in tropical peatlands (but see Novita, 2016). Estimation on the changes of carbon stocks, emissions, and ecosystems' productivity resulting from forest degradation and conversion into early seral (ex-peat forest area that is dominated by grasses and ferns, which was cleared by logging and burning) and oil palm plantations is urgently needed.

This study was conducted in the mosaic of land uses within a peat dome in Ketapang, West Kalimantan, Indonesia. Intact - Peat Swamp Forests (PSF) is located around the center of peat dome and surrounded by the logged peat swamp forests (LPSF). Based upon observation of satellite images and interviews with local people, the forests were first being logged around 1988. The logged area were burned and cleared for agriculture activities about six years later (1994). Many of these cleared peatlands were abandoned and frequently burned during dry seasons, thus forming early seral communities (ES). ES is dominated by ferns and grasses. Oil palm plantations (OP) were developed in 2010 by converting LPSF and ES. The OP plantations were surrounded by the ES and LPSF.

The objectives of this study were: a). to quantify C stocks of tropical coastal peat swamp forest, and the potential impact of forest degradation due to draining and logging activities on the forest's carbon stocks; b). to examine the change in ecosystem C stocks and the potential C emissions in relation to land conversion from intact peat swamp forest (PSF) to logged peat forest (LPSF), early seral (ES) and oil palm plantation (OP); and c). to estimate net primary production (NPP) and net ecosystem production (NEP) in peat swamp forests, logged peat forest, early seral and smallholder - oil palm plantations. The research questions addressed in this dissertation relevant to the changes in carbon stocks, carbon emissions and ecosystem productivity in response to land use/land cover change are:

a). How do the carbon stocks differ between relatively intact PSF and logged PSF, early seral (ES) and oil palm plantations (OP) that were formed on sites previously occupied by PSF?

Anthropogenic disturbance had shift Indonesian tropical peatland from net carbon sequester into net carbon emitter (Dommain *et al.*, 2014). However, total carbon stocks associated with the degradation and emissions of peat swamp forests has been under studied. In order to fill in the knowledge gap, this study was objected to quantify total ecosystem carbon stocks of coastal peat swamp forests of the Pematang Gadung peat dome, Ketapang, Indonesia.

b). What are the potential emissions that could arise from degradation of PSF to LPSF, and from conversion of PSF to ES and OP?

Recent estimates suggest that Indonesia forest loss is the highest in the world, including peat swamp forest conversion to early seral and oil palm (*Elaeis guineensis)* plantations. These are the main human disturbance to tropical peat forest ecosystems (Hergoualc'h & Verchot, 2011). About three million ha of OP had been developed in South East Asia's peatlands in the last three decades (Miettinen *et al.*, 2016). Conversion of tropical peat forest involves cutting trees, burning and/or developing drainage canals and likely increases decomposition rates and C emissions (Murdiyarso *et al.*, 2010; Hergoualc'h & Verchot, 2011). Yet, no studies has quantified total carbon stocks and carbon emissions from the disturbed peatland ecosystems, except from Central Kalimantan (Novita, 2016). Decision - making for climate change mitigation and adaptation strategies needs to be informed about the dynamics of carbon in tropical peat swamp forests in response to land cover change.

c). What and how the net primary production (NPP) and net ecosystem production (NEP) changes in consequence to conversion of intact peat swamp forests (PSF) to logged PSF (LPSF), early seral (ES) and smallholder - oil palm plantations (OP)?

Tropical peat swamp forests are carbon-rich ecosystems that have been threatened by high rates of land use change (LUC) and degradation for the last three decades. Yet few studies have quantified changes in the peat forests' ecosystem productivity associated with deforestation and LUC. To address the research question, I quantified net primary production (NPP) and net ecosystem production (NEP) in peat swamp forests (PSF), logged PSF (LPSF), early seral (ES) and smallholder - oil palm plantations (OP) in a peat dome of West Kalimantan, Indonesia (Appendix Figure 1).

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# Chapter II

# Carbon Stocks of Tropical Peat Swamp Forests in West Kalimantan, Indonesia

## ABSTRACT

Tropical peatlands have been significant global carbon sinks for thousands of years. Tropical peatlands cover as much as 439,238 km2, which is about 11% of all global peatlands. Indonesia has more tropical peat forests than any other nation. Rapid rates of land cover change and the resulting emissions has made Indonesia among the top global GHG (Greenhouse Gas) emitters of all countries. Yet, these estimates are based on few studies of actual ecosystem carbon (C) stocks in either forests or converted lands.

The objectives of this study were to quantify C stocks of tropical coastal peat swamp forest, and the potential impact of forest degradation due to draining and logging activities on the forest's carbon stocks. The study was located at Pematang Gadung peat dome (peat depth up to 10.5 m), Ketapang Regency, West Kalimantan, Indonesia.

The intact and logged forests sampled in this study had significantly different mean of tree densities that were 1,701 and 1,282 trees $ha^{-1}$, respectively. Mean basal area of intact forests (30.8 $m^2$ $ha^{-1}$) was significantly higher than logged forests, i.e., 18.7 $m^2$ $ha^{-1}$. Trees of intact forests are bigger than those in LPSF, i.e., 11.51 cm vs. 10.64 cm dbh.

The intact forests had a significantly higher total aboveground C stocks (158 Mg C $ha^{-1}$) than the logged sites (93 Mg C $ha^{-1}$). Aboveground tree, woody debris, understory and litter C in intact forest were all higher than in the logged forest.

Mean depth of the peat horizons in logged forest was 725 cm and the intact forest was 915 cm ($p= 0.01$). The peat carbon stocks at PSF was 4,243 Mg C $ha^{-1}$, and higher than at LPSF that was 3,675 Mg C $ha^{-1}$. Logging and draining had significant impacts on reducing the biomass of trees and the peat carbon pools.

Tropical coastal peat swamp forest is among largest total carbon storage (4,401 Mg C $ha^{-1}$) of terrestrial ecosystems on earth, e.g., more than 10 to 17 times higher than carbon stocks in tropical forests on mineral soils. The large carbon stocks, high rates of PSF degradation, and the potential of high greenhouse gas emissions points to the relevance for inclusion of PSF in nationally appropriate climate change mitigation and adaptation strategies.

## INTRODUCTION

Tropical peat swamp forests provide many important ecological services. They harbor unique communities of aquatic and terrestrial biodiversity (Rieley et al., 2008). Peat forests regulate the water flow from terrestrial to aquatic ecosystems and slow the transmission of pollutants across this interface (Murdiyarso et al., 2012). Among the most important values of peat forests is that of carbon (C) sequestration (Murdiyarso et al. 2009). The total sequestered C of tropical peatlands has been estimated to range from 81.7 to 91.9 Pg or about 15-19% of global peat carbon stock (610 Pg), in which Indonesia contains about 57 Pg (Verwer & Meer, 2010).

In tropical peatlands, sequestered carbon is stored both as above- and belowground C stocks. The aboveground carbon stocks includes aboveground biomass (living and dead trees), litter, and woody debris (Murdiyarso et al., 2009). In peatlands these carbon stocks are much less than the quantity of C stored in peat soils. Previous studies reported that aboveground C stocks of intact peat forests ranged from 111 to 645 Mg C $ha^{-1}$, compared to about 85 to 142 Mg C $ha^{-1}$ of logged peat forests (Blanc et al., 2009; Suwarna et al., 2012; Novita, 2016). Woody debris store about 16 to 57 Mg C $ha^{-1}$, whereas litter C stocks are about 2 to 6 Mg C $ha^{-1}$ (Verwer & Meer, 2010; Novita, 2016).

Belowground C stocks include the coarse and fine roots (woody support structures) of trees, and soils. Carbon stocks of the tree root in peat forests are only about 2.25% of the total biomass, and has been estimated to be about 37 Mg C $ha^{-1}$ (Verwer & Meer, 2010). In contrast, peat soil C stocks have been reported to be about 252 to 7,889 Mg C $ha^{-1}$, depending on the peat thickness (Jaenicke et al., 2008; Murdiyarso et al., 2009a; Verwer & Meer, 2010; Warren et al., 2012, 2016; Novita, 2016).

Tropical peatlands comprise about 10% (44 Mha) of the global peatland area (400 Mha), in which about 15 to 21 Mha are in Indonesia (Murdiyarso, Hergoualc'h, & Verchot, 2010). The largest area of peatland in Indonesia are in Borneo, with about 6.8 Mha (Radjagukguk in Rieley & Page 1997; Murdiyarso et al. 2009). Unfortunately this valuable ecosystem has been threatened by deforestation and forest degradation in recent years (Koh et al., 2011; Miettinen et al., 2016).

Degradation of tropical peat forest involves forest harvest or removal and/or developing drainage canals (Anshari *et al.*, 2010; Hooijer *et al.*, 2010; Warren *et al.*, 2016). Fires of human origin are also common (Page et al., 2002). This degradation likely increases peat decomposition rates and C emissions from peatlands (Murdiyarso *et al.*, 2010; Hergoualc'h & Verchot, 2011). Anthropogenic disturbance had shifted Indonesian peatlands from net carbon sinks into net sources of greenhouse gases (Dommain et al., 2014). But few studies have measured total ecosystem carbon stocks of tropical peat forests, (Murdiyarso et al., 2009a; Suwarna et al., 2012; Novita, 2016) . Reliable information are needed to increase the accuracy of accounting on the total ecosystem carbon stocks in peat swamp forests, in mitigation strategies such as REDD+ (Hergoualc'h & Verchot, 2011a; Warren *et al.*, 2012).

In order to fill in the knowledge gap, the objectives of this study were to quantify total ecosystem carbon stocks of coastal peat swamp forests of the Pematang Gadung peat dome, Ketapang, Indonesia. My specific research questions included: What are the carbon stocks of the intact peat swamp forests (PSF) of the Pematang Gadung peat dome? How are carbon pools partitioned among aboveground and belowground components? How do they differ between relatively intact and logged forests (LPSF)? How do peat bulk density, nitrogen and carbon to nitrogen ratio differ between intact and logged forests? How significant is the carbon stocks of intact forests in the study area to other ecosystems in the world?

My hypotheses were: a. Carbon stocks (aboveground, belowground and total) of intact peat swamp forests will be higher than those of logged peat swamp forests, because it has limited logging activities and further distance to drainage canal; b. Logged forests will have lower C stocks in tree but higher in woody debris than intact forests, because logging activities had reduced bigger trees and left over timber residues; c. Since logging and drainage canal had significantly disturbed the logged forests condition, thus intact forests will have lower soil bulk density and higher C content than the logged one.

# METHODS

## Study site

The research was located in forested landscapes of the Pematang Gadung peat dome, Ketapang, Indonesia in the province of West Kalimantan (Figure 2.1). The Pematang Gadung is a coastal peat dome (34,651 ha), between the Pawan and Pesaguhan Rivers. These two rivers run to the Karimata strait, between Sumatera and Kalimantan islands, that connects South China Sea and Java Sea. The rainfall in the region averages 2000 mm per year with the majority falling during the months of November to July. The mean annual temperature is 27.5°C. Elevation is about 10 m above sea level (http://www.ketapangkab.go.id).

*Insert Figure 2.1*

I sampled the ecosystem carbon stocks of 9 forests (4 relatively intact - Peat Swamp Forests/PSF and 5 Logged Peat Swamp Forests/LPSF). The forests had a canopy height of approximately 15 m.  All sites occurred near the center of the peat dome. Based upon analyses of Landsat satellite images and interviews with local people, the forests on this dome have been exploited for wood for local (subsistence use) since 1988 (25 years before sampling).  Timber exploitation first began following road development (across the peat dome) and canalization (Carlson et al., 2012).

## Field sampling

I selected research sites based on field observation, discussion with local experts and analyses on Landsat images.  Considerations included availability of intact and logged sites in close proximity to one another.

Ecosystem C stocks (above-and belowground) were measured at each site, following methodologies described by Murdiyarso et al. (2009), Kauffman and Donato (2012), and Kauffman et al. (2016). At each site, 6 plots were established 30 m apart along a 150 m transect. At each plot, aboveground carbon pools including trees, snag, woody debris and litter were measured.  Belowground pools such as roots were estimated using formula from Mokany et al. (2006).  Peats were sampled to the mineral soils.

**Biomass of trees and shrubs**

Common species of peat swamp forests in the forest stands sampled included Aglaia rubiginosa (Hirn.) Pannel, Dactylocladus stenostachys Oliv., Dyera costulata Hook.f., Palaquium spp., Pandanus spp., and Nepenthes spp. Tree density, and basal area of the forests were quantified through measurements of the diameter at 1.3 m height (dbh) of all trees rooted within each plot of each transect (Table 2.1). Plot size for tree measurements was 314 $m^2$ (10 m radius) for trees > 5 cm dbh and a nested plot with a radius of 2 m (12.6 $m^2$) for trees with a dbh of < 5 cm. The diameter of trees with prop roots was measured at the main branch, about 20 cm above the highest prop root.

*Insert Table 2.1*

I used allometric equations to calculate tree biomass, and examined several equations developed specifically for peat swamp forests (Table 2.2). I used as much as possible locally-derived equations, which represented the dbh range of the trees in this study and had a sufficient sample size to create an accurate equation for  biomass estimation. The allometric equation presented by Manuri et al. (2014) was developed in Sumatera and Borneo Islands for peat swamp trees that were 2–167 cm dbh. Belowground root biomass for forest trees was calculated using the formula provided by Mokany et al. (2006). Tree carbon content (C) was calculated from biomass by multiplying by a factor of 0.47 for aboveground and belowground biomass (Murdiyarso et al., 2009; Kauffman and Donato 2012).

*Insert Table 2.2*

I included dead trees in aboveground biomass measurement and calculations. Each dead tree was measured for dbh and assigned to one of three decay classes: Status 1-recently dead trees without leaves but with fine branches; Status 2-dead trees without secondary branches; and Status 3-dead trees without primary or secondary branches (Kauffman and Donato 2012). The biomass of trees of Status 1 and 2 was calculated as the biomass of a living tree (using allometric equation) but reduced with conversion factor of 0.9 and 0.8, respectively. The biomass of trees of Status 3 was calculated as the biomass of the main stem only using their dbh and height data.

**Understory and litterfall**

In each of the six plots I harvested all aboveground understory plants and litter biomass in two 1,444 $cm^2$ microplots (38 x 38 cm rectangular plots). These microplots were established on two of the woody debris transects at a distance of 10 m from the plot center (next section). These samples were placed in a plastic bag and transported back to the laboratory where they were dried to a constant mass for dry-weight biomass determination.

**Woody debris**

Woody debris is defined as any dead wood (twigs, branches or stems of trees or shrubs) that has fallen (Murdiyarso et al., 2009). Dead branches and stems still attached to standing trees or shrubs were excluded. Wood mass was determined using the planar intersect technique (Van Wagner, 1968; Harmon et al., 1996), adapted for peatlands and mangroves (Murdiyarso et al., 2009; Kauffman and Donato 2012; Kauffman et al., 2016). A 14 m tape was established from the plot center to 4 directions, oriented at 45° angles from the main transect line. Wood intersecting the transect plane was measured. Leaning snags that form an angle of > 45° from true vertical were also included as dead wood (Murdiyarso et al. 2009). The piece must be in or above the peat layer to be included; it was not included if its central axis was beneath the soil surface at the point of intersection (Murdiyarso et al., 2009). Uprooted stumps and roots were also measured (Van Wagner, 1968).

This method involves counting intersections of woody pieces along a vertical sampling plane (Donato et al., 2013). Coarse woody debris (CWD) was defined as pieces ≥ 7.6 cm in diameter. For CWD I measured diameter and decay status (sound or rotten) at the point of intersection. Wood was classified as sound if a machete bounced off or only slightly sank when struck. CWD was classified as rotten wood if striking with a machete would deeply penetrate or cause the wood to crumble (Kauffman & Donato, 2012). Transects for this size class were 12 m, from 2 to 14 m on the transect. Fine woody debris (FWD; pieces ≥ 2.5 cm and < 7.6 cm in diameter) were sampled along 5 m subsections of each transect line starting from the 2 m to the 7 m along the transect.

To determine bulk density of wood, a collection of 20 pieces of each down wood class was made. The water displacement method was used for measurements of wood volume (Chave et al., 2006). A container was filled with water and placed on a digital balance. The wood piece was then carefully forced underwater, such that it did not contact the sides or bottom of the container. The measured mass of displaced water is equal to the volume of the wood (water density of 1 g $cm^{-3}$). Each piece was measured for volume and oven-dried to obtain dry mass; these values were then used to compute wood density. Woody debris was converted to C using factor of 0.47 (Murdiyarso et al., 2009b; Kauffman & Donato, 2012).

**Peat**

Three measurements were necessary to obtain total peat organic carbon: peat depth (to obtain soil volume per area), bulk density (to obtain soil mass per area) and percent organic carbon (OC) (to convert mass per area to C per area). Total peat depth was measured at each of the 6 plot centers.

Soil samples were collected with a Russian peat auger. This sampler is efficient for collecting relatively undisturbed cores from peats in peatlands (Warren et al., 2012). The core was systematically divided into depth intervals of 0–15, 15–30, 30–50, 50–100, 100-300, 300-600 and >600 cm (if parent materials or mineral soils were not encountered before 600 cm depth). Volume of subsamples collected for analysis were 67.7 $cm^3$ for a 5 cm slice (Kauffman et al., 2016). Typically the soil sample for each depth interval was taken from just above the mid-point of each depth interval, but it will be applied flexibly in order to obtain a good, representative and undisturbed sample.

Soil samples were brought to the laboratory in plastic containers, and then processed using a drying oven at 60°C to determine bulk density (Murdiyarso et al., 2009). A Leco analyzer (Truspect CHNS) were used to measure C and N concentration, located at Bogor Agricultural University, Indonesia (Murdiyarso et al., 2009)

Differences among peat properties, biomass, and carbon stocks between forest types were tested with t-test, when the data is normally distributed. Mann-Whitney U test was used for non-normally distributed data.

## RESULTS

### Plant biomass and carbon stocks

Logging affected tree density. Tree densities were 1,743 and 1,355 trees $ha^{-1}$, for intact and logged forests ($p = 0.002$). Highest tree densities were found on PSF1 and PSF2 with 1,906 trees $ha^{-1}$, while the lowest density was 1,125 trees $ha^{-1}$ in the LPSF3 site (Table 2.1).

Logging also reduced basal area of the forests ($p=0.001$). The highest basal area was in the PSF2 with 33.1 $m^2$ $ha^{-1}$, while the lowest basal area was 15.1 $m^2$ $ha^{-1}$ in the LPSF4 site. Mean basal area of intact forests (31.4 $m^2$ $ha^{-1}$) was significantly higher than logged forests, i.e., 18.7 $m^2$ $ha^{-1}$.

Trees' diameter of intact forests was bigger than those in logged forests ($p = 0.03$). Mean diameter of trees in intact forests was 11.8 cm and in logged forests was 10.6. Maximum diameter of trees in intact forests was 75.9 cm (5 – 75.9 cm) and in logged forests was 72.8 cm (5 – 72.8 cm). Diameter of trees in PSF ranged from 10.6 to 12.1 cm and in LPSF ranged from 9.73 to 11.7 cm (Table 2.3). Many of the larger trees had been harvested from logged forests sites.

*Insert Table 2.3*

Mean diameter of dead tress was similar between that in intact forests that ranges from 11.06 to 12.14 cm (mean 13.13 cm) and that in logged forests, which ranges from 9.17 to 15.89 cm (mean 11.24 cm). Maximum diameter of dead trees measured in intact forests was 65.5 cm (5 – 65.5 cm). In logged forests the maximum diameter was 59.9 cm (5 – 59.9 cm).

Wood density of coarse (rotten) woody debris in intact forests ranged from 0.37 to 0.45 g $cm^{-3}$ and was higher than in logged forests that ranges from 0.21 to 0.42 g $cm^{-3}$ ($p = 0.01$; Table 2.4). Wood density of fine woody debris in intact forests ranged from 0.39 to 0.54 g $cm^{-3}$ and was higher than in logged forest ranging from 0.28 to 0.39 g $cm^{-3}$ ($p = 0.008$).

*Insert Table 2.4*

Aboveground biomass comprised of trees, woody debris and litter. Aboveground tree biomass in intact forests ranged from 176 to 244 Mg $ha^{-1}$. In contrast the tree mass in logged forest ranged from 92 to 162 Mg ha$^{-1}$ (Table 2.5). Aboveground tree biomass of the intact forests (206 Mg ha$^{-1}$) and logged forests (126 Mg ha$^{-1}$) were significantly different (p = 0.01).

*Insert Table 2.5*

Tree C was significantly greater in intact compared to logged forest (p = 0.005). Mean tree C mass was 96 Mg ha$^{-1}$. Woody debris C in intact forests ranged from 19 to 37 Mg ha$^{-1}$, higher than that in logged forests (6 to 20 Mg ha$^{-1}$; p = 0.003). Mean understorey and litter C in intact forests ranged from 4.63 to 9.8 Mg/ha and was similar to those in LPSF that ranges from 2.86 to 6.38 Mg ha$^{-1}$ (p = 0.06).

Root biomass in intact forests ranged from 52 to 65 Mg ha$^{-1}$. This exceed that of logged forest (27 to 45 Mg ha$^{-1}$; p = 0.01). On the other hand, root C mass in PSF ranges from 24 to 30 Mg ha$^{-1}$. This was also higher than that in logged forests (12 to 20 Mg C ha$^{-1}$; p = 0.005).

In both intact and degraded forests, there was high variation in the total aboveground carbon pools between the different sampled sites (Figure 2.2). Aboveground carbon pools ranged from 122 to 170 Mg C ha$^{-1}$ in the intact forests sites, while in logged forests it ranged from 70 to 109 Mg C ha$^{-1}$. Intact forest sites had higher (p = 0.001) total aboveground carbon pools (mean = 151 Mg C ha$^{-1}$) than the logged forests sites (mean = 93 Mg C ha$^{-1}$). Logging had significantly reduced aboveground carbon stocks of the peat swamp forests.

*Insert Figure 2.2*

**Peat carbon stocks and properties**

Mean peat depths were different between the logged and intact sites (p = 0.001; Table 2.1). The deepest one was found in the PSF2 with a mean depth to the parent material of 953 cm. The other three sampled of intact forests had depths ranging from 841 to 945 cm. The mean depth of the logged forest was 725 cm, lower than that of the intact forest (915 cm; p = 0.01).

At all depth, BD in PSF is significantly lower than in LPSF (t-test, $p < 0.05$), except at depth 4 and 5 (50–300 cm; Figure 2.3a).

*Insert Figure 2.3*

Carbon concentration (C; %), at 0-15 cm) ranged from 53.6 to 58.5 in PSF (Table 2.6). This was lower than in LPSF that ranged from 57.1 to 58.7 ($p=0.01$; Figure 2.3b). At depth 2 (15-30 cm) C in intact forests was lower than in logged forests ($p=0.03$). In contrast, at depth 7 (600-900 cm) C in intact forests was significantly higher than in logged forests ($p=0.008$). Moreover, C concentration in the soils of this study were quite high (up to 68.5%), which appears to be the highest soil carbon concentration ever recorded.

*Insert Table 2.6*

Nitrogen concentration (N; %) in PSF is lower than in LPSF all through the peat profile (t-test, $p<0.1$), except at depth 6 and 7 (>300 cm). On the other hand, carbon to nitrogen ratio (C/N) in PSF is higher than in LPSF only at most of the first meter depth (t-test, $p<0.1$), except at depth 2 (15-30 cm; Figure 2.4).

*Insert Figure 2.4*

At depth 1 (0-15 cm), 3 (30-50 cm) and 6 (300-600 cm) carbon density (CD; g $cm^{-3}$) ranges in intact forest was lower than in logged forests ($p < 0.05$). CD was similar in other layers of depth between intact and logged forests.

As expected, similar to CD distribution along soil profile, carbon stock (C stock; Mg $ha^{-1}$), at depth 1 (0-15 cm), 3 (30-50 cm) and 6 (300-600 cm) was lower in intact forest than in logged forests ($p < 0.05$).

Carbon concentration and bulk density were not correlated in peat's layer of 0 – 15 cm ($r^2 = 0.08$). In contrast, significant correlation ($r^2 = 0.8$) were found in the layer below 3 m (Figure 2.5a and 2.5b). Further analyses show that this discrepancy was found mostly in LPSF (Figure 2.5b). The soil carbon and bulk density were higher on logged forests than intact forests at surface (0 – 30 cm) and at the deeper soil layer (3 – 6 m; $p < 0.05$).

*Insert Figure 2.5*

The total soil carbon stock varied greatly within and between the intact and logged forests (e.g., from 3,650 Mg C $ha^{-1}$ at PSF2 site to 5,442 Mg C $ha^{-1}$ at the PSF1 site and from 3,390 Mg C $ha^{-1}$ at LPSF1 to 4,047 Mg C $ha^{-1}$ at LPSF5). Mean peat carbon stocks in intact forests (4,243 Mg C $ha^{-1}$) was significantly higher than logged forests (3,675 Mg C $ha^{-1}$; $p = 0.07$).

**Total ecosystem carbon stocks**

The total ecosystem C stocks is the combination of tree (aboveground and belowground), down wood, litter and peat C pools. Intact forests has significantly higher C stocks (4,401 Mg $ha^{-1}$) than in logged forests (3,768 Mg $ha^{-1}$; $p = 0.07$). Stocks in intact forests sites varied greatly from 3,801 Mg C $ha^{-1}$ at the PSF2 site to 5,591 Mg C $ha^{-1}$ at the PSF1 site (Figure 2.6). The total ecosystem stocks for LPSF sites varied from 3,496 Mg C $ha^{-1}$ at the LPSF1 site to a maximum of 4,148 Mg C $ha^{-1}$ at the LPSF5 site. Both sites' soils comprise > 96% of the total ecosystem carbon stock.

*Insert Figure 2.6*

**DISCUSSION**

It was estimated that the mean peat C stock of peat swamp forests in Indonesia to be about 2,772 Mg C $ha^{-1}$ (Page *et al.*, 2011). The PSF soil carbon stocks in this study ranged from 3,650 to 5,442 Mg C $ha^{-1}$ with a mean of 4,243 Mg C $ha^{-1}$, which is 153% greater than the global mean suggested by Page (2011). Yet, my value is also higher than the estimated value of carbon stocks from Siak Kanan which was 3,800 Mg C $ha^{-1}$ (Dommain *et al.*, 2014). Other studies from peat swamp forest in Riau, Sumatera island (Istomo, 2006; Suwarna *et al.*, 2012) and in Tanjung Puting, Kalimantan island (Murdiyarso *et al.*, 2009) reported lower values, i.e., 3,500, 2,000 and 1,500 Mg C $ha^{-1}$, respectively.

Soil carbon stocks of the forests sampled in this study area are the highest of those reported from tropical coastal peat swamp forests (Istomo, 2006; Page *et al.*, 2011a; Suwarna *et* *al.*, 2012). This is because the deeper peat depth (915 cm) and incredibly high C concentration.

Not surprisingly, the ecosystem carbon stocks of forests of this study are the highest carbon stocks among terrestrial ecosystems that I could find in the literature (Figure 2.7). Tropical coastal peat swamp forest is among largest total carbon storage (4,401 Mg C $ha^{-1}$) of terrestrial ecosystems on earth, e.g., more than 10 to 17 times higher than carbon stocks in tropical forests on mineral soils (IPCC, 2006). Peat forests of this study had 4 and 3 times more of ecosystem C stocks than Mangrove forests and Boreal peatlands respectively (Weishampel *et al.*, 2009; Donato *et al.*, 2012; Murdiyarso *et al.*, 2015). It is even had 2 times more of C stocks than the world's most carbon-densed ecosystem (Keith *et al.*, 2009), i.e. the Australian temperate moist Eucalyptus regnans forests (1,867 Mg C $ha^{-1}$).

*Insert Figure 2.7*

Peat carbon concentration in the soils of this study were quite high (Table 2.6; mean ranges from 14.5 to 63.6%), and recorded a maximum value at 68.5%, which appears to be the highest soil carbon concentration ever recorded from tropical peat swamp forests (Page *et al.*, 2011; Warren *et al.*, 2012). I am confident that the value was accurate because I found a good match between soil carbon concentration measured in Indonesian laboratory and in US laboratory.

Similar to other studies (Istomo, 2006; Suwarna *et al.*, 2012), I observed that the disturbed forest sites had significantly less tree- aboveground and belowground biomass and carbon pools than those in intact forest. Similarly, there was significantly less soil carbon stock in logged forests than that of intact forests (3,675 and 4,243 Mg C $ha^{-1}$, respectively). I also found significant differences ($p = 0.07$) in the total ecosystem carbon stocks (4,401 and 3,768 Mg C $ha^{-1}$, respectively). Logging had direct impacts on reducing the biomass of trees and the peat carbon pools. Logging will likely reduce the ecosystem's capacity in sequestering atmospheric carbon into the peat carbon pools. It will decrease the photosynthesis process in logged forests, thus limiting biomass and peat accumulation mechanism through increased mineralization (Brady, 1997; Page *et al.*, 2011). On the other hand, draining likely accelerated peat decomposition process through the lowering groundwater table. Lower water table created aerobic zone for oxidation process of peat by microbes, thus reducing soil carbon stock of logged.

Warren et al. (2012) suggested that a model of carbon density as function of BD data can help for a rapid estimation of soil C stocks for well-developed peat soils. They suggested that it may overcome the hurdle of an expensive and often not available instruments for measurement of accurate C concentration in many developing countries. But I found that the model cannot reliably predict C concentration when all areas have the high C ranges in concentration and ranges in low bulk densities as found in this study.

Some reports suggest that bulk density (BD) is unpredictably variable through the peat profile (Kool *et al.*, 2006; Page *et al.*, 2011). This was not the case in my sites. In PSF soil bulk density varied little throughout the profile. Further changes in BD in the logged forests were similar throughout the sampled areas (Figure 2.5b)

I found negative correlation between carbon concentration and bulk density ($r^2 = 0.8$) in the layer below 3 m of LPSF (Figure 2.5b). Soil carbon density and bulk density were higher on LPSF than PSF at surface (0 – 30 cm) and at the deeper soil layer (3 – 6 m; $p < 0.05$). This may suggest that compaction and consolidation have occurred at those two layers. In the middle layer there was no compaction. This raised an insightful question about how degradation had impacted the BD and C in the deeper layer of peat swamp forests soils.

One may argue that my approach faces uncertainties of peat depth variations in comparing the total ecosystem carbon stocks between forest types (Hergoualc'h & Verchot, 2011). But as I demonstrated in this study that with careful sampling design and knowledge about peat depth distribution it is possible to limit these uncertainties of peat depth. Uncertainties in carbon losses and shifts due to logging may also be related to the highly varied ecosystem peat carbon stocks in my samples (3,650 to 5,442 Mg C $ha^{-1}$).

My study demonstrated that tropical coastal peat swamp forests has the largest total carbon stocks among terrestrial ecosystems in the world. It has significantly higher soil carbon stocks than previously reported for PSF and this is due to the very deep peats in this region. Logging significantly reduced above- and belowground C stocks, soil carbon stock and concentration, and nitrogen concentration, while an increases on soil bulk density were found in the deeper layers. In a world where millions of people are threatened by intensified extreme events and crisis of food and arable land due to global warming (Stern, 2013; IPCC, 2014), the degradation and loss of PSF's huge carbon stocks can significantly amplify the warming trend. The large carbon stocks, high rates of degradation, and the potential for high greenhouse gas emissions following logging points to the relevance for inclusion of PSF in nationally appropriate climate change mitigation and adaptation strategies.

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**Figures**

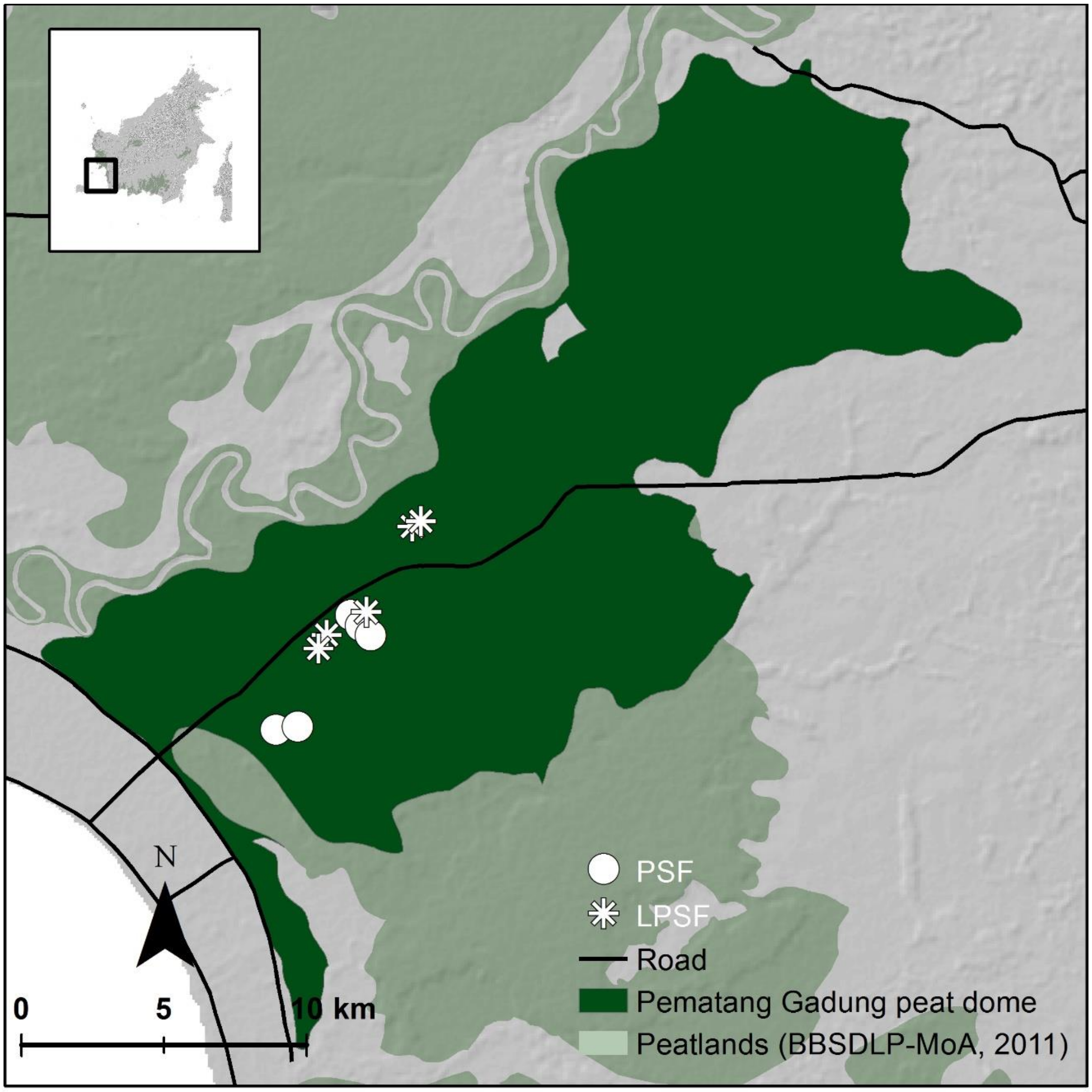



Figure 2.1. Plot locations (9 sites) within the study area, Pematang Gadung peat dome, Ketapang, West Kalimantan, Indonesia. Peat dome area (dark green) was delineated by BDSLDP - MoA (2011). White symbols represent the sample sites. Black line represents road. White areas represent the sea (Karimata Straits), light green areas represent the peatland areas. Grey areas represent the non-peat areas.

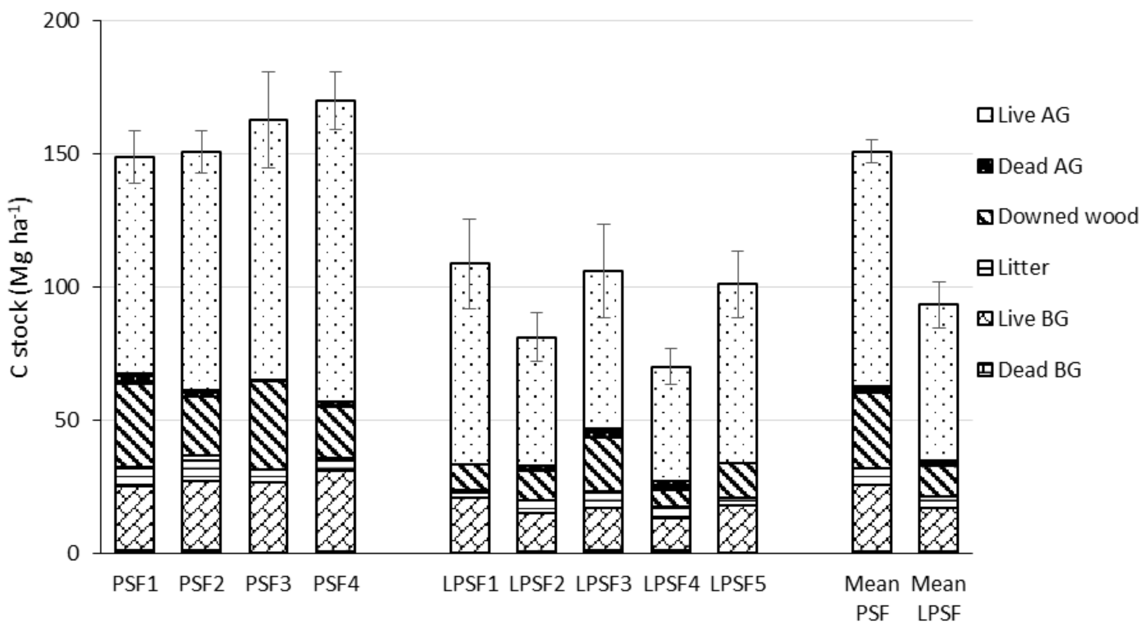
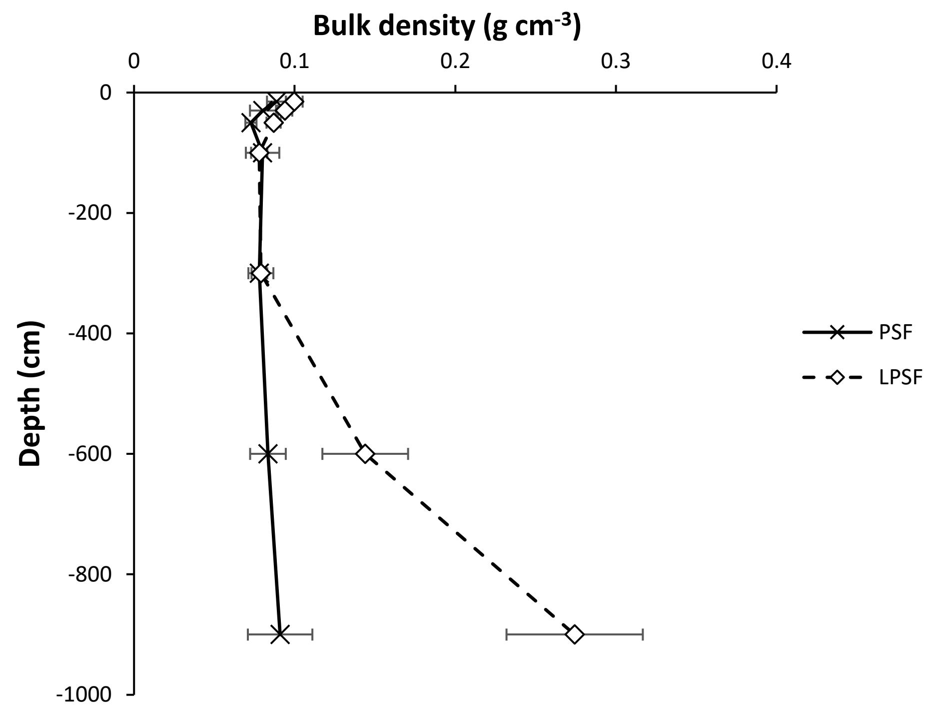
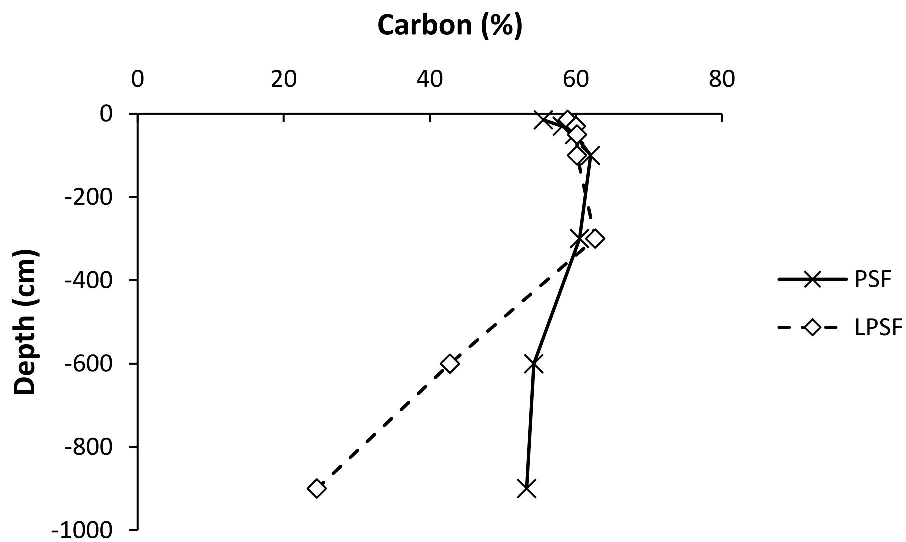



Figure 2.2. The total plant carbon stocks (Mg C ha$^{-1}$) of peat swamp forests (PSF), and logged PSF (LPSF) at the Pematang Gadung peat dome, Ketapang, Indonesia. Vertical bars are one standard error. AG represents aboveground; BG represents belowground.

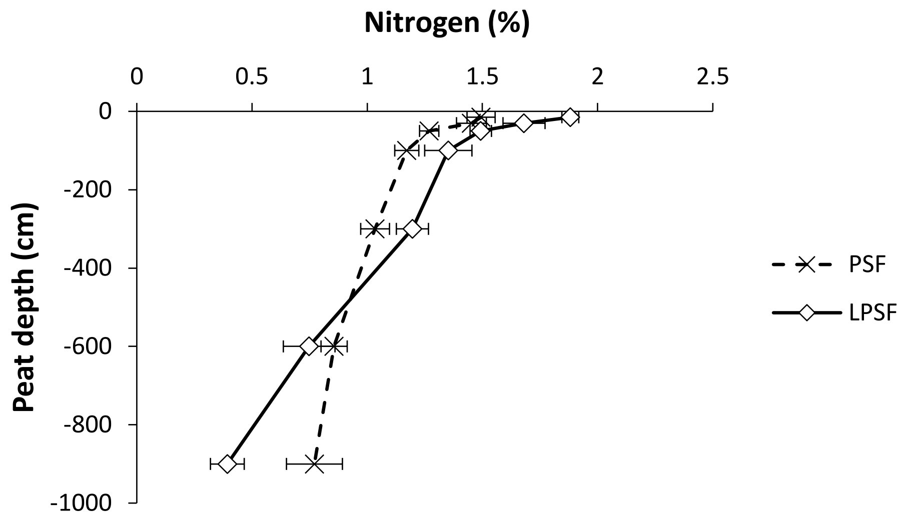



a)

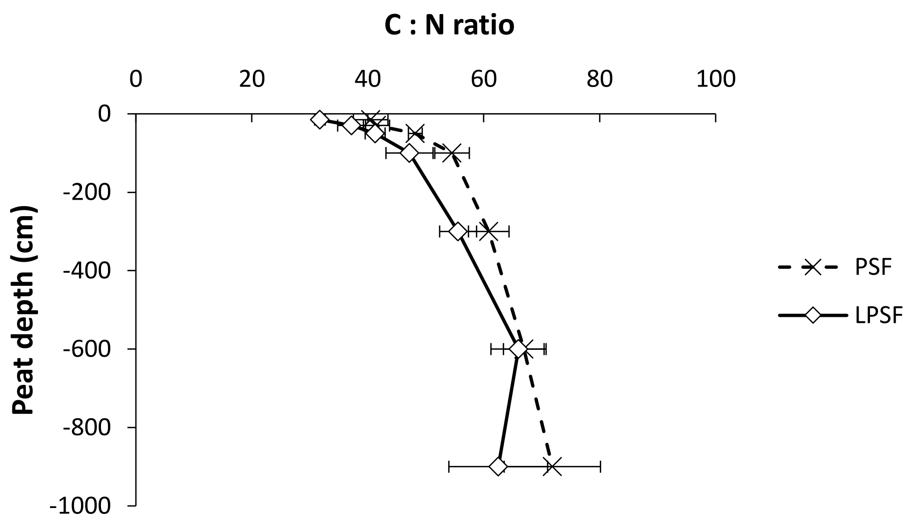



b)

Figure 2.3. Bulk density (BD) and carbon concentration (C) of PSF and LPSF along peat depth. (a) BD of LPSF is increasing sharply after 3 m depth, while (b) C is decreasing. Horizontal bars are one standard error.




a)




b)

Figure 2.4. Nitrogen (%) and carbon to nitrogen ratio (C : N ratio) of PSF and LPSF along the peat profile depth. Horizontal bars are one standard error.

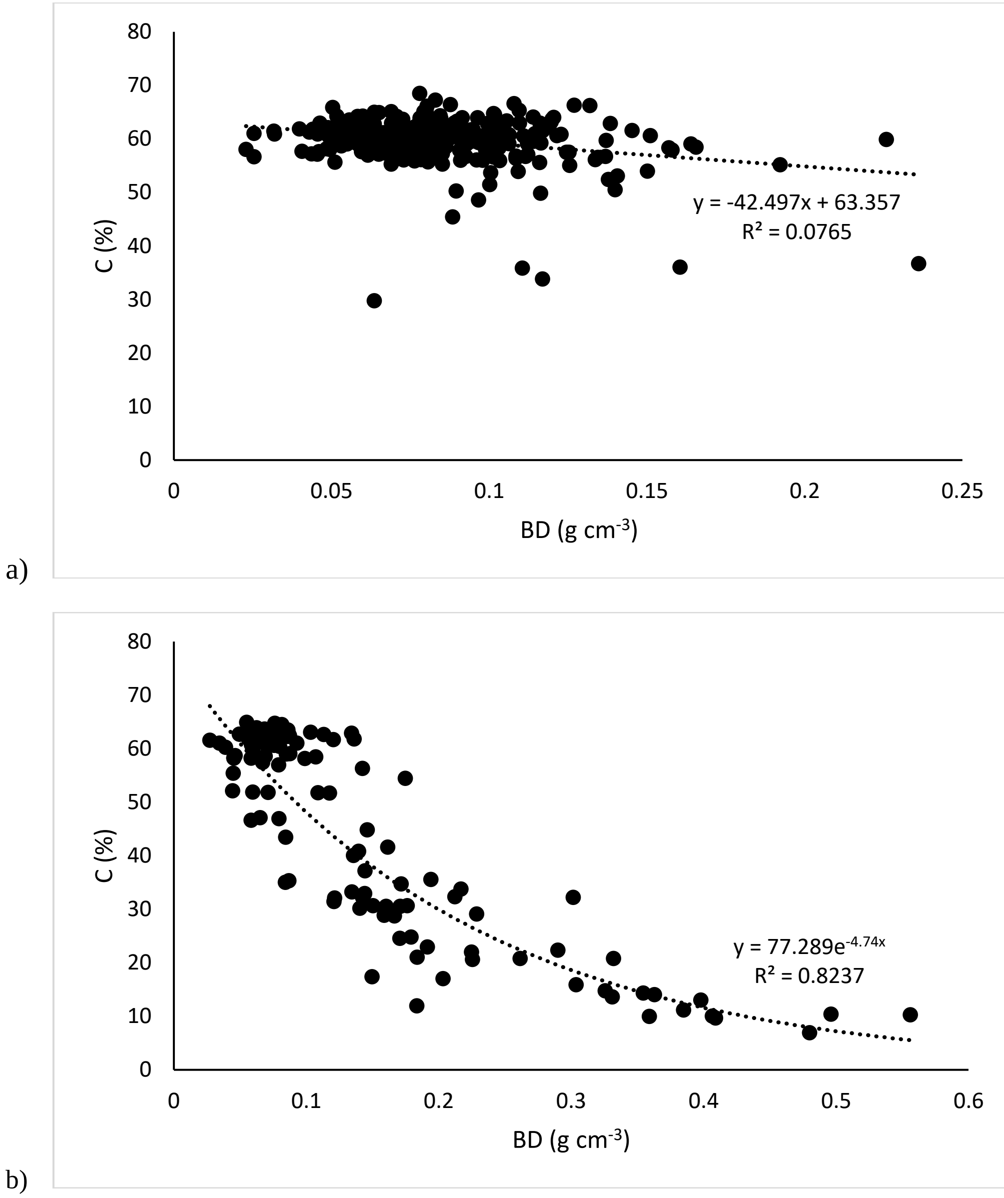



Figure 2.5. Correlation between carbon concentration (%) and bulk density (g $cm^{-3}$) of soil at different depths in 54 forest sites: (a) 0 – 3 m and (b) > 3 m. At peat depth > 3m carbon content (%) is significantly correlated ($r^2$ = 0.8) with bulk density (g $cm^{-3}$).

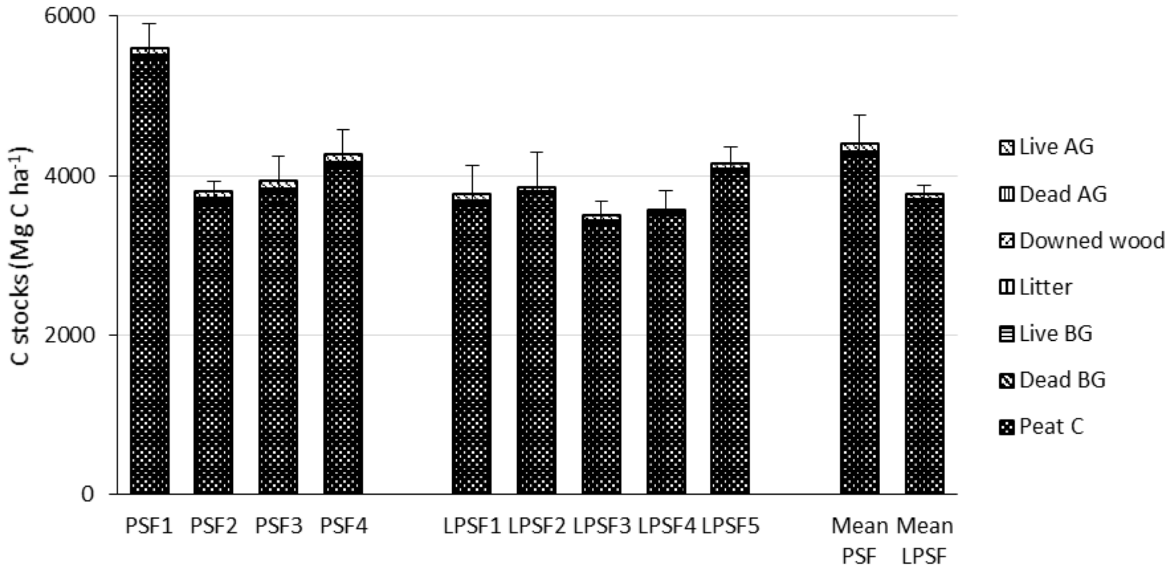



Figure 2.6. The total ecosystem carbon stocks (Mg C ha$^{-1}$) of peat swamp forests (PSF), and logged PSF (LPSF) at the Pematang Gadung peat dome, Ketapang, Indonesia. Vertical bars are one standard error.

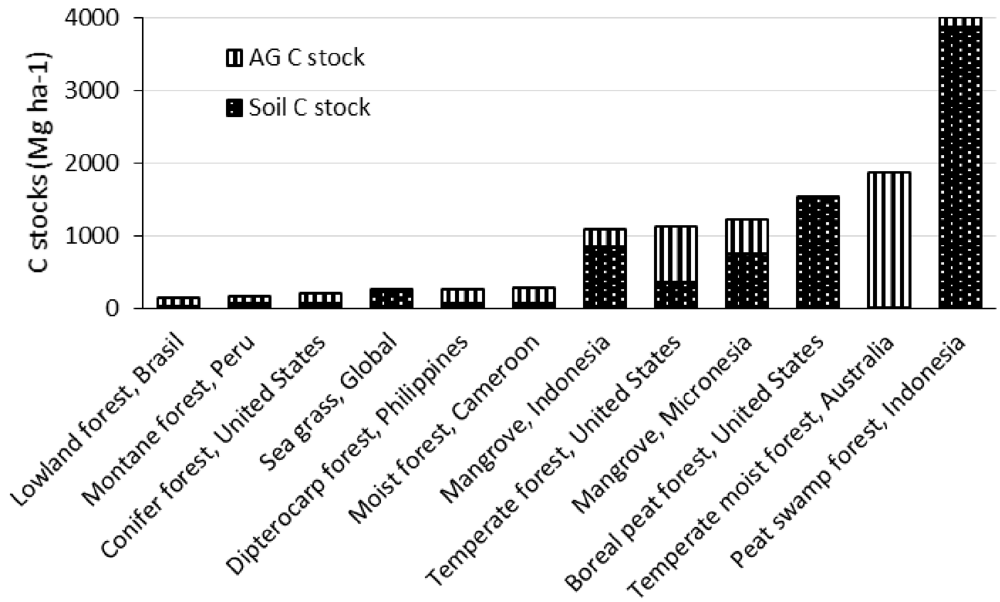



Figure 2.7. Ecosystem carbon stocks of selected forests of the world. Tropical Peat Swamp Forests have the highest carbon stocks among global terrestrial ecosystems. Data for lowland forest, Brazil, are from (Johnson *et al.*, 2001). Montane forest, Peru, is from (Roman-Cuesta *et al.*, 2011). Conifer forest, United States, is from (Weishampel *et al.*, 2009). Sea grass, global, is from (Fourqurean *et al.*, 2012). Dipterocarp forest, Philippine, is from (Lasco *et al.*, 2006). Moist forest, Cameroon, is from (Djomo *et al.*, 2011). Mangrove, Indonesia, is from (Murdiyarso *et al.*, 2015). Temperate forest, United States is from (Smithwick, 2002). Mangrove, Micronesia, is from (Donato *et al.*, 2012). Boreal peat forest, United States, is from (Weishampel *et al.*, 2009). Peat swamp forest, Indonesia, is from this study.

# Tables

Table 2.1. Characteristics of sampling locations within the Pematang Gadung peat dome, Ketapang, Indonesia.

| **Site** | **Date** | **Latitude** | **Longitude** | **Peat depth (cm)** | **Tree density (tree $ha^{-1}$)** | **Tree Basal Area ($m^2$ $ha^{-1}$)** | **Transect Direction from North** |
|---|---|---|---|---|---|---|---|
| PSF1 | 8/31/2013 | -1.899 | 110.128 | 945 ± 18 | 1906 ± 185 | 28.7 ± 3.2 | 310 |
| PSF2 | 8/31/2013 | -1.898 | 110.135 | 953 ± 24 | 1906 ± 97 | 33.1 ± 2.6 | 310 |
| PSF3 | 9/3/2013 | -1.867 | 110.155 | 922 ± 40 | 1523 ± 91 | 31.6 ± 2.6 | 90 |
| PSF4 | 9/4/2013 | -1.870 | 110.158 | 841 ± 10 | 1635 ± 62 | 32.3 ± 2.7 | 180 |
| **Mean PSF** | | | | **915 ± 25** | **1743 ± 97** | **30.8 ± 2.8** | |
| LPSF1 | 10/10/2013 | -1.862 | 110.157 | 793 ± 41 | 1226 ± 165 | 18 ± 2.7 | 210 |
| LPSF2 | 10/11/2013 | -1.869 | 110.144 | 660 ± 4 | 1348 ± 112 | 17.8 ± 3.2 | 210 |
| LPSF3 | 9/7/2013 | -1.874 | 110.141 | 748 ± 21 | 1125 ± 147 | 22 ± 3.1 | 90 |
| LPSF4 | 10/12/2013 | -1.835 | 110.171 | 683 ± 20 | 1359 ± 204 | 15.1 ± 2 | 220 |
| LPSF5 | 10/13/2013 | -1.833 | 110.174 | 743 ± 17 | 1354 ± 104 | 20.5 ± 3.1 | 85 |
| **Mean LPSF** | | | | **725 ± 24[*]** | **1282 ± 47[**]** | **18.7 ± 2.8[**]** | |

[*] the mean value is significantly different with the PSF at $p < 0.1$

[**] the mean value is significantly different with the PSF at $p < 0.05$

Table 2.2. Measurement data used in referenced equations.

| Data | Equation | Reference | Result |
|---|---|---|---|
| Tree dbh (cm) | $0.136*(\text{tree dbh})^{2.51}$ | Manuri et al. 2014. | Tree biomass |
| Tree biomass (kg) | 0.489*(tree biomass^0.89) | Mokany et al. 2006. | Tree root biomass |
| Snag height/h and dbh (cm); Wood density/WD ($g/cm^3$) | 0.8*WD*(h*(0.314*( dbh/2)^2)) | Murdiyarso et al. 2009. | Snag biomass |

Table 2.3. Diameter distribution of tree and snag in different forest sites.Trees of PSF are bigger than those in LPSF (t-test, p = 0.03).

| | Diameter (cm) | | | | | |
|---|---|---|---|---|---|---|
| | Tree | | | Snag | | |
| **Site** | **Mean ± SE** | **Min** | **Max** | **Mean ± SE** | **Min** | **Max** |
| **PSF1** | 11.06 ± 2.4 | 5 | 42.7 | 11.88 ± 2.37 | 5 | 28.5 |
| **PSF2** | 11.73 ± 2.45 | 5 | 40.5 | 12.76 ± 3.28 | 5 | 41 |
| **PSF3** | 12.14 ± 3.27 | 5 | 55.9 | 13.21 ± 3.65 | 5.1 | 45.6 |
| **PSF4** | 12.07 ± 3.4 | 5 | 75.9 | 11.63 ± 3.77 | 5.1 | 65.5 |
| **Mean PSF** | **11.51 ± 2.78** | **5** | **75.9** | **13.08 ± 4.25** | **5** | **80** |
| **LPSF1** | 10.43 ± 3.14 | 5 | 72.8 | 10.35 ± 3.01 | 5 | 41.8 |
| **LPSF2** | 10.68 ± 2.31 | 5 | 31.3 | 13.24 ± 3.96 | 5.6 | 44.7 |
| **LPSF3** | 11.7 ± 3.02 | 5 | 52.8 | 9.17 ± 2.04 | 5 | 33 |
| **LPSF4** | 9.73 ± 2.19 | 5 | 45.8 | 10.63 ± 2.77 | 5 | 41.6 |
| **LPSF5** | 10.62 ± 3 | 5 | 63.5 | 15.89 ± 5.81 | 5.4 | 59.9 |
| **Mean LPSF** | **10.64 ± 2.76**** | **5** | **72.8** | **11.24 ± 3.74** | **5** | **59.9** |

* the mean value is significantly different with the PSF at p < 0.1

** the mean value is significantly different with the PSF at p < 0.05

Table 2.4. Composition of wood density (by size and quality) and carbon (by size) of woody debris in the intact and logged over forest sites. Wood density and carbon stocks reported as mean ± SE. Wood density and carbon stocks of woody debris in PSF sites are higher than in LPSF (t-test, p < 0.05).

| | --------- Wood density ($g\ cm^{-3}$)-------- | | | --------- Carbon stocks ($Mg\ ha^{-1}$) -------- | | |
|---|---|---|---|---|---|---|
| **Site** | **Fine** | **Coarse - Sound** | **Coarse - Rotten** | **Fine** | **Coarse** | **Total** |
| PSF1 | 0.54 ± 0.04 | 0.53 ± 0.09 | 0.45 ± 0.10 | 24.10 ± 3.90 | 6.90 ± 2.10 | 31.00 ± 5.30 |
| PSF2 | 0.51 ± 0.05 | 0.48 ± 0.05 | 0.44 ± 0.08 | 12.60 ± 3.10 | 9.60 ± 1.80 | 22.20 ± 3.80 |
| PSF3 | 0.39 ± 0.02 | 0.51 ± 0.01 | 0.37 ± 0.03 | 13.70 ± 2.80 | 19.30 ± 3.30 | 33.10 ± 4.40 |
| PSF4 | 0.41 ± 0.06 | 0.68 ± 0.05 | 0.40 ± 0.05 | 8.30 ± 3.00 | 10.70 ± 6.50 | 19.00 ± 8.50 |
| **Mean PSF** | **0.46 ± 0.06** | **0.55 ± 0.07** | **0.42 ± 0.08** | **14.70 ± 4.70** | **11.60 ± 5.00** | **26.30 ± 7.30** |
| LPSF1 | 0.39 ± 0.07 | 0.55 ± 0.06 | 0.42 ± 0.04 | 8.60 ± 3.40 | 11.90 ± 3.30 | 20.40 ± 3.40 |
| LPSF2 | 0.28 ± 0.02 | 0.50 ± 0.16 | 0.26 ± 0.03 | 5.00 ± 1.20 | 5.60 ± 1.00 | 10.70 ± 1.20 |
| LPSF3 | 0.33 ± 0.02 | 0.59 ± 0.10 | 0.21 ± 0.02 | 3.70 ± 1.40 | 5.70 ± 3.10 | 9.40 ± 3.80 |
| LPSF4 | 0.29 ± 0.03 | 0.33 ± 0.03 | 0.24 ± 0.02 | 3.20 ± 1.20 | 3.20 ± 0.70 | 6.40 ± 1.30 |
| LPSF5 | 0.29 ± 0.05 | 0.40 ± 0.04 | 0.26 ± 0.05 | 4.20 ± 1.50 | 9.00 ± 2.60 | 13.10 ± 2.80 |
| **Mean LPSF** | **0.32 ± 0.02**** | **0.46 ± 0.04** | **0.28 ± 0.02**** | **4.93 ± 0.96**** | **7.07 ± 1.52**** | **12.00 ± 2.36**** |

* the mean value is significantly different with the PSF at p < 0.1

** the mean value is significantly different with the PSF at p < 0.05

Table 2.5. Plant related biomass and carbon stocks (Mg C $ha^{-1}$) in PSF and LPSF sites. Biomass and carbon stocks reported as mean ± SE. Total aboveground carbon stocks in PSF is higher than in LPSF (t-test, $p < 0.05$).

| Site name | Live AG tree biomass | Dead AG tree biomass | Live BG tree biomass | Dead BG tree biomass | Live AG tree C | Dead AG tree C | Live BG tree C | Dead BG tree C | Downed wood C | Litter C | Total AG C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **PSF1** | 176.24 ± 22.08 | 8.15 ± 2.65 | 52.04 ± 6.15 | 2.33 ± 0.64 | 81.78 ± 10.25 | 3.78 ± 1.23 | 24.15 ± 2.85 | 1.08 ± 0.3 | 31 ± 5.32 | 7.22 ± 0.96 | 149 ± 12.48 |
| **PSF2** | 192.94 ± 18.33 | 5.41 ± 1.79 | 56.2 ± 4.26 | 1.68 ± 0.53 | 89.52 ± 8.51 | 2.51 ± 0.83 | 26.07 ± 1.98 | 0.78 ± 0.24 | 22.25 ± 3.79 | 9.8 ± 1.69 | 150.94 ± 9.95 |
| **PSF3** | 210.88 ± 33.51 | 1.51 ± 0.53 | 56.45 ± 7.06 | 0.52 ± 0.17 | 97.85 ± 15.55 | 0.7 ± 0.25 | 26.2 ± 3.27 | 0.24 ± 0.08 | 33.09 ± 4.37 | 4.84 ± 0.55 | 162.91 ± 21.13 |
| **PSF4** | 243.63 ± 23.29 | 4.93 ± 2.52 | 65.49 ± 4.24 | 1.43 ± 0.62 | 113.04 ± 10.81 | 2.29 ± 1.17 | 30.39 ± 1.97 | 0.66 ± 0.29 | 19.02 ± 8.49 | 4.63 ± 0.54 | 170.03 ± 11.83 |
| **Mean PSF** | **176.24 ± 22.08** | **8.15 ± 2.65** | **52.04 ± 6.15** | **2.33 ± 0.64** | **81.78 ± 10.25** | **3.78 ± 1.23** | **24.15 ± 2.85** | **1.08 ± 0.3** | **31 ± 5.32** | **7.22 ± 0.96** | **149 ± 12.48** |
| **LPSF1** | 162.46 ± 29.51 | 0.62 ± 0.19 | 75.38 ± 13.69 | 0.24 ± 0.07 | 44.63 ± 6.75 | 0.29 ± 0.09 | 20.71 ± 3.13 | 0.11 ± 0.03 | 9.35 ± 3.76 | 2.95 ± 0.41 | 105.99 ± 20.88 |
| **LPSF2** | 104.3 ± 19.39 | 4.4 ± 4.13 | 48.4 ± 9 | 1.18 ± 1.07 | 31.31 ± 5.55 | 2.04 ± 1.92 | 14.53 ± 2.58 | 0.55 ± 0.5 | 10.66 ± 1.16 | 4.88 ± 0.51 | 81.06 ± 11.76 |
| **LPSF3** | 128.1 ± 34.46 | 6.42 ± 3.01 | 59.44 ± 15.99 | 1.74 ± 0.79 | 34.41 ± 6.95 | 2.98 ± 1.4 | 15.97 ± 3.22 | 0.81 ± 0.37 | 20.42 ± 3.35 | 6.38 ± 1.08 | 108.8 ± 19.9 |
| **LPSF4** | 92.42 ± 17.51 | 7.13 ± 5.82 | 42.88 ± 8.12 | 1.73 ± 1.3 | 26.82 ± 4.32 | 3.31 ± 2.7 | 12.44 ± 2.01 | 0.8 ± 0.6 | 6.45 ± 1.32 | 4.03 ± 0.77 | 69.91 ± 8.62 |
| **LPSF5** | 144.52 ± 25.01 | 0.1 ± 0.04 | 67.06 ± 11.6 | 0.05 ± 0.02 | 38.52 ± 4.96 | 0.05 ± 0.02 | 17.87 ± 2.3 | 0.02 ± 0.01 | 13.14 ± 2.76 | 2.86 ± 0.3 | 101 ± 14.79 |
| **Mean LPSF** | **126.36 ± 12.8**[**] | **3.73 ± 1.45** | **58.63 ± 5.94**[**] | **0.99 ± 0.36** | **35.14 ± 3.05**[**] | **1.73 ± 0.67** | **16.3 ± 1.42**[**] | **0.46 ± 0.17** | **12 ± 2.36**[**] | **4.22 ± 0.66**[*] | **93.35 ± 7.61**[**] |

[*] the mean value is significantly different with the PSF at $p < 0.1$

[**] the mean value is significantly different with the PSF at $p < 0.05$

Table 2.6. The bulk density (g cm$^{-3}$), carbon density (g cm$^{-3}$), carbon concentration (%), and carbon mass (Mg ha$^{-1}$) of peats partitioned by depth, and total C stocks in intact and logged peat swamp forests, Ketapang, Indonesia. Peat characteristics reported as mean ± SE.

| | ---- Soil depth (cm) ---- | | | | | | | Total C stocks |
|---|---|---|---|---|---|---|---|---|
| **Site** | **0-15** | **15-30** | **30-50** | **50-100** | **100-300** | **300-600** | **>600** | |
| **PSF1** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.09 ± 0.02 | 0.09 ± 0.01 | 0.08 ± 0.01 | 0.11 ± 0.01 | 0.1 ± 0.01 | 0.09 ± 0.01 | 0.09 ± 0.01 | |
| C % | 58.5 ± 1.4 | 59.6 ± 0.6 | 60.3 ± 0.5 | 63.6 ± 0.7 | 62.3 ± 0.3 | 62.4 ± 0.2 | 62.7 ± 0.5 | |
| CD (g cm$^{-3}$) | 0.05 ± 0.01 | 0.05 ± 0 | 0.05 ± 0.01 | 0.07 ± 0 | 0.06 ± 0 | 0.05 ± 0.01 | 0.06 ± 0.01 | |
| C stock (Mg ha$^{-1}$) | 81 ± 14 | 77 ± 6 | 100 ± 11 | 345 ± 22 | 1,190 ± 78 | 1,635 ± 170 | 2,013 ± 155 | 5,442 ± 315 |
| **PSF2** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.08 ± 0.01 | 0.05 ± 0.01 | 0.07 ± 0.01 | 0.08 ± 0 | 0.07 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0 | |
| C % | 56.7 ± 0.3 | 57.9 ± 0.4 | 60.2 ± 0.5 | 61.6 ± 0.2 | 61.8 ± 0.8 | 58.3 ± 4.6 | 62.2 ± 1 | |
| CD (g cm$^{-3}$) | 0.05 ± 0 | 0.03 ± 0 | 0.04 ± 0 | 0.05 ± 0 | 0.04 ± 0 | 0.04 ± 0 | 0.03 ± 0 | |
| C stock (Mg ha$^{-1}$) | 79 ± 5 | 47 ± 7 | 79 ± 7 | 251 ± 15 | 886 ± 100 | 1,090 ± 119 | 1,219 ± 83 | 3,650 ± 110 |
| **PSF3** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.1 ± 0.03 | 0.07 ± 0 | 0.07 ± 0 | 0.06 ± 0.01 | 0.07 ± 0.01 | 0.06 ± 0.01 | 0.17 ± 0.01 | |
| C % | 54.9 ± 3.9 | 56.3 ± 1.4 | 60.3 ± 0.7 | 61.5 ± 0.2 | 60 ± 1.5 | 57.2 ± 1.7 | 30 ± 1.5 | |
| CD (g cm$^{-3}$) | 0.05 ± 0.01 | 0.04 ± 0 | 0.04 ± 0 | 0.03 ± 0 | 0.04 ± 0 | 0.03 ± 0.01 | 0.05 ± 0 | |
| C stock (Mg ha$^{-1}$) | 78 ± 12 | 62 ± 2 | 80 ± 6 | 161 ± 14 | 824 ± 88 | 958 ± 198 | 1,611 ± 284 | 3,775 ± 312 |
| **PSF4** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.07 ± 0 | 0.1 ± 0.01 | 0.08 ± 0.02 | 0.1 ± 0.02 | 0.08 ± 0.01 | 0.12 ± 0.02 | 0.08 ± 0 | |
| C % | 53.6 ± 4.8 | 58.9 ± 1.4 | 60.7 ± 0.4 | 61.4 ± 0.7 | 57 ± 3 | 46.3 ± 4.7 | 55.5 ± 2.9 | |
| CD (g cm$^{-3}$) | 0.04 ± 0 | 0.06 ± 0.01 | 0.04 ± 0.01 | 0.06 ± 0.01 | 0.05 ± 0 | 0.05 ± 0.01 | 0.04 ± 0 | |
| C stock (Mg ha$^{-1}$) | 55 ± 6 | 90 ± 11 | 86 ± 14 | 294 ± 50 | 923 ± 75 | 1,564 ± 213 | 1,091 ± 113 | 4,104 ± 292 |
| **Mean PSF** | | | | | | | | |
| **BD (g cm$^{-3}$)** | **0.09 ± 0.01** | **0.08 ± 0.01** | **0.08 ± 0** | **0.09 ± 0.01** | **0.08 ± 0.01** | **0.08 ± 0.01** | **0.1 ± 0.02** | |

| Site | ---- Soil depth (cm) ---- 0-15 | 15-30 | 30-50 | 50-100 | 100-300 | 300-600 | >600 | Total C stocks |
|---|---|---|---|---|---|---|---|---|
| **C %** | **55.93 ± 1.07** | **58.18 ± 0.72** | **60.38 ± 0.11** | **62.03 ± 0.53** | **60.28 ± 1.2** | **56.05 ± 3.44** | **52.6 ± 7.71** | |
| **CD (g cm$^{-3}$)** | **0.05 ± 0** | **0.05 ± 0.01** | **0.04 ± 0** | **0.05 ± 0.01** | **0.05 ± 0** | **0.04 ± 0** | **0.05 ± 0.01** | |
| **C stock (Mg/ha)** | **73 ± 6** | **69 ± 9** | **86 ± 5** | **263 ± 39** | **956 ± 81** | **1312 ± 169** | **1484 ± 208** | **4243 ± 411** |
| **LPSF1** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.11 ± 0.02 | 0.09 ± 0.01 | 0.08 ± 0.02 | 0.07 ± 0.01 | 0.07 ± 0 | 0.12 ± 0.03 | 0.22 ± 0.03 | |
| C % | 57.1 ± 0.7 | 59.6 ± 0.5 | 60.3 ± 0.9 | 55.3 ± 4.5 | 62.1 ± 0.6 | 45.6 ± 5 | 23.7 ± 4.8 | |
| CD (g cm$^{-3}$) | 0.06 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.04 ± 0.01 | 0.04 ± 0 | 0.05 ± 0.01 | 0.05 ± 0 | |
| C stock (Mg ha$^{-1}$) | 95 ± 14 | 78 ± 12 | 99 ± 20 | 181 ± 28 | 868 ± 50 | 1,409 ± 220 | 660 ± 101 | 3,390 ± 192 |
| **LPSF2** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.11 ± 0.01 | 0.09 ± 0.01 | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.06 ± 0 | 0.07 ± 0 | 0.17 ± 0.06 | |
| C % | 58.7 ± 0.5 | 59.1 ± 0.4 | 59.3 ± 0.6 | 60.2 ± 0.9 | 61.9 ± 0.4 | 62.5 ± 0.5 | 46.5 ± 9.3 | |
| CD (g cm$^{-3}$) | 0.06 ± 0.01 | 0.05 ± 0 | 0.04 ± 0.01 | 0.04 ± 0 | 0.04 ± 0 | 0.05 ± 0 | 0.06 ± 0.01 | |
| C stock (Mg ha$^{-1}$) | 96 ± 12 | 81 ± 7 | 87 ± 10 | 223 ± 22 | 701 ± 44 | 1,365 ± 87 | 1,218 ± 384 | 3,771 ± 433 |
| **LPSF3** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.08 ± 0.01 | 0.11 ± 0.03 | 0.09 ± 0.02 | 0.07 ± 0.01 | 0.08 ± 0.01 | 0.15 ± 0.01 | 0.42 ± 0.04 | |
| C % | 57.3 ± 0.9 | 58.5 ± 0.6 | 58.8 ± 1.2 | 61.4 ± 0.7 | 64.4 ± 0.6 | 41.1 ± 6.9 | 14.5 ± 3.6 | |
| CD (g cm$^{-3}$) | 0.05 ± 0 | 0.06 ± 0.02 | 0.05 ± 0.01 | 0.04 ± 0 | 0.05 ± 0 | 0.06 ± 0.01 | 0.06 ± 0.01 | |
| C stock (Mg ha$^{-1}$) | 72 ± 7 | 97 ± 23 | 105 ± 17 | 221 ± 21 | 980 ± 72 | 1,835 ± 307 | 349 ± 70 | 3,659 ± 359 |
| **LPSF4** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.09 ± 0.01 | 0.09 ± 0 | 0.09 ± 0.01 | 0.1 ± 0.01 | 0.1 ± 0.01 | 0.14 ± 0.02 | 0.29 ± 0.05 | |
| C % | 60.1 ± 0.7 | 61.5 ± 0.4 | 61 ± 0.4 | 63.5 ± 0.6 | 59.7 ± 4.8 | 38.9 ± 7.8 | 17.7 ± 4.1 | |
| CD (g cm$^{-3}$) | 0.06 ± 0 | 0.05 ± 0 | 0.05 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0 | 0.05 ± 0.01 | 0.04 ± 0 | |
| C stock (Mg ha$^{-1}$) | 84 ± 5 | 79 ± 4 | 108 ± 11 | 310 ± 25 | 1,120 ± 99 | 1,563 ± 197 | 483 ± 127 | 3,506 ± 235 |
| **LPSF5** | | | | | | | | |
| BD (g cm$^{-3}$) | 0.1 ± 0.01 | 0.09 ± 0.01 | 0.1 ± 0.01 | 0.08 ± 0.01 | 0.09 ± 0.01 | 0.24 ± 0.03 | 0.26 ± 0.05 | |
| C % | 61.2 ± 1 | 61.5 ± 0.3 | 61.5 ± 0.7 | 60.3 ± 2 | 65.1 ± 1.6 | 25.8 ± 3.5 | 20.5 ± 3.9 | |

Table 2.6 (Continued)

| Site | Soil depth (cm) 0-15 | 15-30 | 30-50 | 50-100 | 100-300 | 300-600 | >600 | Total C stocks |
|---|---|---|---|---|---|---|---|---|
| CD (g $cm^{-3}$) | 0.06 ± 0 | 0.06 ± 0.01 | 0.06 ± 0.01 | 0.05 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0 | 0.04 ± 0 | |
| C stock (Mg $ha^{-1}$) | 92 ± 5 | 87 ± 8 | 122 ± 16 | 228 ± 31 | 1,217 ± 121 | 1,666 ± 117 | 634 ± 83 | 4,047 ± 212 |
| **Mean LPSF** | | | | | | | | |
| **BD (g $cm^{-3}$)** | **0.1 ± 0.01**$^{*}$ | **0.09 ± 0.01**$^{*}$ | **0.09 ± 0.01**$^{*}$ | **0.08 ± 0** | **0.08 ± 0** | **0.14 ± 0.01**$^{**}$ | **0.24 ± 0.03**$^{**}$ | |
| **C %** | **58.9 ± 0.44**$^{**}$ | **60.05 ± 0.3**$^{**}$ | **60.16 ± 0.39** | **60.16 ± 1.06** | **62.67 ± 1.02**$^{*}$ | **42.77 ± 3.14**$^{*}$ | **22.8 ± 3.36**$^{**}$ | |
| **CD (g $cm^{-3}$)** | **0.06 ± 0**$^{**}$ | **0.06 ± 0** | **0.05 ± 0**$^{**}$ | **0.05 ± 0** | **0.05 ± 0** | **0.05 ± 0**$^{**}$ | **0.04 ± 0** | |
| **C stock (**Mg $ha^{-1}$**)** | **88 ± 4**$^{**}$ | **85 ± 5**$^{*}$ | **104 ± 7**$^{**}$ | **232 ± 13** | **977 ± 48** | **1,568 ± 89**$^{*}$ | **621 ± 102**$^{*}$ | **3,674 ± 113**$^{*}$ |

$^{*}$ the mean value is significantly different with the PSF at $p < 0.1$

$^{**}$ the mean value is significantly different with the PSF at $p < 0.05$

# Chapter III

## Ecosystem Carbon Stocks and Potential Emissions from the Conversion of Tropical Peat Swamp Forests to Logged Forests, Oil Palm Plantations, or Early Seral in West Kalimantan, Indonesia

## ABSTRACT

Land cover change in tropical peatland ecosystems results in a shift from a net carbon (C) sink to a net C source. Yet, there is lack of information about how much carbon is lost from the ecosystem when converted to other uses. I quantified the ecosystem C stocks of tropical peat swamp forests, and the potential C emissions arising from logging and land conversion. The study was conducted in the Pematang Gadung peat dome (peat depth up to 10.5 m) in West Kalimantan, Indonesia.

Relatively intact peat swamp forests (PSF) had a greater tree density compared to logged forest and degraded areas. Tree density was 1,743, 1,355 and 25 trees $ha^{-1}$, in intact forests, logged forests and early seral, respectively.

Intact forest sites had higher total aboveground carbon stocks (158 Mg C $ha^{-1}$) than the logged forest (93 Mg C $ha^{-1}$), early seral (12 Mg C $ha^{-1}$) and oil palm sites (8 Mg C $ha^{-1}$). The C pools of trees, root, downed wood and litter were higher in intact forests than in converted sites.

Peat characteristics in disturbed areas were different than those in intact forests. Bulk density was higher in disturbed sites at the surface (0-30 cm) and deepest layers (> 300 cm). C content of disturbed sites was higher at surface layer (0-30 cm), but lower at deepest layer (> 300 cm) than intact forest sites. Soil carbon pool of converted sites was significantly lower than that of intact forests.

Mean peat depth was greater in the intact forests compared to the logged forests, early serals and oil palm plantation. The intact forests had a mean depths of 915 cm. Mean depths of the logged forests, early serals and oil palm were 725 cm, 702 cm, and 700 cm, respectively. I found that the mean of soil carbon stocks in logged forests, early serals and oil palms (3,675, 3,135 and 3,435 Mg C $ha^{-1}$, respectively) was significantly lower than that in intact forests (4,243 Mg C $ha^{-1}$).

PSF stocks was significantly higher among others. At all sites, soils comprised > 96% of the mean ecosystem carbon stock.

Using the estimation based on ecosystem carbon loss to total peat depths, the conversion of intact to logged forests was estimated to result in a net loss of 1,982 Mg $CO_2$ $ha^{-1}$ in 25 years. Conversion of intact forest to (logged forest -) early seral was estimated to result in a total ecosystem net loss of 4,259 Mg $CO_2$ $ha^{-1}$. While the conversion of intact forest to (logged forest

– early seral -) oil palm plantation was estimated to result in a total ecosystem net loss of 3,176 Mg $CO_2$ $ha^{-1}$.

Given the values and magnitude of the carbon stocks and potential emissions from tropical peatlands, significant efforts in conservation and restoration are relevant for climate change mitigation and adaptation.

## INTRODUCTION

Tropical peatland ecosystems have among the largest ecosystem C stocks on earth (Page *et al.*, 2011; Basuki *et al.*, 2016), and comprise about 10% (44 Mha) of the global peatland area (Page *et al.*, 2007). Indonesia alone has about 15 - 21 Mha peatland area (Murdiyarso *et al.*, 2010; BP-REDD+, 2015). The C stocks of tropical peatlands range from 82 to 92 Pg C or about 15-19% of global peat carbon stocks (610 Pg), in which Indonesia contains ≈ 57 Pg C (Verwer & Meer, 2010). Currently, these C-rich ecosystems are shifting from net C sinks to net C sources because of intensive land conversion including draining and frequent peat fires (Dommain *et al.*, 2014). Few studies have been conducted to estimate total ecosystem carbon stocks in peatlands (Murdiyarso *et al.*, 2009b; Suwarna *et al.*, 2012, Novita, 2016). Furthermore, there have been even fewer studies that estimate ecosystem carbon loss in response to land cover change in tropical peatlands (but see Novita, 2016). Thus, it is important to accurately estimate how land use affects carbon stocks and GHG emissions.

Recent low estimate suggests that Indonesia's forest loss is >1,000 $km^2$/year (Hansen *et al.*, 2013), and high estimate suggests at >5,000 $km^2$/year (BP-REDD+, 2015). Deforestation and forest degradation, including forest conversion to oil palm (*Elaeis guineensis)* plantations, are the main human disturbance to peat forest ecosystems (Hergoualc'h & Verchot, 2011). About three million ha of OP had been developed in South East Asia's peatlands in the last three decades (Miettinen *et al.*, 2016). Peat forests may also be converted into croplands and timber plantations (Murdiyarso *et al.*, 2010; Hergoualc'h & Verchot, 2011). Conversion of tropical peat forest involves cutting trees, burning and often developing drainage canals (Anshari *et al.*, 2010; Hooijer *et al.*, 2010). This conversion likely increases decomposition rates and C emissions (Murdiyarso *et al.*, 2010; Hergoualc'h & Verchot, 2011). I know of no studies that has quantified total carbon stocks and carbon emissions from the disturbed peatland ecosystems, except oil palms at Tanjung Puting in Central Kalimantan (Novita, 2016). We need to understand impacts of land cover change on the dynamics of carbon in tropical peat swamp forests in order to inform decision-making for climate change mitigation and adaptation strategies.

This study is among the first that combines intensive field measurements of carbon stocks to provide estimates of the changes in C stocks and emissions with land use. As I quantified the significant amount of C stored in PSF (Chapter 2, this dissertation), here I aimed to quantify the changes in C stocks and emissions resulting from forest degradation and conversion of peat swamp forests of Pematang Gadung peat dome, Ketapang, West Kalimantan, Indonesia.

My specific research questions included: a. How do the carbon stocks differ between relatively intact peat swamp forests (PSF), logged peat swamp forests (LPSF), early seral/ degraded sites (ES) and oil palm plantations (OP) that were formed on sites previously occupied by intact forests?, and b. What are the potential greenhouse gas emissions that could arise from degradation of peat swamp forest by logging, and by conversion to early serals and oil palm plantations?

My hypotheses were: a. Carbon stocks (aboveground, belowground and total) of intact peat swamp forests will be higher than those of logged peat swamp forests, early seral and oil palm plantation, because it has limited logging activities and further in distance to drainage canal (Wösten *et al.*, 2008; Hooijer *et al.*, 2012); b. In regards to the management absence of early seral sites that leads to its higher risk of peat fires, carbon stocks of early seral will be significantly lower than others and its emission factor will be the highest; c. Logging and land use changes will significantly increase soil bulk density and decrease C:N ratio of degraded and converted peat swamp forests, as those human induced disturbances had lowered the water level, dried and shrink the peat, increased peat decomposition and reduced the peat volume (Hooijer *et al.*, 2012).

## METHODS

### Study site

The study area is located in Pematang Gadung peat dome, Ketapang, Indonesia in the province of West Kalimantan (Figure 3.1). The Pematang Gadung is a coastal peat dome (34,651 ha) located between the Pawan and Pesaguhan Rivers that flow on the northern and the southern end of the peat dome, respectively. These two rivers run to the Karimata strait between Sumatera and Kalimantan islands. The rainfall in the region averages 2000 mm $yr^{-1}$ with the majority falling during the months of November to July. The mean annual temperature is 27.5°C. Elevation ranges from 11-22 m above sea level.

*Insert Figure 3.1*

All forests (4 relatively intact - Peat Swamp Forests/PSF and 5 partially logged Peat Swamp Forests/LPSF) had a mean canopy heights of ≈ 15 m and occurred around the center of the peat dome. In addition to the forests, I sampled five early seral/degraded areas (ES) and five oil palm smallholder plantations (OP). The OP plantations were surrounded by the ES and LPSF. Based upon observation of satellite images and interviews with local people, the forests were logged about 25 years before sampling (in 1988) and the abandoned lands were formed about 19 years before sampling (Appendix Figure 2). All abandoned lands had frequently been burned during the dry seasons. The five oil palm plantations were one (1), two (2) and three (2) years old. They were established on degraded sites (ES) following burning and canal construction around their perimeter. These were formed on abandoned lands. All sampled sites were assumed to have been similar in structure and carbon pools prior to disturbance.

### Field sampling

I selected research sites based on field observation, discussion with local experts and analyses of Landsat images. Considerations include availability of PSF and other land cover types in close proximity to PSF, as well as the sites's relative position within the peat dome.

I quantified the ecosystem carbon stocks and structure of 19 different coastal peatlands including four PSF sites, five LPSF sites, five ES sites, and five OP plantations. In order to ensure the sequential changes of land cover types (from forests to ES and OP plantation), I selected a set of each cover type insuring that all sites were in close proximity to each other. Thus I had five groups of the different land cover types. I was only able to find four sites to represent PSF areas. Thus one PSF site was included in two of the land cover groupings This PSF site was in close proximity to all other cover types.

Ecosystem C stocks (above-and belowground) were measured, in each site, following adapted standard methodologies (Murdiyarso *et al.*, 2009; Kauffman & Donato, 2012; Kauffman et al. 2016) . Within each forest, early seral and oil palm site, six plots were established 30 m apart along a 150 m transect (Appendix Figure 3). At each plot, I collected data necessary to calculate total C stocks derived from standing tree biomass, dead wood on forest floor, understory vegetation, litter and and peat soils down to mineral soils.

**Biomass of trees and shrubs**

Tree density, and basal area were quantified through measurements of the diameter at 1.3 m height (diameter at breast height or dbh) of all trees rooted within each plot of each transect. Plot size for tree measurements was 314 $m^2$ (10 m radius) for trees > 5 cm dbh and a nested plot with a radius of 2 m for trees with a dbh of < 5 cm. The diameter of trees with prop root was measured at the main branch, 30 cm above the highest prop root.

In OP plantations, heights of all oil palm trees in the plots was measured from the ground surface to the base of their young leaves (base of the apical meristem). The plot design in early seral and oil palm was identical to that of forests.

I used allometric equations to calculate tree biomass, and examined several equations developed for the ecosystems encountered in this study (Table 3.1). I assessed the equations based on where they were developed, whether the equations encompassed the dbh range of the PSF in this study, and was a sufficient sample size used to create an accurate estimate of biomass. I used the allometric equation developed by (Manuri *et al.*, 2014) using tree data from Sumatera and Kalimantan/Borneo islands of peat swamp forest trees 2–167 cm dbh. For oil palms, I used the allometric equation reported by Dewi *et al.* (2010) developed also in Sumatera and Borneo islands for oil palm trees < 1- to 8 m height on peatlands. Belowground root biomass for forest trees was calculated using the equation by (Mokany *et al.*, 2006) and for oil palm trees was calculated using a default value of 14.2% of the tree biomass as suggested by (Henson & Dolmat, 2003). Tree and root carbon content (C) was calculated from biomass by multiplying by a factor of 0.47 for biomass (Murdiyarso *et al.*, 2009).

*Insert Table 3.1*

I included standing dead trees in aboveground biomass calculations. Each dead tree was measured for dbh and assigned to one of three decay classes: Status 1-dead trees without leaves, Status 2-dead trees without secondary branches, and Status 3-dead trees without primary or secondary branches (Kauffman & Donato, 2012). In the forests, the biomass of dead trees of Status 1 and 2 was assumed to have less biomass and density loss with conversion factor of 0.9 and 0.8, respectively (Murdiyarso *et al.*, 2009). The biomass of trees of Status 3 was calculated as the biomass of the main stem only and estimated for volume as a modified cylinder of 0.8 $\pi r^2$ (Murdiyarso *et al.*, 2009). This also required estimation of the dead tree height in this decay class.

**Understory and forest litter**

In each of the six plots I harvested all aboveground understory and litter in two 1,444 $cm^2$ micro-plots (38 x 38 cm rectangular plots). These micro-plots were established on two of the wood transects (next section) at a distance of 10 m from the plot center.

These samples were placed in a plastic bag, weighed and transported to the laboratory where they were dried to a constant mass for dry-weight biomass, and C and N content determination.

**Woody debris**

I used the planar intersect technique adapted for peatlands to calculate mass of dead and downed wood (Murdiyarso *et al.*, 2009a; Kauffman & Donato, 2012; Adame *et al.*, 2013). From the center of each plot, four 14 m transects were established. The first was established in a direction that was offset 45$^{o}$ from the azimuth of the main transect. The other three were established 90º, 180º and 270º clockwise from the first transect. Along each transect, the diameter of any dead wood intersecting transect line was measured. Dead wood >2.5 cm but <7.5 cm in diameter (hereafter ‘‘small’’ debris) at the point of intersection was measured from the second to the seventh meter of the transect line. Woody debris >7.5 cm in diameter (hereafter ‘‘large’’ debris) at the point of intersection was measured from the second meter to the end of the transect line (12 m length in total). Large wood was separated in two decay categories: sound and rotten. Dead wood was considered rotten if it visually appeared decomposed and broken apart when kicked.

Dead wood samples were collected from each transect, mixed and placed in a plastic bag and transported to the laboratory. Then those samples were dried for specific gravity determination. The volume of large and small wood debris were calculated using the equations provided by (Van Wagner, and 1968; Brown, 1974). The volume value was multiplied with the wood specific gravity to estimate biomass of woody debris. Biomass of woody debris was converted to C using the factor of 0.47 (Murdiyarso *et al.*, 2009).

**Peat**

At each plot, known-volume (a 67.7 $cm^3$) of peat samples were collected using a Russian peat sampler. This sampler is efficient for collecting relatively undisturbed cores in peatlands (Warren *et al.*, 2012). The core was systematically divided into depth intervals of 0 – 15, 15 – 30, 30 – 50, 50 – 100 cm, 100 - 300, 300 - 600, 600 - 900, and > 900 cm (if parent materials were not encountered before 900 cm depth). Depth of parent materials was noted. Samples of known volume were collected from each depth interval. At each sampling site, the depth to parent materials (mineral soil) was measured. The peat depth was measured near the center of each plot.

Samples were transported to laboratory, dried at 60°C to constant mass, and then weighed to determine bulk density. Laboratory analysis was conducted at analytical laboratory at Bogor Agricultural University (IPB). In the laboratory, the concentration of C and N were determined using the dry combustion method (induction furnace) with a LECO Analyzer. Bulk density and carbon concentration were then combined with peat depth measurements to determine the peat C stocks.

**Potential emissions from degradation and conversion of peat swamp forests**

I calculated the potential emissions from the conversion of PSF to LPSF, ES and OP using the Intergovernmental Panel on Climate Change (IPCC) stock change protocol (IPCC, 2003). The protocol used for tracking changes in carbon stocks and predicting emissions from land cover change in this study. Using this approach, I calculated cumulative potential emissions that occurred since degradation of the site.

Differences in carbon stocks were converted to emissions using the formula:

$\Delta CLU = \Delta CT - \Delta CUL - \Delta CWD - \Delta CSOC$;

where $\Delta$CLU = change in carbon stocks (or total C emissions or sequestration) due to land use; $\Delta$CT = Change in tree C stocks; $\Delta$CUL = Change in understorey and litter C stocks; $\Delta$CDW = Change in woody debris C stock; $\Delta$CSOC = Change in soil C stock.

Peat collapse and disturbances due to deforestation, and the absence of a reliable marker in the deep peats (reference layer of the sampled peat swamp forests, logged peat swamp forests, early serals and oil palm plantations) compounds difficulties in the comparisons of peat properties based upon depth or volume. Therefore I analyzed carbon loss and potential emissions from degradation and conversion of peat swamp forests based upon paired comparisons of the closest distance possible among sites of all land cover types. I assumed that all sites have common peat depth and had the same initial state as peat swamp forests.

The ecosystem carbon losses are reported as potential $CO_2$ emissions, or C-$CO_2$—obtained by multiplying C values by 3.67, the molecular ratio of $CO_2$ to C.

**Scaling carbon stocks of peat land cover types to peat dome scales**

I scaled site level carbon stock measurements to the scale of the entire peat dome. This peat dome is approximately 34,651 ha in area (Figure 3.1). To scale the carbon stocks of peatland cover types to a peat dome scale, I determined land cover in the area using peat data from BBSDLP-MoA (2011) and land cover types data from Indonesian Ministry of Environment and Forestry (http://webgis.dephut.go.id/ArcGIS/services). Peat swamp forests (PSF and LPSF) and oil palm plantation sites were the dominant land cover types, each representing about 33 % of the total. Both intact and logged peat swamp forests covered an area of 12,332 ha and oil palm plantations covered 12,632 ha. Early seral represented 18 % (6,790 ha), while rice field and bare soils covered about 11 and 3.5 % (4,149 and 1,320 ha) of the land area. Other land cover types including gold mining, roads and towns, and water features represented only a minor amount of land area (<2 %).

*Insert Figure 3.1*

**GHG emissions from peat swamp forests degradation and conversion to early seral and oil palm at the peat dome scale**

The field sampling was concentrated along the main road and about 5 km from the banks of the Pawan River (Figure 3.1). To upscale changes in carbon stocks due to land conversion from peat swamp forest sites to a peat dome scale, I used the same supporting data and maps as I utilized in upscaling the carbon stocks of land cover types.

**Data analyses**

The normality distribution of research data among ecosystems (land cover types) was tested using Saphiro-Wilks and Kolmogorov-Smirnov tests. Differences in aboveground, belowground/soil and total ecosystem carbon stocks among land cover types were tested with analysis of variance (ANOVA), when the data is normally distributed. If the ANOVA was significant, a least significant difference (LSD) test was performed to determine which means were significantly different. Kruskal-Wallis H test was used for non-normally distributed data. Mann-Whitney U test was performed to determine which means were significantly different. Regression analyses was used to model the growth of forest trees using diameter at breast height data. Statistical analyses was conducted using IBM SPSS software version 20.

## RESULTS

**Aboveground biomass and carbon stocks**

Tree density was significantly different ($p = 0.001$) among land cover types. Peat swamp forests had higher tree density (1,743 ± 97 trees $ha^{-1}$), than logged forests and early seral sites, e.g., 1,282 ± 46 and 12 ± 11 trees $ha^{-1}$, respectively. Highest tree densities were found on PSF1 and PSF2 with 1,906 ± 185 and 1,906 ± 97 trees $ha^{-1}$, while the lowest density was no tree $ha^{-1}$ in the ES2 site (Table 3.2).

*Insert Table 3.2*

Wood density of coarse (sound and rotten) downed wood were significantly different among peatland ecosystems ($p < 0.1$). Wood density of coarse (rotten) wood in PSF ranged from 0.37 to 0.45 g $cm^{-3}$ and was higher than in LPSF and OP that ranged from 0.21 to 0.42 g/$cm^{-3}$ and from 0.19 to 0.35 g/$cm^{-3}$, respectively ($p < 0.05$; Table 3.2). However, the density of the downed wood (coarse – sound) in PSF (0.55 ± 0.06 g $cm^{-3}$) was lower than in ES (0.71 ± 0.1 g/$cm^{-3}$; p= 0.04).

Aboveground organic materials (OM) comprised of live and dead trees, woody debris and litter. Aboveground OM was significantly different among land cover types ($p < 0.05$). Tree OM in PSF ranged from 176 to 244 Mg $ha^{-1}$ and was higher than in LPSF, ES and OP that ranged from 92 to 162 Mg $ha^{-1}$, from 0 to 4 Mg $ha^{-1}$ and from 0 to 1 Mg $ha^{-1}$, respectively (Table 3.3). Root OM in PSF ranged from 52 to 65 Mg $ha^{-1}$ and was higher than in LPSF, ES and OP that ranged from 27 to 45 Mg $ha^{-1}$, 0 to 2 Mg $ha^{-1}$ and <1 Mg $ha^{-1}$, respectively ($p < 0.05$). Dead tree OM in PSF and LPSF was similar and ranged from 0 to 8 Mg $ha^{-1}$ and was higher than in ES and OP that both were ≤ 1 Mg $ha^{-1}$ ($p = 0.002$). Dead root OM in PSF ranged from 1 to 4 Mg $ha^{-1}$, similar with those in LPSF but was higher than in ES and OP that both ranges far below 1 Mg $ha^{-1}$, respectively ($p = 0.01$).

*Insert Table 3.3*

Similar to aboveground organic materials, the carbon pools of live and dead trees (and their roots), woody debris, and litter were significantly different among land cover types ($p = 0.001$). Tree C in PSF ranged from 82 to 113 Mg $ha^{-1}$ and was higher than in LPSF, ES and OP ($p = 0.005$; Table 3.4). Tree roots C in PSF ranges from 24 to 30 Mg $ha^{-1}$ and was the highest among other ecosystems ($p = 0.005$). Woody debris C in PSF ranged from 19 to 33 Mg $ha^{-1}$ and was also higher than other cover types ($p < 0.05$). Mean understory and litter in PSF ranged from 5 to 10 Mg $ha^{-1}$ and was higher than in OP (a range from 1 to 5 Mg $ha^{-1}$; $p = 0.001$).

For all land cover types, there was high variation in the total aboveground carbon stocks between the different sites (Figure 3.2). However, intact peat forests has the highest aboveground carbon stocks ranged from 149 to 170 Mg C $ha^{-1}$ (mean = 158 Mg C $ha^{-1}$).

*Insert Figure 3.2*

**Peat properties and carbon stocks**

Mean peat depths were greater in the peat swamp forests compared to the logged forests, early seral sites and oil palm plantations ($p < 0.1$; Table 3.4). This was especially true for the PSF2 with a mean depth of 953 cm. The other three sampled PSF had depths ranging from 841 to 945 cm. Mean depths of the LPSF, ES and OP were 725 ± 24 cm, 702 ± 29 cm, and 700 ± 29 cm, respectively.

*Insert Table 3.4*

Bulk density of soils was significantly different among land cover types at all depths ($p < 0.1$), except at the 50 – 100 cm and 100 – 300 cm depths (Table 3.5). Land use affected bulk density even at the deepest depths (> 300 cm; Figure 3.3a) where the bulk density was significantly lower in PSF than in LPSF, ES and OP ($p < 0.05$). For example, at 300 – 600 cm depth, the bulk density of PSF was 0.08 g $cm^{-3}$ while at the other were ≤ 0.14, g $cm^{-3}$, respectively.

*Insert Table 3.5*

*Insert Figure 3.3*

Carbon concentration was significantly different among land cover types throughout the soil profile ($p < 0.05$; Figure 3.3b). At upper layers (depth 0 - 300cm) carbon concentration in PSF was lower than in LPSF, WS and OP ($p < 0.05$). In contrast, at the deepest layer (e.g., 300 – 600 cm depth) carbon concentration in PSF (56%) was significantly higher than in LPSF (43%), ES (38%) and OP (37%; $p < 0.05$).

Carbon density (CD; g $cm^{-3}$) was only significantly different among land cover types at the first 50 cm of peat layers ($p < 0.1$; Table 3.6). Carbon density in PSF (0.05 g $cm^{-3}$) was lower than that in LPSF and OP (0.06 g $cm^{-3}$). The carbon density increased with land use change likely reflecting the increase in bulk density. In contrast, at depths of > 3 m, peats in LPSF, ES and OP were higher than PSF in bulk density but their carbon density was similar. At that depth, their lower value in carbon concentration than the PSF had balanced their higher bulk density (Figure 3.4).

Soil Carbon stocks were significantly different among land cover types ($p = 0.07$; Table 3.6). The soil C stock in PSF (4,243 Mg $ha^{-1}$) was not significantly different with LPSF (3,675 Mg $ha^{-1}$) but significantly higher than ES (3,135 Mg $ha^{-1}$; $p = 0.05$) and OP (3,435 Mg $ha^{-1}$; $p = 0.09$).

*Insert Figure 3.4*

The total soil carbon stock varied greatly within the forest types ranging from 3,390 to 4,047 Mg C $ha^{-1}$ in logged forest, and from 3,650 to 5,442 Mg C $ha^{-1}$ in PSF (Table 3.6). In early seral and oil palm plantations, soil carbon stock ranged from 2,062 to 4,018 Mg C $ha^{-1}$ and from 2,555 to 4,384 Mg C $ha^{-1}$, respectively.

**Total ecosystem carbon stocks**

The mean ecosystem carbon stock for the peat swamp forest sites was 4,401 Mg C $ha^{-1}$. Ecosystem carbon stocks of logged peat swamp forests, early seral and oil palm plantation was 3,768, 3,147, 3,442 Mg C $ha^{-1}$, respectively. PSF stocks was significantly higher than the other cover types ($p = 0.07$).

The total carbon stocks for LPSF sites varied greatly from a minimum of 3,496 Mg C $ha^{-1}$ at the LPSF1 site to a maximum of 4,148 Mg C $ha^{-1}$ at the LPSF5 site (Figure 3.5). The total stocks for ES sites varied greatly from a minimum of 2080 Mg C $ha^{-1}$ at the ES3 site to a maximum of 4,036 Mg C $ha^{-1}$ at the ES1 site. The total ecosystem stocks for OP sites varied from a minimum of 2,566 Mg C $ha^{-1}$ at the OP5 site to a maximum of 4,389 Mg C $ha^{-1}$ at the OP1 site. At PSF and LPSF sites, soils comprised 96 and 98% of the mean ecosystem carbon stock, respectively. At all ES and OP sites, peat carbon pools comprised a mean of 99% of the total ecosystem pool (Figure 3.6).

*Insert Figure 3.5*

*Insert Figure 3.6*

Ecosystem carbon stock changes due to logging totaled 541 Mg C $ha^{-1}$ using the carbon stock difference approach that included the entire ecosystem stocks. The aboveground carbon stocks declined by 41 % and peat carbon stocks declined by 13 % (Figure 3.7). The peat component accounted for a mean of 88 % of the mean ecosystem carbon loss due to logging.

Carbon stocks in ES ranged from 492 Mg C $ha^{-1}$ to 1,858 Mg C $ha^{-1}$ lower than PSF with a mean loss of 1,161 Mg C $ha^{-1}$. This value is the potential cumulative carbon loss from clearing of the intact peat including several fires. The aboveground carbon stocks declined by 92 % and peat carbon stocks declined by 26 % due to conversion. The peat component accounted for a mean of 87 % of the mean ecosystem carbon loss due to deforestation. Similar to ES, the mean carbon stock in OP was 866 Mg C $ha^{-1}$ lower than the PSF. The aboveground carbon stocks declined by 96 % and peat carbon stocks declined by 19 % due to conversion. The peat component accounted for a mean of 82 % of the mean ecosystem carbon loss due to conversion.

*Insert Figure 3.7*

**Total ecosystem carbon stocks at the peat dome scale**

I estimated that the ecosystem carbon stocks of the entire peat dome, associated with the peat swamp forests (12,332 ha) to be 50 Tg C (95 % confidence range: 44–62 Tg C). Although higher in area, carbon stocks in oil palm plantation (12,632 ha) would be less (43 Tg C with 95

% confidence range: 34–53 Tg C). Carbon stocks in early seral (6,790 ha) would be 21 Tg C (95 % confidence range: 15–26 Tg C). Thus, the total ecosystem carbon stocks of the entire peat dome was about 115 Tg C.

### Emission of forest degradation and deforestation

The mean potential emission arising from logging of peat swamp forests was 1,982 Mg C-$CO_2$ $ha^{-1}$ (Figure 3.7). Of this emission estimate, about 1,741 Mg C-$CO_2$ $ha^{-1}$ arose from peat sources and about 241 Mg C-$CO_2$ $ha^{-1}$ came from vegetation. Assuming there was only 10% of intact peat swamp forest left, total emission from logging was 22 Tg C-$CO_2$.

The mean potential emission from PSF conversion to ES was 4,259 Mg C-$CO_2$ $ha^{-1}$. About 3,720 Mg C-$CO_2$ $ha^{-1}$ arose from peat sources and the rest (539 Mg C-$CO_2$ $ha^{-1}$) came from plant carbon pools. At peat dome scale, total emission from PSF conversion to ES was 54 Tg C-$CO_2$.

The mean potential emission from PSF conversion to OP was 3,176 Mg C-$CO_2$ $ha^{-1}$, which about 2,178 Mg C-$CO_2$ $ha^{-1}$ were from peat sources and 558 Mg C-$CO_2$ $ha^{-1}$ were from plant carbon pools. The total potential emissions ranged from 1,182 Mg C-$CO_2$ $ha^{-1}$ in the OP3 to 6,264 Mg C-$CO_2$ $ha^{-1}$ in the OP5. PSF conversion to OP had emitted as much as 22 Tg C-$CO_2$.

The total emission due to land cover change of the entire peat dome was 98 Tg C-$CO_2$.

## DISCUSSION

### How land use change influenced the above and belowground carbon stocks?

I demonstrated that the losses of aboveground carbon stocks by land use change was significant ($p = 0.001$). Peat swamp forest sites had lost 241 Mg C-$CO_2$ $ha^{-1}$ (41%) of aboveground carbon stocks due to logging. This loss had been contributed mostly from reduced living trees (57%), downed wood (22%) and roots (16%). Logged forest clearing, draining and burning into early seral further reduced carbon stocks that resulted in losses of 539 Mg C-$CO_2$ $ha^{-1}$. This carbon loss was dominated by reduced living trees (65%), roots (18%) and downed wood (14%). Finally, the clearing of logged forest, draining, burning and development of oil palm plantation had reduced forest carbon stocks as much as 558 Mg C-$CO_2$ $ha^{-1}$. Similar to the early seral sites, this loss was mostly contributed by reduced living trees (63%), roots (18%) and downed wood (15%). Intact peat swamp forests had lost significant carbon from aboveground pools (41% in logged peat forest, 92% in early seral and 96% in oil palm plantation). However, they are much less in contributing to the total ecosystem carbon loss (<18%) compared with that from soil carbon stocks.

I found that peat C stock was significantly higher in the intact forest than in logged forest, oil palm and early seral sites ($p < 0.1$). Logging and draining had decreased soil carbon stock of the logged forests by 1,741 Mg C-$CO_2$ $ha^{-1}$. This likely because of reduced primary productivity as the trees were harvested (Chapter 4, this dissertation), and of accelerated decomposition process following draining (Whittington & Price, 2006a; Comeau *et al.*, 2013; Novita, 2016). In early seral and oil palm, soil carbon stocks had been reduced as much as 3,720 and 2,618 Mg C-$CO_2$ $ha^{-1}$, respectively, because of the combination effects of draining, logging, and peat fires.

Others have found significant soil carbon stock change using a peat subsidence approach (Wösten *et al.*, 1997; Hooijer *et al.*, 2012), $CO_2$ flux measurements (Comeau *et al.*, 2013) and carbon stock difference approaches (Schipper & McLeod, 2002; Novita, 2016). It is clear that LUC had significantly reduced carbon stocks of the intact peat swamp forests, both from aboveground and belowground sources.

My results on soil and ecosystem carbon stock changes among land cover types had been influenced by high variation in pool sizes within each and across land cover types (Figure 3.6 and 3.7). A carbon stock change approach would be improved if there was a reference maker in the soil such as a layer of volcanic ash (Schipper & McLeod, 2002) which was not present at my research site.

I observed changing peat properties and peat loss after the wildland fire of 2014 in LPSF, ES and OP sites. I also found significant changes in peat properties between the PSF and the degraded and converted forests due to land use change (Figure 3.3). Bulk density at 0-50 cm depth of peat in the degraded sites was higher than in intact peat forests. LUC has led to compaction on the ground, likely due to draining, logging and land clearing (Kool *et al.*, 2006; Anshari *et al.*, 2010). Moreover, at depths of > 3 m, peats in LPSF, ES and OP were also higher in bulk density but lower in carbon concentration than the PSF (Figure 3.3). Possible explanations to this is peat collapse and consolidation, due to similar causes of compaction on peat surface that were draining and other human activities (Schwarzel *et al.,* 2002; Whittington & Price, 2006b). Draining and human activities created additional pressure to peat profile that ultimately reduce its volume (subsidence). This led to a decrease on peat porosity, but an increase on bulk density. Both compaction on the ground surface and consolidation at the bottom of peat profile may decrease the peat's hydraulic conductivity (Kurnianto, in prep.) and water storage capacity (Whittington & Price, 2006b), but increasing carbon loss through decomposition and DOC leaching.

My findings on the changes in peat bulk density (consolidation) and C concentration of LPSF, ES and OP below the 3 m depth is significant (Figure 3.3 and 3.4) and of importance to the determination of land use impact on carbon emissions. It is in contrast with previous study that have only reported bulk density increases at the soil surface or above the average water table depth (Kool *et al.*, 2006; Hooijer *et al.*, 2012). Thus, it is crucial to measure changes deeper into the peat profile or total peat depth in order to avoid inaccuracy in estimating the total soil C loss from peat subsidence.

**Carbon loss from land cover change**

There are few studies that have investigated soil carbon losses from PSF conversion to OP. Most used different methodologies than ours, e.g., peat subsidence (Wösten *et al.*, 1997; Hooijer *et al.*, 2012) and $CO_2$ flux measurements ( Carlson *et al.*, 2012; Comeau *et al.*, 2013). Carlson et al. (2012) reported losses of 57.3 Mg C-$CO_2$ $ha^{-1}$ $yr^{-1}$ with forest conversion in Kalimantan peatlands; while Hooijer *et al.*, (2012) and Comeau *et al*. (2013), reported a loss of 100 and 45.5 Mg C-$CO_2$ $ha^{-1}$ $yr^{-1}$ from Sumatera peatlands, respectively. Dividing the total soil carbon loss by the number of years since the sites were deforested (25 years), I estimate the emission from my study sites was about 127 Mg C-$CO_2$ $ha^{-1}$ $yr^{-1}$. My estimate was similar to the recent report from another part of Borneo (Novita, 2016). I argue that previous studies had underestimated soil carbon loss from PSF conversion to oil palm. This is because they did not consider the ecosystem C losses from land use prior to the establishment of oil palm plantation.

Loss of carbon in the soil of oil palm plantations converted from tropical forests on mineral soils (Schroth *et al.,* 2002) is much less than what I found in my plantation sites (i.e., 9.9 vs 2,618 Mg C-$CO_2$ $ha^{-1}$). It clearly suggests that the conversion of intact peat forest for oil palm plantation should be avoided, considering its tremendous potential in emitting carbon compared to other forest ecosystems.

Using a carbon stock difference approach, Schipper and McLeod (2002) reported that the conversion of a natural peat bog to drained dairy farm reduced soil carbon up to 3.7 Mg C $ha^{-1}$ $yr^{-1}$ in New Zealand. My study suggests a much higher value of annual soil carbon loss from conversion of PSF to ES ( i.e., 46.4 Mg C $ha^{-1}$ $yr^{-1}$). Frequent fires occur following forest clearance (about 19 years ago) likely contributed to my higher values of soil carbon loss.

Kauffman et al., (2016) reported that the losses in total ecosystem carbon stocks from mangrove conversion to pasture (1,464 Mg C-$CO_2$ $ha^{-1}$ for 30 years) were 7-fold greater than emissions from dry forests and 3-fold greater than emissions from Amazon forest to pasture conversion. I found the carbon stocks loss from PSF conversion to early seral (dominated by grasses and ferns) to be 4,259 Mg C-$CO_2$ $ha^{-1}$ for 25 years. This is greater than emissions from mangrove to pasture conversion (Kauffman *et al.*, 2016) and many other forest conversions in terrestrial ecosystem (Figure 3.8).

*Insert Figure 3.8*

I may be comparing ecosystem carbon stocks of land cover types that inherently possessed different peat depths. The uncertainties can be decreased by doing additional analyses on the difference between present soil carbon stocks with the future stocks (five to ten years interval period), by measuring peat subsidence rates, or by conducting peat carbon gain-loss approaches (Chapter 4, this dissertation).

## Significance and conclusion

Oil palm plantations and early seral sites in the Pematang Gadung peat dome comprise 12,632 ha and 6,790 ha, respectively. Given the assumption that all the oil palm plantations and early seral sites were derived from the conversion of PSF, with annual emission rate of 127 and 170 Mg C-$CO_2$ $ha^{-1}$ respectively, the total emissions arising from this land use change has been 0.9 Tg C-$CO_2$ $yr^{-1}$ and 2.1 Tg C-$CO_2$ $yr^{-1}$. The combined emissions (3 Tg C-$CO_2$ $ha^{-1}$ $yr^{-1}$) is equivalent to the total annual loss of 5,455 ha of tropical rain forest area (550 Mg C-$CO_2$ $ha^{-1}$; IPCC, 2006).

Overall, the 12,332 ha of remaining peat forests of the Pematang Gadung peat dome (Figure 3.1) store substantial quantities of carbon (50 Tg C). Adding the early stocks of seral sites and oil palm plantation, the total 34,651 ha of peat dome stores about 115 Tg C.

In Indonesia, there are about 3 Mha of deep peatland (>4m depth). Upscaling my findings to the country level, Indonesian peatland would store about 13.1 Pg C as peat swamp forests. However, about only 11.2, 9.3 or 10.3 Pg C will remain if the intact forests will be converted into logged forests, early seral sites or oil palm plantations, respectively. This suggests a high vulnerability for continues and large potential emissions from forest degradation and conversion in Indonesian deep peatland, ranging from 6.9 to 13.7 Pg C-$CO_2$. Clearly, protection and conservation of the threatened tropical peat swamp forests can significantly mitigate the progression of climate change.

During 1990 to 2015 period, about 3.1 Mha of oil palm plantations were developed in the peatland ecosystems of South East Asia (Miettinen *et al.*, 2016). Along with the plantation, 1.1 Mha of unmanaged lands were also formed (defined as my early seral sites; Miettinen *et al.*, 2016). It is likely that peat swamp forests have been converted with a rate of 0.17 Mha $yr^{-1}$. Based on my estimate on the total emission from peat forests conversion into oil palm and early seral sites (3,176 and 4,259 Mg C-$CO_2$ $ha^{-1}$, respectively), the conversion had emitted as much as 0.4 Pg C-$CO_2$ $yr^{-1}$. This is equal to the estimated annual $CO_2$ emission from combination of deforestation, forest degradation and degraded peat decomposition in Indonesia in 2013 (BP-REDD+, 2015). I believe that restoration of PSF in areas where land uses have declined or are marginally profitable will sequester large quantities of carbon.

## ACKNOWLEDGMENTS

I wish to thank Randi Ade Chandra, Samsudin and community of Sungai Pelang village, for assistance in the field. Yudi Almanggari, M. Agus Salim, Beni Okarda, Sigit D. Sasmito and Erwin Tumengkol for their advice in spatial and statistical data. I also wish to thank Flora Fauna Indonesia, United State Agency International Development - Indonesia Forest and Climate Support (USAID - IFAC), Yayasan Palung, and International Animal Rescue, for collaborating during the research preparation. Dr. Iswandi Anas and Mrs. Asih Karyati of the Biotechnology Laboratory, Bogor Agricultural University for carbon analysis. This study was possible through funding provided by the the United States Agency for International Development—The Kalimantan Wetland and Climate Studies Project.

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**Figures**

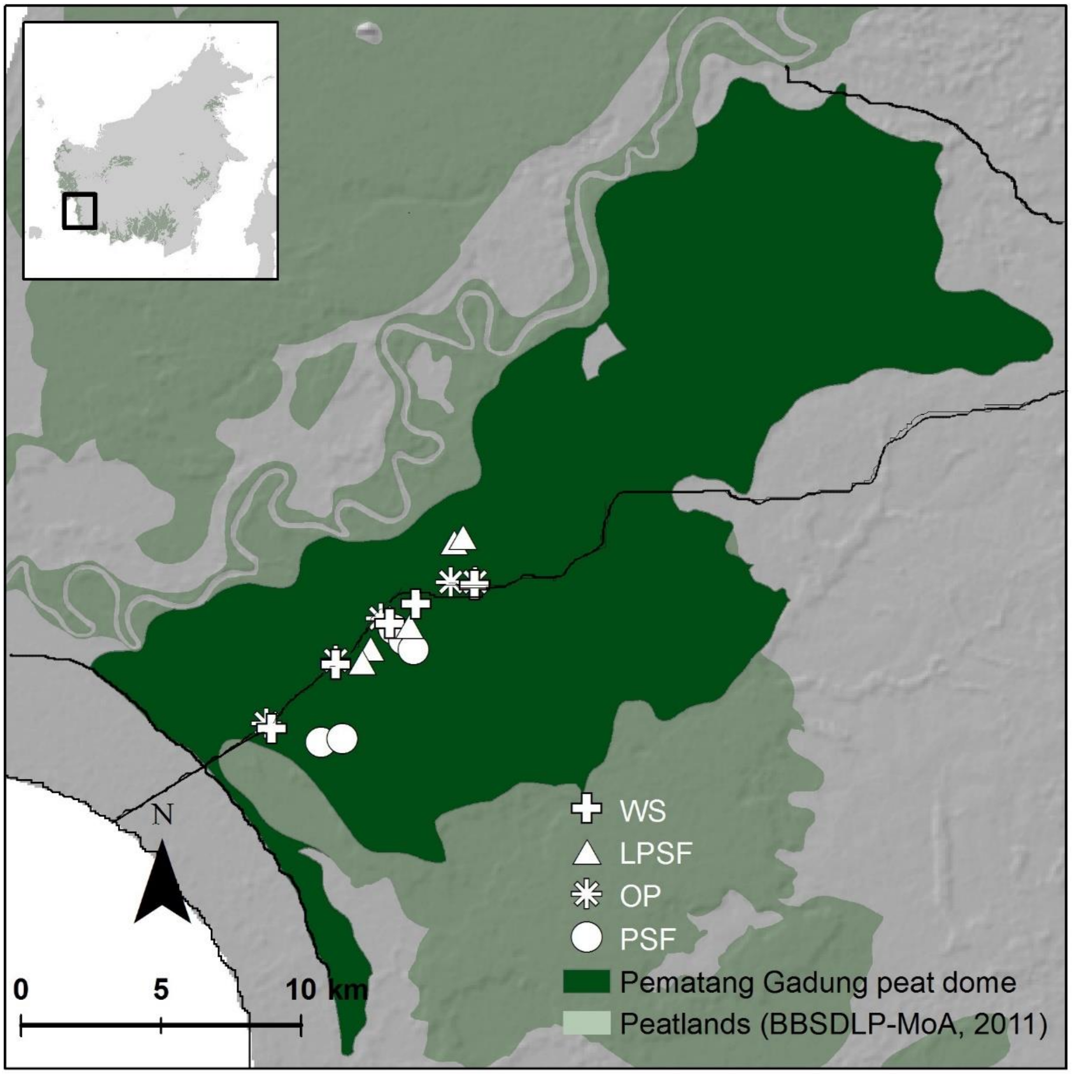



Figure 3.1. Plot locations (19 sites) within the study area, Pematang Gadung peat dome, Ketapang, West Kalimantan, Indonesia. Peat dome area (dark green) was delineated by BDSLDP - MoA (2011). White symbols represent the sample sites. Red line represents road. White areas represent the sea (Karimata Straits), light green areas represent the peatland areas. Grey areas represent the non-peat areas.

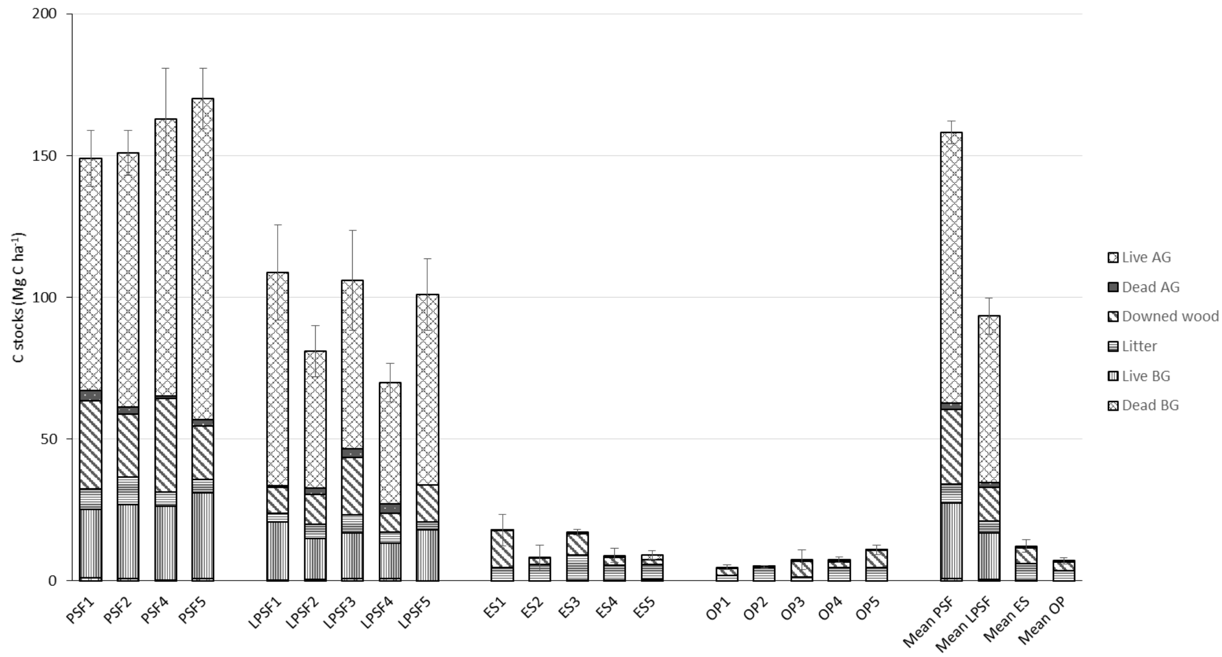



Figure 3.2. The total aboveground carbon stocks (Mg C $ha^{-1}$) of peat swamp forests (PSF), logged peat swamp forests (LPSF), early seral (ES) and oil palm plantation (OP) at the Pematang Gadung peat dome, Ketapang, Indonesia. Vertical bars are one standard error. Total aboveground carbon stocks is significantly different among all land cover types (Kruskal-wallis, p=0.001).

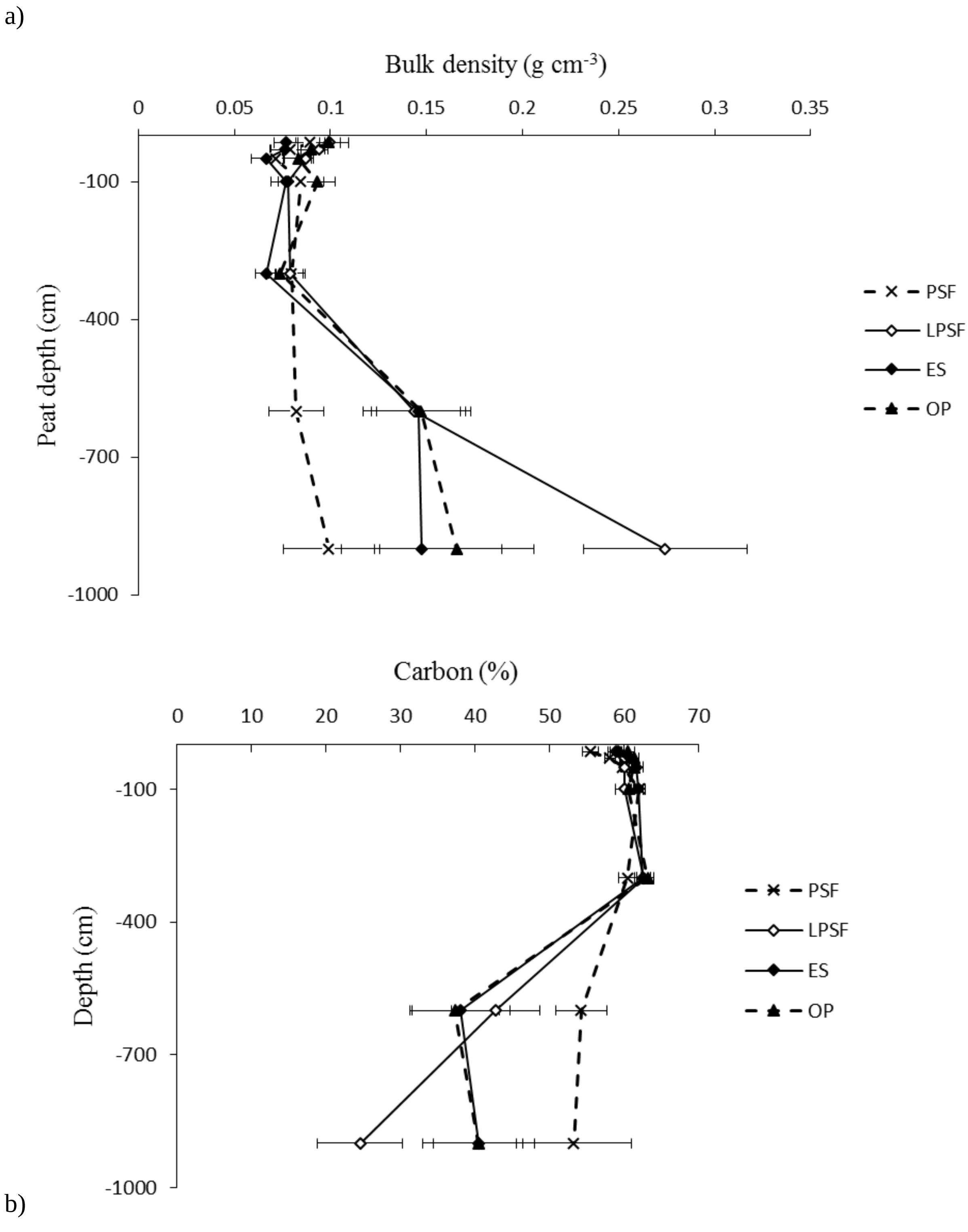
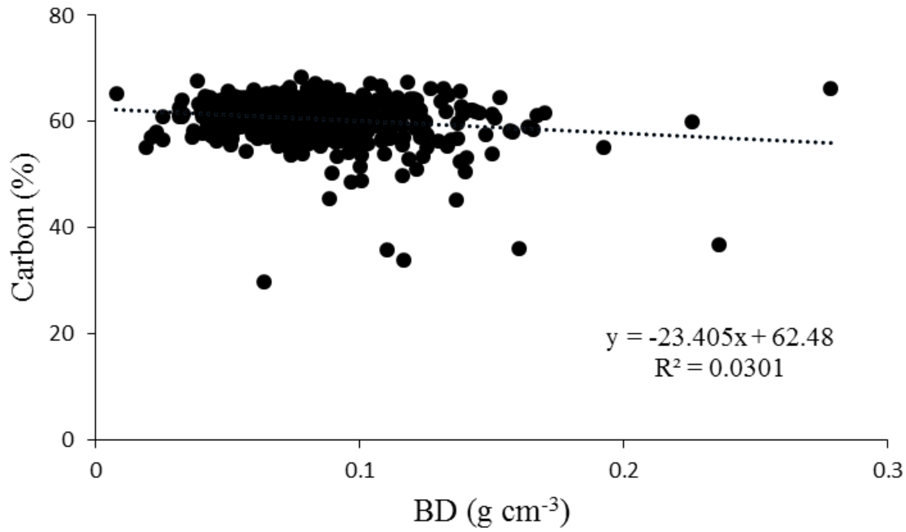
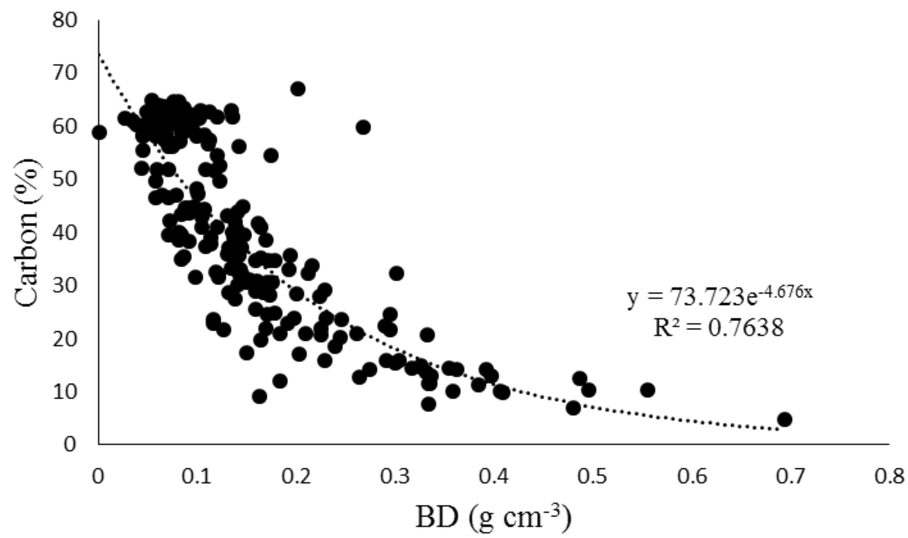



Figure 3.3. Bulk density (g cm$^{-3}$) of soils by sampled depths for intact peat forest (PSF), logged PSF, early seral (ES) and oil palm plantation (OP). BD at the deepest layer (>300 cm) in PSF is significantly lower than in LPSF, ES and OP (t-test, $p < 0.05$).




a)




b)

Figure 3.4. The relationship of Carbon concentration and bulk density. There was no correlation in soils up to 3m depth ($r^2$ = 0.03; Figure 5a). In contrast, significant correlation ($r^2$ = 0.8) was found in the layer below 3 m (Figure 5b).

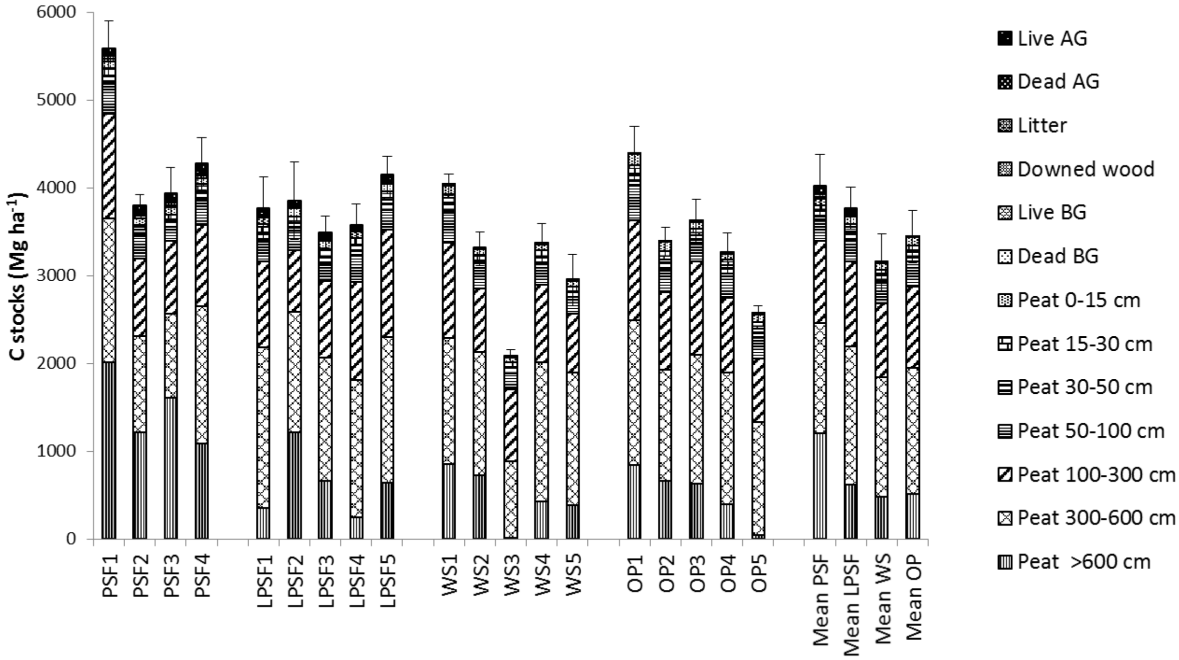
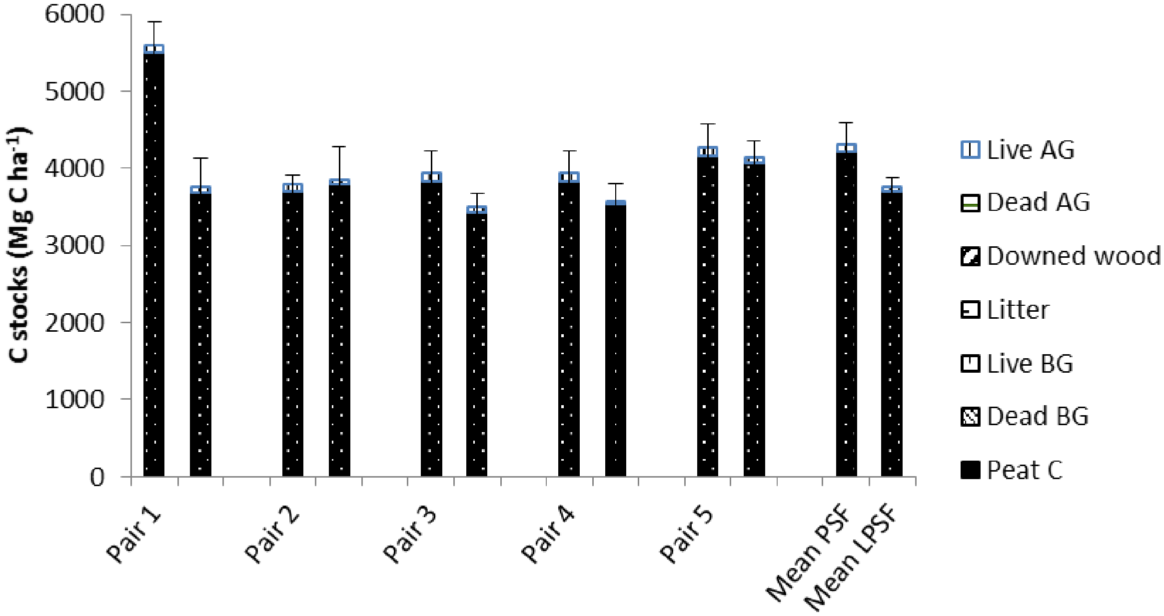


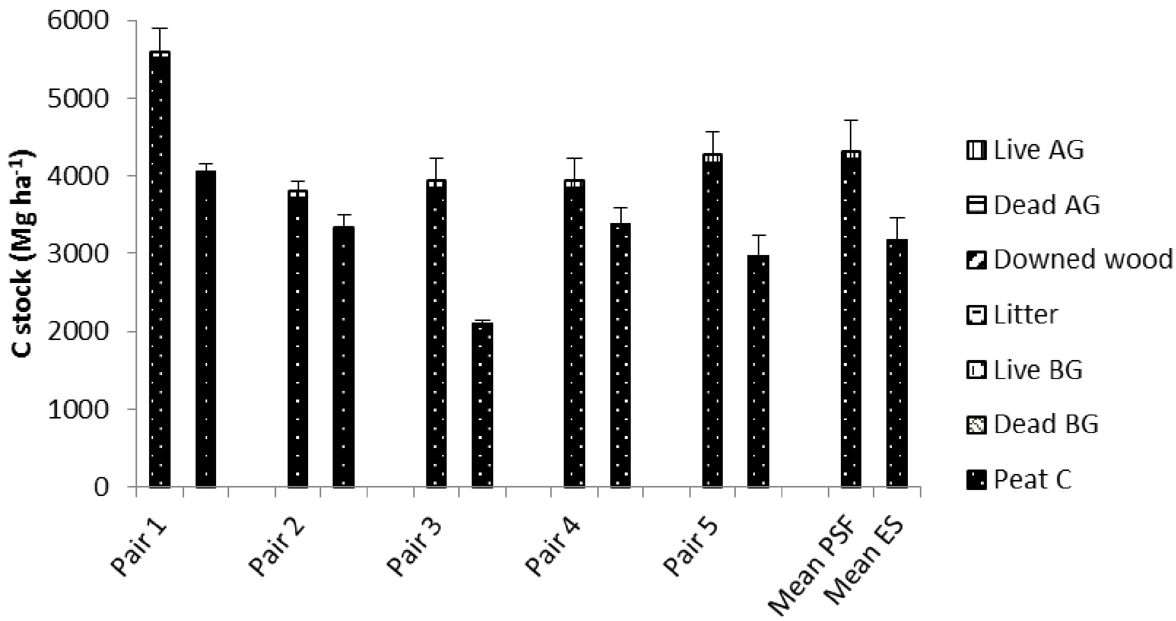

Figure 3.5. The total ecosystem carbon stocks (Mg ha$^{-1}$) of peat swamp forests (PSF), logged peat swamp forests (LPSF), wet shrubs (ES) and oil palm plantation (OP) at the Pematang Gadung peat dome, Ketapang, Indonesia. Vertical bars are one standard error.

a)



C stocks (Mg C ha-1)
6000
5000
4000
3000
2000
1000
0
Pair 1
Pair 2
Pair 3
Pair 4
Pair 5
Mean PSF
Mean LPSF
Live AG
Dead AG
Downed wood
Litter
Live BG
Dead BG
Peat C


b)



C stock (Mg ha-1)
6000
5000
4000
3000
2000
1000
0
Pair 1
Pair 2
Pair 3
Pair 4
Pair 5
Mean PSF
Mean ES
Live AG
Dead AG
Downed wood
Litter
Live BG
Dead BG
Peat C

c)

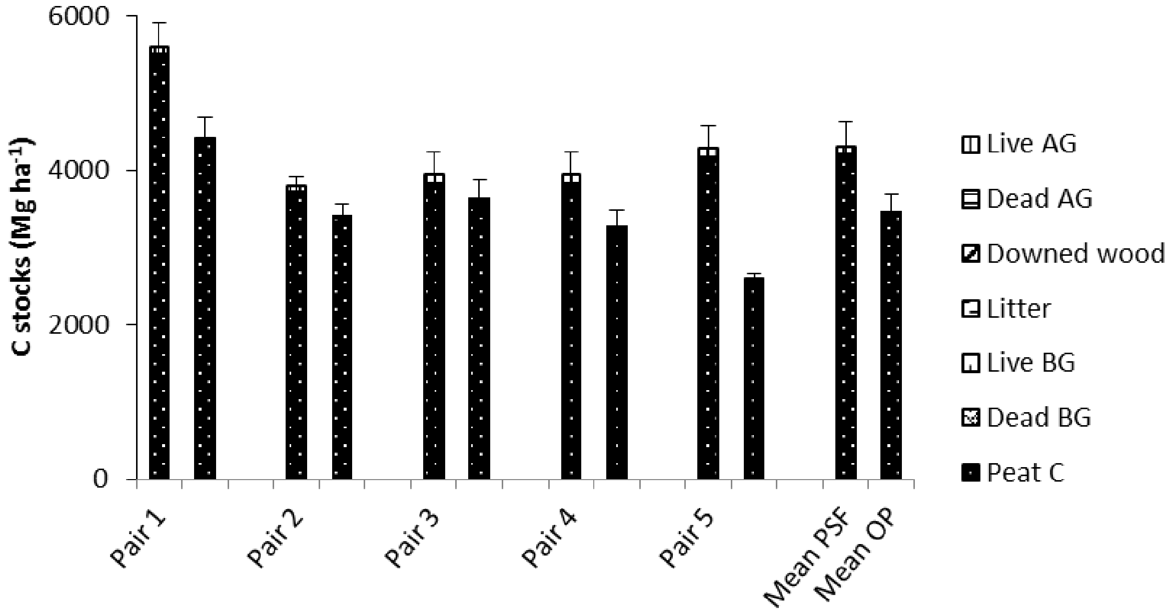
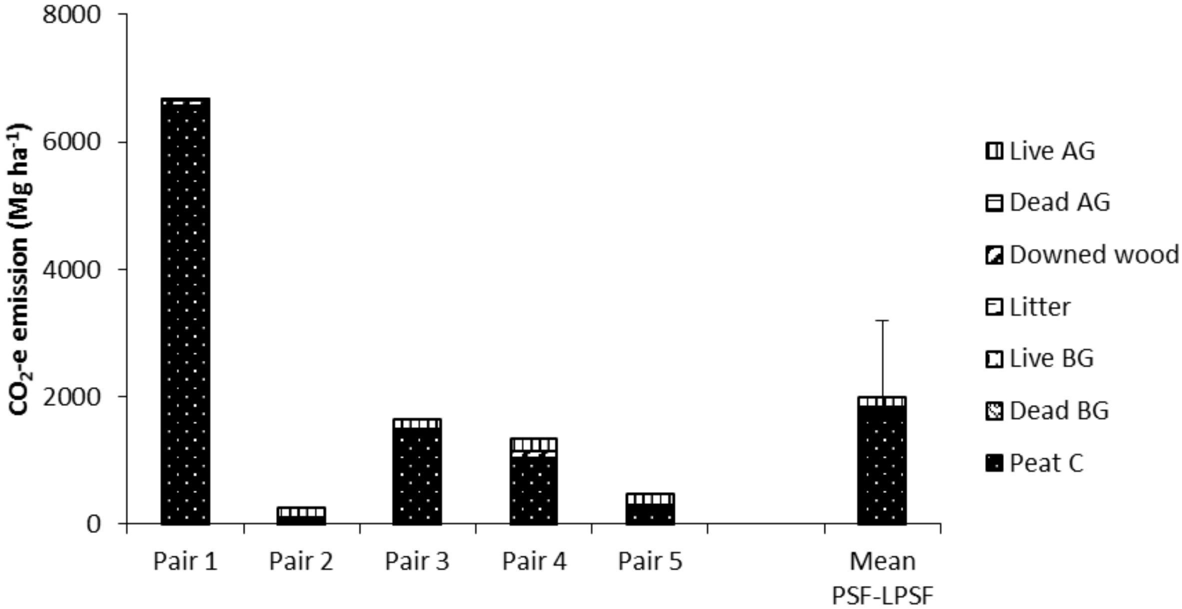
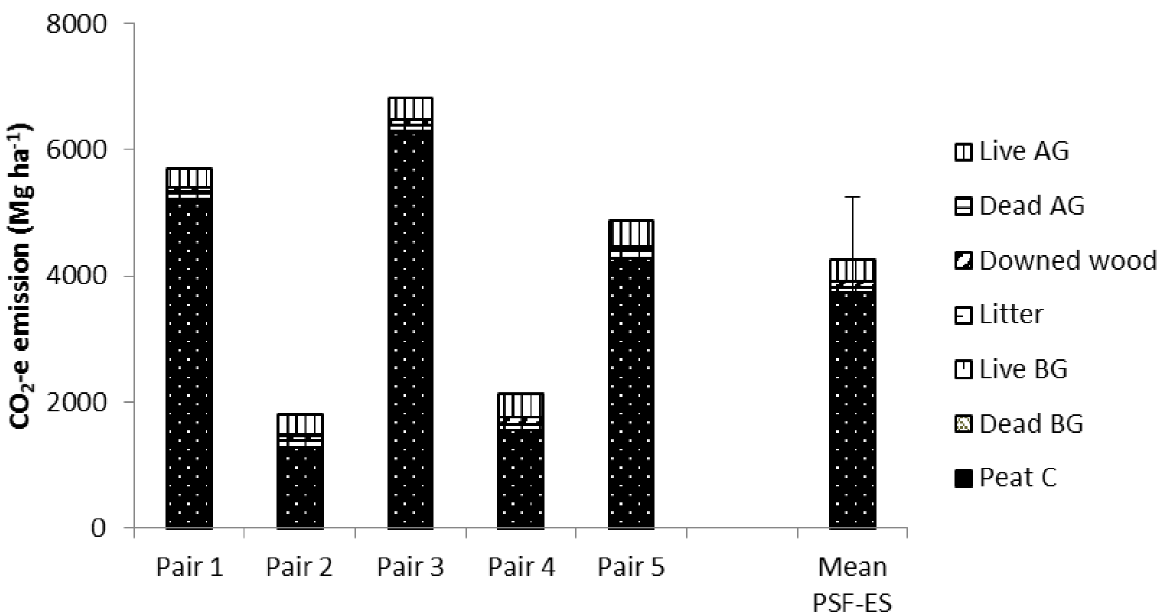



Figure 3.6. Ecosystem C stocks in peat swamp forests (PSF) and adjacent logged peat swamp forests (LPSF; a), early seral (ES; b) and oil palm plantations (OP; c), Ketapang, Indonesia. Vertical bars are one standard error. Pair represents paired land cover types that were compared on their C stocks, e.g. pair of PSF and LPSF, pair of PSF and ES or pair of PSF and OP.

a)


8000
6000
4000
2000
0
$CO_2$-e emission (Mg ha$^{-1}$)
Pair 1
Pair 2
Pair 3
Pair 4
Pair 5
Mean
PSF-LPSF
Live AG
Dead AG
Downed wood
Litter
Live BG
Dead BG
Peat C

b)


8000
6000
4000
2000
0
$CO_2$-e emission (Mg ha$^{-1}$)
Pair 1
Pair 2
Pair 3
Pair 4
Pair 5
Mean
PSF-ES
Live AG
Dead AG
Downed wood
Litter
Live BG
Dead BG
Peat C

c)

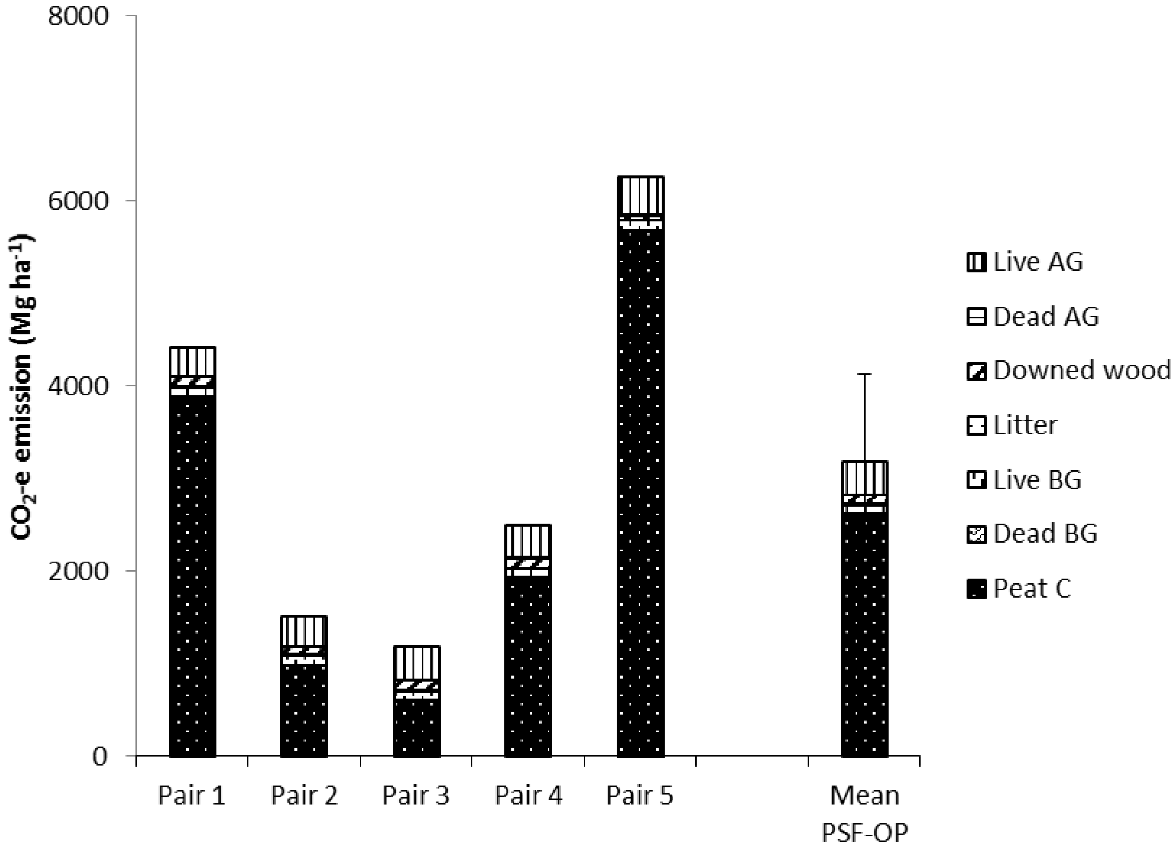



Figure 3.7. Predicted emissions (Mg $CO_2$-e $ha^{-1}$) arising from the degradation and conversion of peat swamp forest (PSF) to logged peat swamp forests (LPSF; a), early seral (ES; b) and oil palm plantations (OP; c) in the Pematang Gadung peat dome, Ketapang, Indonesia, based upon based upon a stock-change approach (CSD). Vertical bars above the means are one standard error. Pair represents paired land cover types that were compared on their C stocks, e.g. pair of PSF and LPSF, pair of PSF and ES or pair of PSF and OP.

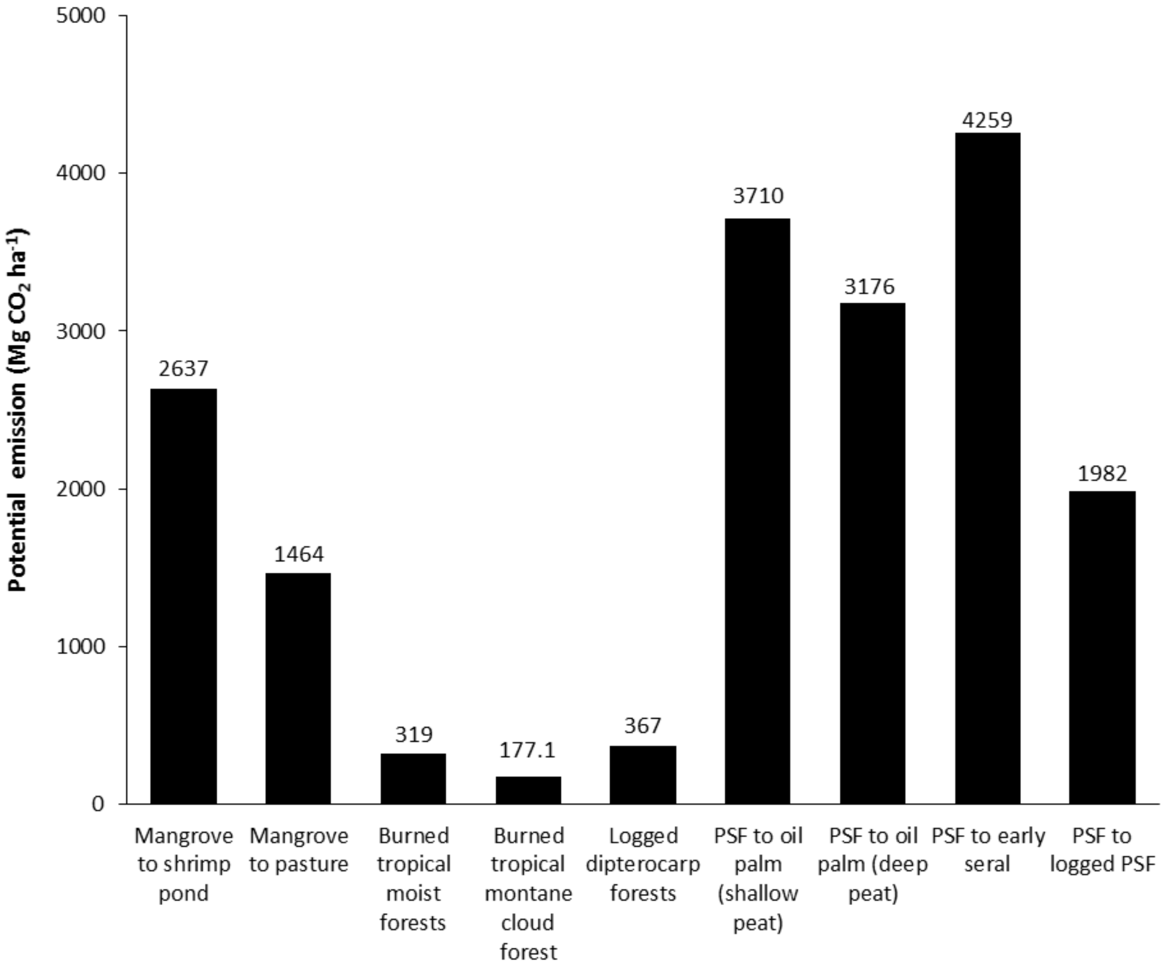



Figure 3.8. Potential emission from forest conversion, burning and logging among global terrestrial ecosystems. Data for mangrove conversion to shrimp pond are from (Kauffman *et al.*, 2014). Mangrove conversion to pasture are from (Kauffman *et al.*, 2016). Burned tropical montane cloud forest are from (Roman-Cuesta *et al.*, 2011). PSF to oil palm, early seral and logged PSF are from this study and (Novita, 2016).

## Tables

Table 3.1. Measurement data used in the referenced equations

| Data | Equation | Reference | Results |
|---|---|---|---|
| Tree dbh (cm) | $0.136*(\text{tree dbh})^{2.51}$ | Manuri et al. 2014 | Tree biomass |
| Tree biomass (kg) | 0.489*(tree biomass^0.89) | Mokany et al. 2006 | Tree root biomass |
| Snag height and dbh (cm); Wood density/WD ($g/cm^3$) | 0.8*WD*(snag height*(0.314* (snag dbh/2)^2)) | Murdiyarso et al. 2009 | Snag biomass |
| Oil palm height (cm) | 0.0976*(oil palm height) + 0.0706 | Dewi et al. 2010 | Oil palm biomass |
| Oil palm biomass (kg) | 14.2%*Oil palm biomass | Henson and Dolmat 2003 | Oil palm root biomass |

Table 3.2. Composition of wood density (by size and quality) and carbon (by size) of woody debris in the four land cover sites. Higher carbon stock of woody debris in PSF sites than in LPSF, ES and OP ($p < 0.05$).

| Site | ------ Wood density ($g\ cm^{-3}$) ------ | | | ------ Carbon ($Mg\ ha^{-1}$) ------ | | |
|---|---|---|---|---|---|---|
| | Fine | Coarse - Sound | Coarse - Rotten | Fine | Coarse | Total |
| PSF1 | 0.54 ± 0.04 | 0.53 ± 0.09 | 0.45 ± 0.1 | 24.1 ± 3.9 | 6.9 ± 2.1 | 31 ± 5.3 |
| PSF2 | 0.51 ± 0.05 | 0.48 ± 0.05 | 0.44 ± 0.08 | 12.6 ± 3.1 | 9.6 ± 1.8 | 22.2 ± 3.8 |
| PSF3 | 0.39 ± 0.02 | 0.51 ± 0.01 | 0.37 ± 0.03 | 13.7 ± 2.8 | 19.3 ± 3.3 | 33.1 ± 4.4 |
| PSF4 | 0.41 ± 0.06 | 0.68 ± 0.05 | 0.4 ± 0.05 | 8.3 ± 3 | 10.7 ± 6.5 | 19 ± 8.5 |
| **Mean PSF** | **0.46 ± 0.06** | **0.55 ± 0.07** | **0.42 ± 0.08** | **14.7 ± 4.7** | **11.6 ± 5** | **26.3 ± 7.3** |
| LPSF1 | 0.39 ± 0.07 | 0.55 ± 0.06 | 0.42 ± 0.04 | 8.6 ± 3.4 | 11.9 ± 3.3 | 20.4 ± 3.4 |
| LPSF2 | 0.28 ± 0.02 | 0.5 ± 0.16 | 0.26 ± 0.03 | 5 ± 1.2 | 5.6 ± 1 | 10.7 ± 1.2 |
| LPSF3 | 0.33 ± 0.02 | 0.59 ± 0.1 | 0.21 ± 0.02 | 3.7 ± 1.4 | 5.7 ± 3.1 | 9.4 ± 3.8 |
| LPSF4 | 0.29 ± 0.03 | 0.33 ± 0.03 | 0.24 ± 0.02 | 3.2 ± 1.2 | 3.2 ± 0.7 | 6.4 ± 1.3 |
| LPSF5 | 0.29 ± 0.05 | 0.4 ± 0.04 | 0.26 ± 0.05 | 4.2 ± 1.5 | 9 ± 2.6 | 13.1 ± 2.8 |
| **Mean LPSF** | **0.32 ± 0.04**** | **0.47 ± 0.09** | **0.28 ± 0.05**** | **4.9 ± 2.16**** | **7.1 ± 2.8*** | **12 ± 3.48**** |
| ES1 | 0.44 ± 0.08 | 0.62 ± 0.06 | 0.28 ± 0 | 10.71 ± 5.2 | 2.3 ± 0.7 | 13.01 ± 5.3 |
| ES2 | 0.5 ± 0.05 | 0.58 ± 0.02 | 0.33 ± 0.06 | 4.23 ± 2 | 3.19 ± 1.1 | 7.42 ± 2.9 |
| ES3 | 0.42 ± 0.12 | 0.8 ± 0.02 | 0.37 ± 0.06 | 2.06 ± 1.3 | 0.83 ± 0.4 | 2.89 ± 1.4 |
| ES4 | 0.44 | 0.59 ± 0.29 | 0.45 ± 0.16 | 0.66 ± 0.7 | 1.02 ± 0.5 | 1.67 ± 1 |
| ES5 | 0.42 | 0.97 | 0.36 | 1.24 ± 1.2 | 0.91 ± 0.8 | 2.15 ± 1.3 |
| **Mean ES** | **0.44 ± 0.07** | **0.71 ± 0.09*** | **0.36 ± 0.06** | **3.8 ± 3.2**** | **1.6 ± 0.9**** | **5.4 ± 3.5**** |
| OP1 | 0.82 | 0.36 ± 0 | 0.19 ± 0.04 | 0.6 ± 0.6 | 1.7 ± 0.9 | 2.3 ± 1 |
| OP2 | - | 0.55 ± 0.07 | 0.28 ± 0.05 | 0 | 2.1 ± 0.9 | 2.1 ± 0.9 |
| OP3 | 0.62 | 0.66 ± 0.02 | 0.19 | 1.8 ± 1.8 | 3.5 ± 3.1 | 5.3 ± 3.3 |
| OP4 | 0.41 ± 0.05 | 0.47 ± 0.04 | 0.35 ± 0.01 | 4 ± 1.3 | 2 ± 0.7 | 6 ± 1.5 |
| OP5 | - | 0.68 | - | 0 | 0.2 ± 0.2 | 0.2 ± 0.2 |
| **Mean OP** | **0.37 ± 0.08** | **0.54 ± 0.06** | **0.2 ± 0.04**** | **1.3 ± 1.3**** | **1.9 ± 1.6**** | **3.2 ± 2**** |

[*] the mean value is significantly different with the PSF at $p < 0.1$
[**] the mean value is significantly different with the PSF at $p < 0.05$

Table 3.3. Vegetation biomass and carbon pools (Mg $ha^{-1}$) of land cover types in Pematang Gadung peat dome, Ketapang, Indonesia Land cover change significantly affects total aboveground (AG) and belowground (BG) carbon stocks (ANOVA, p = 0.001).

| Site | Live AG tree biomass | Dead AG tree biomass | Live BG tree biomass | Dead BG tree biomass | Live AG tree C | Dead AG tree C | Live BG tree C | Dead BG tree C | Woody debris C | Litter C | Total AG C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **PSF1** | 176.24 ± 22.08 | 8.15 ± 2.65 | 52.04 ± 6.15 | 2.33 ± 0.64 | 81.78 ± 10.25 | 3.78 ± 1.23 | 24.15 ± 2.85 | 1.08 ± 0.3 | 31 ± 5.32 | 7.22 ± 0.96 | 149 ± 12.48 |
| **PSF2** | 192.94 ± 18.33 | 5.41 ± 1.79 | 56.2 ± 4.26 | 1.68 ± 0.53 | 89.52 ± 8.51 | 2.51 ± 0.83 | 26.07 ± 1.98 | 0.78 ± 0.24 | 22.25 ± 3.79 | 9.8 ± 1.69 | 150.94 ± 9.95 |
| **PSF3** | 210.88 ± 33.51 | 1.51 ± 0.53 | 56.45 ± 7.06 | 0.52 ± 0.17 | 97.85 ± 15.55 | 0.7 ± 0.25 | 26.2 ± 3.27 | 0.24 ± 0.08 | 33.09 ± 4.37 | 4.84 ± 0.55 | 162.91 ± 21.13 |
| **PSF4** | 243.63 ± 23.29 | 4.93 ± 2.52 | 65.49 ± 4.24 | 1.43 ± 0.62 | 113.04 ± 10.81 | 2.29 ± 1.17 | 30.39 ± 1.97 | 0.66 ± 0.29 | 19.02 ± 8.49 | 4.63 ± 0.54 | 170.03 ± 11.83 |
| **PSF mean** | **205.92 ± 14.42** | **5 ± 1.36** | **57.55 ± 2.84** | **2.32 ± 0.63** | **95.55 ± 6.69** | **1.49 ± 0.38** | **26.7 ± 1.32** | **0.69 ± 0.17** | **26.34 ± 3.39** | **6.62 ± 1.21** | **158.22 ± 5** |
| **LPSF1** | 162.46 ± 29.51 | 0.62 ± 0.19 | 44.63 ± 6.75 | 0.24 ± 0.07 | 75.38 ± 13.69 | 0.29 ± 0.09 | 20.71 ± 3.13 | 0.11 ± 0.03 | 9.35 ± 3.76 | 2.95 ± 0.41 | 108.8 ± 19.9 |
| **LPSF2** | 104.3 ± 19.39 | 4.4 ± 4.13 | 31.31 ± 5.55 | 1.18 ± 1.07 | 48.4 ± 9 | 2.04 ± 1.92 | 14.53 ± 2.58 | 0.55 ± 0.5 | 10.66 ± 1.16 | 4.88 ± 0.51 | 81.06 ± 11.76 |
| **LPSF3** | 128.1 ± 34.46 | 6.42 ± 3.01 | 34.41 ± 6.95 | 1.74 ± 0.79 | 59.44 ± 15.99 | 2.98 ± 1.4 | 15.97 ± 3.22 | 0.81 ± 0.37 | 20.42 ± 3.35 | 6.38 ± 1.08 | 105.99 ± 20.88 |
| **LPSF4** | 92.42 ± 17.51 | 7.13 ± 5.82 | 26.82 ± 4.32 | 1.73 ± 1.3 | 42.88 ± 8.12 | 3.31 ± 2.7 | 12.44 ± 2.01 | 0.8 ± 0.6 | 6.45 ± 1.32 | 4.03 ± 0.77 | 69.91 ± 8.62 |
| **LPSF5** | 144.52 ± 25.01 | 0.1 ± 0.04 | 38.52 ± 4.96 | 0.05 ± 0.02 | 67.06 ± 11.6 | 0.05 ± 0.02 | 17.87 ± 2.3 | 0.02 ± 0.01 | 13.14 ± 2.76 | 2.86 ± 0.3 | 101 ± 14.79 |
| **LPSF mean** | **126.36 ± 12.8**** | **3.73 ± 1.45** | **35.14 ± 3.05**** | **0.99 ± 0.36** | **58.63 ± 5.94**** | **1.73 ± 0.67** | **16.3 ± 1.42**** | **0.46 ± 0.17** | **12 ± 2.36**** | **4.22 ± 0.66** | **93.35 ± 7.61**** |
| **ES1** | 0.27 ± 0.27 | 0.24 ± 0.07 | 0.08 ± 0.08 | 0.11 ± 0.03 | 0.12 ± 0.12 | 0.11 ± 0.03 | 0.04 ± 0.04 | 0.05 ± 0.01 | 13.01 ± 5.33 | 4.6 ± 0.5 | 17.84 ± 5.6 |
| **ES2** | 0 ± 0 | 0.17 ± 0.1 | 0 ± 0 | 0.07 ± 0.04 | 0 ± 0 | 0.08 ± 0.04 | 0 ± 0 | 0.03 ± 0.02 | 2.15 ± 1.29 | 5.81 ± 0.73 | 8.04 ± 1.5 |
| **ES3** | 1.43 ± 1.23 | 0.06 ± 0.03 | 0.49 ± 0.42 | 0.03 ± 0.01 | 0.66 ± 0.57 | 0.03 ± 0.02 | 0.23 ± 0.19 | 0.01 ± 0.01 | 7.42 ± 2.91 | 8.91 ± 2.09 | 17.02 ± 4.57 |
| **ES4** | 1.28 ± 1.11 | 0.05 ± 0.02 | 0.43 ± 0.36 | 0.03 ± 0.01 | 0.59 ± 0.51 | 0.02 ± 0.01 | 0.2 ± 0.17 | 0.01 ± 0 | 2.89 ± 1.35 | 5.22 ± 0.56 | 8.72 ± 1.02 |
| **ES5** | 3.78 ± 2.72 | 0 ± 0 | 1.23 ± 0.82 | 0 ± 0 | 1.75 ± 1.26 | 0 ± 0 | 0.57 ± 0.38 | 0 ± 0 | 1.67 ± 1.04 | 5.23 ± 0.38 | 8.66 ± 2.41 |
| **ES mean** | **1.35 ± 0.67**** | **0.1 ± 0.04**** | **0.45 ± 0.22**** | **0.05 ± 0.02**** | **0.62 ± 0.31**** | **0.05 ± 0.02**** | **0.21 ± 0.1**** | **0.02 ± 0.01**** | **5.43 ± 2.15**** | **5.95 ± 0.76** | **12.29 ± 2.18**** |
| **OP1** | 1.01 ± 0.09 | 0 ± 0 | 0.06 ± 0.01 | 0 ± 0 | 0.47 ± 0.04 | 0 ± 0 | 0.03 ± 0 | 0 ± 0 | 2.33 ± 1.01 | 1.98 ± 0.18 | 4.78 ± 0.86 |
| **OP2** | 0.2 ± 0.05 | 0.16 ± 0.08 | 0.01 ± 0 | 0.07 ± 0.03 | 0.09 ± 0.02 | 0.07 ± 0.03 | 0.01 ± 0 | 0.03 ± 0.01 | 0.19 ± 0.19 | 4.61 ± 0.29 | 4.97 ± 0.38 |
| **OP3** | 1.14 ± 0.13 | 0.13 ± 0.04 | 0.07 ± 0.01 | 0.07 ± 0.02 | 0.53 ± 0.06 | 0.06 ± 0.02 | 0.03 ± 0 | 0.03 ± 0.01 | 5.35 ± 3.26 | 1.4 ± 0.29 | 7.33 ± 3.53 |

Table 3.3 (continued)

| Site | Live AG tree biomass | Dead AG tree biomass | Live BG tree biomass | Dead BG tree biomass | Live AG tree C | Dead AG tree C | Live BG tree C | Dead BG tree C | Woody debris C | Litter C | Total AG C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **OP4** | 1.19 ± 0.16 | 0.05 ± 0.03 | 0.07 ± 0.01 | 0.02 ± 0.01 | 0.55 ± 0.07 | 0.02 ± 0.01 | 0.03 ± 0 | 0.01 ± 0.01 | 2.09 ± 0.91 | 4.62 ± 1.15 | 7.28 ± 0.98 |
| **OP5** | 0.24 ± 0.02 | 0.33 ± 0.06 | 0.01 ± 0 | 0.16 ± 0.03 | 0.11 ± 0.01 | 0.15 ± 0.03 | 0.01 ± 0 | 0.08 ± 0.01 | 5.99 ± 1.52 | 4.68 ± 0.38 | 10.93 ± 1.62 |
| **OP mean** | **0.76 ± 0.22**** | **0.13 ± 0.06**** | **0.04 ± 0.01**** | **0.06 ± 0.03**** | **0.35 ± 0.1**** | **0.06 ± 0.03**** | **0.02 ± 0**** | **0.03 ± 0.01**** | **3.19 ± 1.08**** | **3.46 ± 0.73**** | **7.53 ± 0.99**** |

[*] the mean value is significantly different with the PSF at $p < 0.1$

[**] the mean value is significantly different with the PSF at $p < 0.05$

Table 3.4. Characteristics of sampling locations within the Pematang Gadung peat dome, Ketapang, Indonesia.

| **Site** | **Type** | **Latitude** | **Longitude** | **Peat depth (cm)** | **Tree density (tree** ha$^{-1}$**)** |
|---|---|---|---|---|---|
| PSF1 | Peat Swamp Forest | -1.899 | 110.128 | 945 ± 18 | 1906 ± 185 |
| PSF2 | Peat Swamp Forest | -1.898 | 110.135 | 953 ± 24 | 1906 ± 97 |
| PSF3 | Peat Swamp Forest | -1.867 | 110.155 | 922 ± 40 | 1523 ± 91 |
| PSF4 | Peat Swamp Forest | -1.870 | 110.158 | 841 ± 10 | 1635 ± 62 |
| **Mean PSF** | | | | **915 ± 25** | **1743 ± 97** |
| LPSF1 | Logged Peat Swamp Forest | -1.874 | 110.141 | 660 ± 4 | 1348 ± 112 |
| LPSF2 | Logged Peat Swamp Forest | -1.869 | 110.144 | 793 ± 41 | 1226 ± 165 |
| LPSF3 | Logged Peat Swamp Forest | -1.862 | 110.157 | 748 ± 21 | 1125 ± 147 |
| LPSF4 | Logged Peat Swamp Forest | -1.835 | 110.171 | 683 ± 20 | 1359 ± 204 |
| LPSF5 | Logged Peat Swamp Forest | -1.833 | 110.174 | 743 ± 17 | 1354 ± 104 |
| **Mean LPSF** | | | | **725 ± 53** | **1355 ± 104** |
| ES1 | Early Seral | -1.895 | 110.112 | 766 ± 11 | 5 ± 5 |
| ES2 | Early Seral | -1.874 | 110.133 | 750 ± 0 | 0 ± 0 |
| ES3 | Early Seral | -1.861 | 110.150 | 603 ± 2 | 69 ± 57 |
| ES4 | Early Seral | -1.855 | 110.158 | 702 ± 2 | 42 ± 36 |
| ES5 | Early Seral | -1.849 | 110.177 | 687 ± 46 | 11 ± 11 |
| **Mean ES** | | | | **702 ± 29** | **25 ± 13** |
| OP1 | Oil palm | -1.893 | 110.111 | 737 ± 40 | 191 ± 12 |
| OP2 | Oil palm | -1.873 | 110.133 | 783 ± 21 | 127 ± 8 |
| OP3 | Oil palm | -1.859 | 110.147 | 683 ± 17 | 159 ± 12 |
| OP4 | Oil palm | -1.848 | 110.170 | 687 ± 8 | 170 ± 13 |
| OP5 | Oil palm | -1.848 | 110.178 | 608 ± 2 | 53 ± 13 |
| **Mean OP** | | | | **700 ± 29** | **140 ± 24** |

Table 3.5. The bulk density (BD; g/cm$^3$), carbon density (CD; g cm$^{-3}$), carbon concentration (C; %), and carbon stock (Mg ha$^{-1}$) of peats partitioned by depth in four land cover types, Ketapang, Indonesia.

| | | Soil depth (cm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | | 0-15 | 15-30 | 30-50 | 50-100 | 100-300 | 300-600 | >600 | Total |
| PSF1 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.09 ± 0.02 | 0.09 ± 0.01 | 0.08 ± 0.01 | 0.11 ± 0.01 | 0.1 ± 0.01 | 0.09 ± 0.01 | 0.09 ± 0.01 | |
| | C (%) | 58.5 ± 1.4 | 59.6 ± 0.6 | 60.3 ± 0.5 | 63.6 ± 0.7 | 62.3 ± 0.3 | 62.4 ± 0.2 | 62.7 ± 0.5 | |
| | carbon density (g cm$^{-3}$) | 0.05 ± 0.01 | 0.05 ± 0 | 0.05 ± 0.01 | 0.07 ± 0 | 0.06 ± 0 | 0.05 ± 0.01 | 0.06 ± 0.01 | |
| | C stock (Mg ha$^{-1}$) | 81 ± 14 | 77 ± 6 | 100 ± 11 | 345 ± 22 | 1190 ± 78 | 1635 ± 170 | 2013 ± 155 | 5442 ± 315 |
| PSF2 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.08 ± 0.01 | 0.05 ± 0.01 | 0.07 ± 0.01 | 0.08 ± 0 | 0.07 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0 | |
| | C (%) | 56.7 ± 0.3 | 57.9 ± 0.4 | 60.2 ± 0.5 | 61.6 ± 0.2 | 61.8 ± 0.8 | 58.3 ± 4.6 | 62.2 ± 1 | |
| | CD (g cm$^{-3}$) | 0.05 ± 0 | 0.03 ± 0 | 0.04 ± 0 | 0.05 ± 0 | 0.04 ± 0 | 0.04 ± 0 | 0.03 ± 0 | |
| | C stock (Mg ha$^{-1}$) | 79 ± 5 | 47 ± 7 | 79 ± 7 | 251 ± 15 | 886 ± 100 | 1090 ± 119 | 1219 ± 83 | 3650 ± 110 |
| PSF3 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.1 ± 0.03 | 0.07 ± 0 | 0.07 ± 0 | 0.06 ± 0.01 | 0.07 ± 0.01 | 0.06 ± 0.01 | 0.17 ± 0.01 | |
| | C (%) | 54.9 ± 3.9 | 56.3 ± 1.4 | 60.3 ± 0.7 | 61.5 ± 0.2 | 60 ± 1.5 | 57.2 ± 1.7 | 30 ± 1.5 | |
| | CD (g cm$^{-3}$) | 0.05 ± 0.01 | 0.04 ± 0 | 0.04 ± 0 | 0.03 ± 0 | 0.04 ± 0 | 0.03 ± 0.01 | 0.05 ± 0 | |
| | C stock (Mg ha$^{-1}$) | 78 ± 12 | 62 ± 2 | 80 ± 6 | 161 ± 14 | 824 ± 88 | 958 ± 198 | 1611 ± 284 | 3774 ± 312 |
| PSF4 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.07 ± 0 | 0.1 ± 0.01 | 0.08 ± 0.02 | 0.1 ± 0.02 | 0.08 ± 0.01 | 0.12 ± 0.02 | 0.08 ± 0 | |
| | C (%) | 53.6 ± 4.8 | 58.9 ± 1.4 | 60.7 ± 0.4 | 61.4 ± 0.7 | 57 ± 3 | 46.3 ± 4.7 | 55.5 ± 2.9 | |
| | CD (g cm$^{-3}$) | 0.04 ± 0 | 0.06 ± 0.01 | 0.04 ± 0.01 | 0.06 ± 0.01 | 0.05 ± 0 | 0.05 ± 0.01 | 0.04 ± 0 | |
| | C stock (Mg ha$^{-1}$) | 55 ± 6 | 90 ± 11 | 86 ± 14 | 294 ± 50 | 923 ± 75 | 1564 ± 213 | 1091 ± 113 | 4104 ± 292 |

Table 3.5 (continued)

| Site | | Soil depth (cm 0-15 | 15-30 | 30-50 | 50-100 | 100-300 | 300-600 | >600 | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Mean PSF** | | | | | | | | | |
| | **BD (**g cm$^{-3}$**)** | **0.09 ± 0.01** | **0.08 ± 0.01** | **0.08 ± 0** | **0.09 ± 0.01** | **0.08 ± 0.01** | **0.08 ± 0.01** | **0.1 ± 0.02** | |
| | C (%) | **55.93 ± 1.07** | **58.18 ± 0.72** | **60.38 ± 0.11** | **62.03 ± 0.53** | **60.28 ± 1.2** | **56.05 ± 3.44** | **52.6 ± 7.71** | |
| | **CD (**g cm$^{-3}$**)** | **0.05 ± 0** | **0.05 ± 0.01** | **0.04 ± 0** | **0.05 ± 0.01** | **0.05 ± 0** | **0.04 ± 0** | **0.05 ± 0.01** | |
| | **C stock (**Mg ha$^{-1}$**)** | **73 ± 6** | **69 ± 9** | **86 ± 5** | **263 ± 39** | **956 ± 81** | **1312 ± 169** | **1484 ± 208** | **4243 ± 411** |
| LPSF1 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.11 ± 0.02 | 0.09 ± 0.01 | 0.08 ± 0.02 | 0.07 ± 0.01 | 0.07 ± 0 | 0.12 ± 0.03 | 0.22 ± 0.03 | |
| | C (%) | 57.1 ± 0.7 | 59.6 ± 0.5 | 60.3 ± 0.9 | 55.3 ± 4.5 | 62.1 ± 0.6 | 45.6 ± 5 | 23.7 ± 4.8 | |
| | CD (g cm$^{-3}$) | 0.06 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.04 ± 0.01 | 0.04 ± 0 | 0.05 ± 0.01 | 0.05 ± 0 | |
| | C stock (Mg ha$^{-1}$) | 95 ± 14 | 78 ± 12 | 99 ± 20 | 181 ± 28 | 868 ± 50 | 1409 ± 220 | 660 ± 101 | 3390 ± 192 |
| LPSF2 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.11 ± 0.01 | 0.09 ± 0.01 | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.06 ± 0 | 0.07 ± 0 | 0.17 ± 0.06 | |
| | C (%) | 58.7 ± 0.5 | 59.1 ± 0.4 | 59.3 ± 0.6 | 60.2 ± 0.9 | 61.9 ± 0.4 | 62.5 ± 0.5 | 46.5 ± 9.3 | |
| | CD (g cm$^{-3}$) | 0.06 ± 0.01 | 0.05 ± 0 | 0.04 ± 0.01 | 0.04 ± 0 | 0.04 ± 0 | 0.05 ± 0 | 0.06 ± 0.01 | |
| | C stock (Mg ha$^{-1}$) | 96 ± 12 | 81 ± 7 | 87 ± 10 | 223 ± 22 | 701 ± 44 | 1365 ± 87 | 1218 ± 384 | 3771 ± 433 |
| LPSF3 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.08 ± 0.01 | 0.11 ± 0.03 | 0.09 ± 0.02 | 0.07 ± 0.01 | 0.08 ± 0.01 | 0.15 ± 0.01 | 0.42 ± 0.04 | |
| | C (%) | 57.3 ± 0.9 | 58.5 ± 0.6 | 58.8 ± 1.2 | 61.4 ± 0.7 | 64.4 ± 0.6 | 41.1 ± 6.9 | 14.5 ± 3.6 | |
| | CD (g cm$^{-3}$) | 0.05 ± 0 | 0.06 ± 0.02 | 0.05 ± 0.01 | 0.04 ± 0 | 0.05 ± 0 | 0.06 ± 0.01 | 0.06 ± 0.01 | |
| | C stock (Mg ha$^{-1}$) | 72 ± 7 | 97 ± 23 | 105 ± 17 | 221 ± 21 | 980 ± 72 | 1835 ± 307 | 349 ± 70 | 3659 ± 359 |
| LPSF4 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.09 ± 0.01 | 0.09 ± 0 | 0.09 ± 0.01 | 0.1 ± 0.01 | 0.1 ± 0.01 | 0.14 ± 0.02 | 0.29 ± 0.05 | |
| | C (%) | 60.1 ± 0.7 | 61.5 ± 0.4 | 61 ± 0.4 | 63.5 ± 0.6 | 59.7 ± 4.8 | 38.9 ± 7.8 | 17.7 ± 4.1 | |
| | CD (g cm$^{-3}$) | 0.06 ± 0 | 0.05 ± 0 | 0.05 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0 | 0.05 ± 0.01 | 0.04 ± 0 | |
| | C stock (Mg ha$^{-1}$) | 84 ± 5 | 79 ± 4 | 108 ± 11 | 310 ± 25 | 1120 ± 99 | 1563 ± 197 | 483 ± 127 | 3506 ± 235 |

Table 3.5 (continued)

| Site | | Soil depth (cm) 0-15 | 15-30 | 30-50 | 50-100 | 100-300 | 300-600 | >600 | Total |
|---|---|---|---|---|---|---|---|---|---|
| LPSF5 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.1 ± 0.01 | 0.09 ± 0.01 | 0.1 ± 0.01 | 0.08 ± 0.01 | 0.09 ± 0.01 | 0.24 ± 0.03 | 0.26 ± 0.05 | |
| | C (%) | 61.2 ± 1 | 61.5 ± 0.3 | 61.5 ± 0.7 | 60.3 ± 2 | 65.1 ± 1.6 | 25.8 ± 3.5 | 20.5 ± 3.9 | |
| | CD (g cm$^{-3}$) | 0.06 ± 0 | 0.06 ± 0.01 | 0.06 ± 0.01 | 0.05 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0 | 0.04 ± 0 | |
| | C stock (Mg ha$^{-1}$) | 92 ± 5 | 87 ± 8 | 122 ± 16 | 228 ± 31 | 1217 ± 121 | 1666 ± 117 | 634 ± 83 | 4047 ± 212 |
| **Mean LPSF** | | | | | | | | | |
| | **BD (**g cm$^{-3}$**)** | **0.1 ± 0.01*** | **0.09 ± 0*** | **0.09 ± 0.01**** | **0.08 ± 0.01** | **0.08 ± 0.01** | **0.14 ± 0.03**** | **0.27 ± 0.04**** | |
| | C (%) | **58.88 ± 0.79**** | **60.04 ± 0.62**** | **60.18 ± 0.51** | **60.14 ± 1.35** | **62.64 ± 0.97**** | **42.78 ± 5.93**** | **24.58 ± 5.69**** | |
| | **CD (**g cm$^{-3}$**)** | **0.06 ± 0**** | **0.05 ± 0**** | **0.05 ± 0**** | **0.05 ± 0** | **0.05 ± 0** | **0.05 ± 0**** | **0.05 ± 0** | |
| | **C stock (**Mg ha$^{-1}$**)** | **88 ± 4**** | **84 ± 4**** | **104 ± 6**** | **233 ± 21** | **977 ± 91** | **1568 ± 86**** | **669 ± 148**** | **3675 ± 113** |
| ES1 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.1 ± 0.01 | 0.1 ± 0.01 | 0.09 ± 0.01 | 0.11 ± 0.01 | 0.09 ± 0 | 0.08 ± 0 | 0.08 ± 0 | |
| | C (%) | 63.3 ± 1.2 | 64.1 ± 0.3 | 63.3 ± 0.5 | 62.8 ± 0.5 | 63.4 ± 0.4 | 62.3 ± 0.7 | 62.7 ± 0.4 | |
| | CD (g cm$^{-3}$) | 0.06 ± 0.01 | 0.07 ± 0 | 0.06 ± 0 | 0.07 ± 0.01 | 0.05 ± 0 | 0.05 ± 0 | 0.05 ± 0 | |
| | C stock (Mg ha$^{-1}$) | 91 ± 8 | 99 ± 5 | 118 ± 8 | 334 ± 38 | 1086 ± 59 | 1442 ± 88 | 848 ± 55 | 4018 ± 127 |
| ES2 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.06 ± 0.01 | 0.06 ± 0.01 | 0.05 ± 0.01 | 0.06 ± 0.01 | 0.06 ± 0.01 | 0.15 ± 0.04 | 0.02 ± 0.02 | |
| | C (%) | 56.9 ± 1.6 | 59.3 ± 1.3 | 60.3 ± 1 | 59.9 ± 0.4 | 63.4 ± 1.3 | 25.1 ± 5.3 | 43.2 ± 9.1 | |
| | CD (g cm$^{-3}$) | 0.04 ± 0 | 0.04 ± 0 | 0.03 ± 0 | 0.04 ± 0 | 0.04 ± 0 | 0.03 ± 0 | 0.01 ± 0.01 | |
| | C stock (Mg ha$^{-1}$) | 54 ± 4 | 56 ± 7 | 66 ± 7 | 184 ± 22 | 815 ± 83 | 882 ± 38 | 6 ± 6 | 2062 ± 70 |
| ES3 | | | | | | | | | |
| | BD (g cm$^{-3}$) | 0.07 ± 0.01 | 0.08 ± 0.01 | 0.07 ± 0 | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.16 ± 0.02 | 0.09 ± 0.01 | |
| | C (%) | 59.2 ± 0.6 | 59.7 ± 1.8 | 62.3 ± 0.3 | 63.6 ± 0.3 | 64.2 ± 0.4 | 34.5 ± 4.3 | 48.6 ± 2.5 | |
| | CD (g cm$^{-3}$) | 0.04 ± 0 | 0.05 ± 0 | 0.04 ± 0 | 0.05 ± 0 | 0.04 ± 0.01 | 0.05 ± 0 | 0.04 ± 0.01 | |
| | C stock (Mg ha$^{-1}$) | 64 ± 4 | 74 ± 6 | 83 ± 4 | 234 ± 23 | 887 ± 191 | 1584 ± 86 | 425 ± 52 | 3353 ± 229 |

Table 3.5 (continued)

| | | Soil depth (cm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | | 0-15 | 15-30 | 30-50 | 50-100 | 100-300 | 300-600 | >600 | Total |
| ES4 | | | | | | | | | |
| | BD (g $cm^{-3}$) | 0.09 ± 0 | 0.06 ± 0.01 | 0.05 ± 0.01 | 0.07 ± 0 | 0.06 ± 0.01 | 0.13 ± 0.01 | 0.24 ± 0.05 | |
| | C (%) | 55.9 ± 0.9 | 57.9 ± 0.7 | 58.9 ± 1 | 59.3 ± 0.8 | 58.4 ± 0.6 | 40 ± 1.3 | 21.1 ± 4.2 | |
| | CD (g $cm^{-3}$) | 0.05 ± 0 | 0.03 ± 0 | 0.03 ± 0 | 0.04 ± 0 | 0.03 ± 0 | 0.05 ± 0 | 0.04 ± 0 | |
| | C stock (Mg $ha^{-1}$) | 71 ± 3 | 50 ± 5 | 59 ± 10 | 201 ± 11 | 666 ± 76 | 1511 ± 104 | 574 ± 238 | 2940 ± 288 |
| ES5 | | | | | | | | | |
| | BD (g $cm^{-3}$) | 0.07 ± 0.01 | 0.08 ± 0.01 | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.06 ± 0.01 | 0.21 ± 0.04 | 0.26 ± 0.09 | |
| | C (%) | 60.9 ± 1.9 | 62.9 ± 0.7 | 63.6 ± 0.6 | 64 ± 0.7 | 63.5 ± 1.2 | 28.8 ± 7.6 | 27 ± 5.2 | |
| | CD (g $cm^{-3}$) | 0.04 ± 0.01 | 0.05 ± 0.01 | 0.04 ± 0 | 0.05 ± 0 | 0.04 ± 0 | 0.05 ± 0.01 | 0.05 ± 0.01 | |
| | C stock (Mg $ha^{-1}$) | 60 ± 9 | 71 ± 8 | 85 ± 8 | 237 ± 20 | 717 ± 75 | 1408 ± 166 | 723 ± 82 | 3301 ± 193 |
| **Mean ES** | | | | | | | | | |
| | **BD** (g $cm^{-3}$**)** | **0.08 ± 0.01** | **0.08 ± 0.01** | **0.07 ± 0.01** | **0.08 ± 0.01** | **0.07 ± 0.01**** | **0.15 ± 0.02**** | **0.14 ± 0.05**** | |
| | C (%) | **59.24 ± 1.34**** | **60.78 ± 1.17**** | **61.68 ± 0.9**** | **61.92 ± 0.97** | **62.58 ± 1.06**** | **38.14 ± 6.55**** | **40.52 ± 7.5**** | |
| | **CD** (g $cm^{-3}$**)** | **0.05 ± 0** | **0.05 ± 0.01** | **0.04 ± 0.01** | **0.05 ± 0.01** | **0.04 ± 0*** | **0.05 ± 0** | **0.04 ± 0.01** | |
| | **C stock (**Mg $ha^{-1}$**)** | **68 ± 6** | **70 ± 9** | **82 ± 10** | **238 ± 26** | **834 ± 74*** | **1365 ± 125** | **515 ± 146**** | **3135 ± 320** |
| OP1 | | | | | | | | | |
| | BD (g $cm^{-3}$) | 0.13 ± 0.03 | 0.1 ± 0.01 | 0.11 ± 0.01 | 0.13 ± 0.01 | 0.09 ± 0.01 | 0.1 ± 0.01 | 0.1 ± 0.02 | |
| | C (%) | 62.5 ± 1.1 | 62.3 ± 1.1 | 61.9 ± 0.7 | 62.7 ± 0.6 | 63.6 ± 0.5 | 57.4 ± 3.4 | 60.6 ± 1.9 | |
| | CD (g $cm^{-3}$) | 0.08 ± 0.02 | 0.06 ± 0.01 | 0.07 ± 0.01 | 0.08 ± 0.01 | 0.06 ± 0 | 0.06 ± 0 | 0.06 ± 0.02 | |
| | C stock (Mg $ha^{-1}$) | 124 ± 35 | 97 ± 10 | 133 ± 14 | 405 ± 41 | 1132 ± 85 | 1652 ± 119 | 842 ± 248 | 4384 ± 305 |
| OP2 | | | | | | | | | |
| | BD (g $cm^{-3}$) | 0.11 ± 0.01 | 0.11 ± 0.01 | 0.09 ± 0.01 | 0.09 ± 0.01 | 0.07 ± 0.01 | 0.11 ± 0.01 | 0.09 ± 0.01 | |
| | C (%) | 58.5 ± 0.8 | 61.3 ± 1 | 61.2 ± 1 | 61.6 ± 1 | 59.7 ± 1.3 | 38.6 ± 2.4 | 39.8 ± 1 | |
| | CD (g $cm^{-3}$) | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.04 ± 0 | 0.04 ± 0 | 0.04 ± 0 | |
| | C stock (Mg $ha^{-1}$) | 100 ± 8 | 98 ± 8 | 106 ± 15 | 273 ± 26 | 880 ± 98 | 1259 ± 70 | 665 ± 87 | 3248 ± 226 |

Table 3.5 (continued)

| Site | | Soil depth (cm | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | 0-15 | 15-30 | 30-50 | 50-100 | 100-300 | 300-600 | >600 | |
| OP3 | | | | | | | | | |
| | BD (g $cm^{-3}$) | 0.09 ± 0.01 | 0.09 ± 0.01 | 0.06 ± 0 | 0.07 ± 0.02 | 0.08 ± 0.01 | 0.25 ± 0.03 | 0.27 ± 0.06 | |
| | C (%) | 59.4 ± 1 | 58.8 ± 1.3 | 60.3 ± 0.4 | 59.9 ± 1 | 64.6 ± 1.2 | 20.4 ± 2.8 | 31.3 ± 9.8 | |
| | CD (g $cm^{-3}$) | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.04 ± 0 | 0.04 ± 0.01 | 0.1 ± 0.05 | 0.05 ± 0.01 | 0.11 ± 0.06 | |
| | C stock (Mg $ha^{-1}$) | 76 ± 10 | 77 ± 9 | 78 ± 4 | 219 ± 52 | 1060 ± 83 | 1467 ± 256 | 631 ± 199 | 3608 ± 260 |
| OP4 | | | | | | | | | |
| | BD (g $cm^{-3}$) | 0.07 ± 0.01 | 0.07 ± 0.01 | 0.08 ± 0.01 | 0.09 ± 0.01 | 0.07 ± 0.01 | 0.13 ± 0.01 | 0.11 ± 0.01 | |
| | C (%) | 59.2 ± 0.8 | 62.1 ± 0.4 | 61.6 ± 1.5 | 59.4 ± 2.9 | 63.9 ± 0.6 | 37.8 ± 4.9 | 44.3 ± 4.8 | |
| | CD (g $cm^{-3}$) | 0.04 ± 0.01 | 0.04 ± 0 | 0.05 ± 0 | 0.05 ± 0.01 | 0.04 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0 | |
| | C stock (Mg $ha^{-1}$) | 66 ± 9 | 65 ± 6 | 99 ± 10 | 270 ± 29 | 857 ± 165 | 1497 ± 172 | 394 ± 37 | 3382 ± 167 |
| OP5 | | | | | | | | | |
| | BD (g $cm^{-3}$) | 0.09 ± 0.01 | 0.08 ± 0.01 | 0.08 ± 0.01 | 0.08 ± 0.01 | 0.06 ± 0 | 0.13 ± 0.02 | 0.22 ± 0.06 | |
| | C (%) | 63 ± 1 | 62.2 ± 0.6 | 61.7 ± 0.7 | 59.5 ± 1.4 | 64 ± 0.2 | 32.3 ± 4.3 | 26.1 ± 8.4 | |
| | CD (g $cm^{-3}$) | 0.06 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0 | 0.04 ± 0 | 0.04 ± 0 | 0.04 ± 0.01 | |
| | C stock (Mg $ha^{-1}$) | 86 ± 13 | 77 ± 13 | 97 ± 12 | 241 ± 17 | 720 ± 29 | 1294 ± 81 | 41 ± 8 | 2555 ± 87 |
| **Mean OP** | | | | | | | | | |
| | **BD** (g $cm^{-3}$) | **0.1 ± 0.01** | **0.09 ± 0.01** | **0.08 ± 0.01*** | **0.09 ± 0.01*** | **0.07 ± 0.01** | **0.14 ± 0.03**** | **0.16 ± 0.04**** | |
| | C (%) | **60.52 ± 0.93**** | **61.34 ± 0.66**** | **61.34 ± 0.28**** | **60.62 ± 0.65** | **63.16 ± 0.88**** | **37.3 ± 5.99**** | **40.42 ± 5.96**** | |
| | **CD** (g $cm^{-3}$) | **0.06 ± 0.01*** | **0.05 ± 0.01**** | **0.05 ± 0**** | **0.05 ± 0.01*** | **0.06 ± 0.01** | **0.05 ± 0*** | **0.06 ± 0.01** | |
| | **C stock** (Mg $ha^{-1}$) | **90 ± 10*** | **83 ± 6**** | **103 ± 9**** | **282 ± 32*** | **930 ± 74** | **1434 ± 72*** | **515 ± 138**** | **3435 ± 295** |

* the mean value is significantly different with the PSF at $p < 0.1$
** the mean value is significantly different with the PSF at $p < 0.05$.

# Chapter IV

## Net Ecosystem Production in Response to Land Cover Change in Tropical Coastal Peatlands of West Kalimantan, Indonesia

## ABSTRACT

Tropical peat swamp forests are carbon-rich ecosystems that have been threatened by high rates of land use change (LUC) and degradation for the last three decades. Yet few studies have quantified changes in ecosystem productivity associated with deforestation and LUC of tropical peatlands. I quantified net primary production (NPP) and net ecosystem production (NEP) in peat swamp forests (PSF), logged forests (LPSF), early seral (ES) and smallholder - oil palm plantations (OP) in a peat dome of West Kalimantan, Indonesia. LUC and forest degradation resulted in large shifts in NPP and NEP. LPSF, ES and OP have significantly lower NPP (11.1 Mg C $ha^{-1}$ $yr^{-1}$, 10.9 Mg C $ha^{-1}$ $yr^{-1}$ and 3.7 Mg C $ha^{-1}$ $yr^{-1}$, respectively) than PSF (13.2 Mg C $ha^{-1}$ $yr^{-1}$). ES showed lower heterotrophic respiration (30.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) than PSF, LPSF and OP (37.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, 40.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, 38.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$**,** respectively)**.** LPSF and OP were net carbon sources; they have negative mean NEP values (-0.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ and -25.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively). In contrast PSF and ES were net carbon sinks (10.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ and 9.1 $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively). PSF is among the most productive of terrestrial ecosystems, with an NPP exceeding that of many tropical rain forests and similar to the most productive mangrove ecosystems. I found that land use change decreases productivity of the peat swamp forests, by lowering its primary productivity rather than increasing its soil respiration. The early seral had a similar NEP to the forests, but frequent fires in this ecosystem likely offset carbon gains that occur during the fire intervals. Land use change and forest degradation has shifted tropical PSFs from net carbon sinks to net carbon sources.


**Keywords:** Land use changes, forest degradation, tropical peat swamp forests, oil palm plantation, NPP, NEP

## INTRODUCTION

Global deforestation and land use change in forests have contributed significantly to the global greenhouse gas emissions from terrestrial ecosystems. In Indonesia, recent estimates suggests that deforestation is more than 1000 $km^2$ $year^{-1}$ (Hansen *et al.*, 2013), the highest rates in the world. Forests, including peat swamp forests (PSF), have mainly been converted into oil palm (OP; *Elaeis guineensis*), food crops and timber plantations (Murdiyarso *et al.*, 2009; Hergoualc'h & Verchot, 2011).

Conversion of peat swamp forests involves cutting trees, burning and/or developing drainage canals (Anshari *et al.*, 2010; Verwer & Meer, 2010). Since 1990, oil palm plantations have been developed on about 6% (880,000 ha) of peat forests in Indonesia and Malaysia in 2010 (Koh *et al.*, 2011). This conversion was estimated to result in the loss of about 140 terra gram (Tg C = $10^{12}$ g C) of aboveground carbon (C) stocks. In addition, about 4.6 Tg of belowground C was lost from annual peat oxidation (Koh *et al.*, 2011) and about 233 Tg C may lost from land clearing fires (Konecny *et al.*, 2016). Oil palm area increased to be about 30% (2,046,000 ha) in 2015 of all peat swamp forests of Indonesia and about 3 million ha in South East Asia (Miettinen *et al.*, 2016). This created a fragmented mosaic of degraded forests, seral ecosystems and agricultural cover types in peatlands. At a global scale, $CO_2$ emissions from peatland drainage in Southeast Asia is equivalent to 1.3 to 3.1% of global $CO_2$ emissions from the combustion of fossil fuels (Hooijer *et al.*, 2010b). Yet this estimate was based on very few case studies.

Oil palm plantation development and management requires draining saturated soils in peat lands to provide for suitable growing conditions (Wösten *et al.*, 2008; Carlson *et al.*, 2012). Drainage canals decrease the water levels of peatlands thus increasing aerobic decomposition rates (Verwer & Meer, 2010). In a recent review, it was estimated that an increase of drainage depth by 10 cm results in an increased emission of about 9 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ (Hooijer *et al.*, 2012). Another severe consequence of drainage is the increased occurrence of peat fires, that can also result in the release of significant amounts of $CO_2$; as much as 1,400 Mg $CO_2$ $ha^{-1}$ (Page *et al.*, 2002).

C loss from PSF degradation and LUC can be estimated using two approaches: the C stock change and the C accumulation rate changes (IPCC, 2006a). The first approach (C stock changes) has been applied by (Kauffman *et al.*, 1995) in Brazilian Amazon forests, Schipper & McLeod (2002) in New Zealand peat bog, and Novita (2016) and Basuki (2017) in tropical peatlands of Indonesia. C stock changes were quantified by comparing the differences in C stocks in intact ecosystems with those of converted or degraded sites. For example, it was estimated that 3.7 Mg C $ha^{-1}$ $yr^{-1}$ was lost due to the conversion of New Zealand peat bog for dairy farm (Schipper & McLeod, 2002).

The second approach (C accumulation rate changes) has been done mostly in non-tropical peatland ecosystems (Golley *et al.*, 1962; Cao & Woodward, 1998; Komiyama *et al.*, 2008), except in a review study done for South East Asia region. Based upon a review by Hergoualc'h & Verchot (2011) changes on peat C accumulation and losses due to forest conversion into oil palm plantations was about 10.8 Mg C $ha^{-1}$ $yr^{-1}$ over a 25-year period following conversion (270 Mg C $ha^{-1}$).

Changes in carbon accumulation rates and losses of ecosystems can also be assessed using the eddy covariance techniques (Dragoni *et al.*, 2007; Hirano *et al.*, 2007; Aslan-Sungur *et al.*, 2016). This method basically uses the covariance of measured $CO_2$ concentration and the vertical component of air velocity above the vegetation canopy (Komiyama *et al.*, 2008). However, this is an expensive and sophisticated method that requires specific instruments, sources of electricity and complex computations (Janssens *et al.*, 2001).

Remote sensing has also been applied to estimate the emissions at the regional scale. The remote sensing data were combined with emission rate data from field measurements. For example, it was estimated that about 242 Tg C had lost from the 880,000 ha of converted peatlands in Indonesia and Malaysia from 1990 to 2010 (Koh *et al.*, 2011). Yet, this estimation was lack of sufficient information of emissions rates that can represent the variation of tropical peatlands in the region.

Carbon emissions from forest conversion may not be balanced by the regrowth following disturbance (Kauffman *et al.*, 2009). Change in the carbon accumulation rate from degradation and LUC of tropical peat swamp forests should be verified through direct field measurements in order to inform decision making on peat forests and to increase accuracies of estimates.

**Ecosystem and primary production of tropical peatland ecosystems**

Changes in carbon sequestration and emissions as affected by peat forests degradation and LUC can be estimated through determination of the net ecosystem production (NEP; Chapin *et al.*, 2006; Komiyama *et al.*, 2008). Net ecosystem production (NEP) is defined as the difference between gross primary production (GPP) and ecosystem respiration (ER; Chapin et al., 2006). GPP is defined as the gross vegetation uptake of $CO_2$ that is utilized for photosynthesis process (Chapin *et al.*, 2006). Ecosystem respiration is the total $CO_2$ that is released from the ecosystem to the atmosphere through autotrophic (vegetation) and heterotrophic (microbial) respiration processes (Clark & Brown, 2001; Randerson *et al.*, 2002; Chapin *et al.*, 2006). Net primary production (NPP) is defined as the difference between GPP and autotrophic respiration (Woodwell and Whittaker 1968). Therefore NEP can also be defined as the difference between NPP and heterotrophic respiration. Unfortunately, there has been no study on NEP in tropical peatland ecosystems, especially in relation with land use changes.

GPP cannot be directly measured in the field (Clark & Brown, 2001). Instead, NPP have been measured to study carbon dynamics and the role of forests and global climate change. Global NPP is estimated at 57.0 Pg C $yr^{-1}$ (Cao & Woodward, 1998). Monthly global NEP varies from –0.5 Gt C in October to 1.6 Gt C in July, thus create a seasonal amplitude of 2.1 Pg C annually (Cao & Woodward, 1998). The NPP of tropical forests has been reported to range between < 5 Mg C $ha^{-1}$ $yr^{-1}$ and 15 Mg C $ha^{-1}$ $yr^{-1}$ (Clark & Brown, 2001; Girardin *et al.*, 2010; Proctor, 2013). The NPP of tropical mangrove forests was estimated in a range between 2 Mg C $ha^{-1}$ $yr^{-1}$ and 12 Mg C $ha^{-1}$ $yr^{-1}$ (Komiyama *et al.*, 2008). Chimner & Ewel (2005) estimated that the NPP of tropical peat forest on the island of Kosrae in the Federated States of Micronesia was 11.2 Mg C $ha^{-1}$ $year^{-1}$, of which 94.3% was aboveground NPP. Similar to the NEP, NPP of tropical peat swamp forests and other peatland ecosystems in South East Asia remain under studied.

**Ecosystem respiration of tropical peatland**

Respiration of vegetation (stem, branches, canopy and roots), as part of the total ecosystem respiration, uses some photosynthesis products to grow and maintain structure. On the other hand, total soil respiration entails the $CO_2$ emission from both roots and microbial respiration (Ryan & Law, 2005). It reflects the movement of carbon from soil to the atmosphere that influence the balance between photosynthesis and ecosystem respiration (NEP). Soil respiration of autotrophic and heterotrophic sources can vary among seasons and ecosystems (Hanson *et al.*, 2000). Soil respiration is possibly more influential than photosynthesis in driving inter-annual variability of NEP (Valentini *et al.*, 2000).

Melling *et al.*, (2005) reported that soil respiration in peat swamp forests ecosystems was higher (21 Mg C $ha^{-1}$ $yr^{-1}$) than oil palm and sago plantations (15 Mg C $ha^{-1}$ $yr^{-1}$ and 11 Mg C $ha^{-1}$ $yr^{-1}$, respectively) in Sarawak, Malaysia. In contrast, Comeau *et al.*, (2013; in Jambi, Indonesia) found that soil respiration of OP plantation was higher (28.4 Mg C $ha^{-1}$ $yr^{-1}$) than those in PSF and logged PSF (16.0 Mg C $ha^{-1}$ $yr^{-1}$ and 18.5 Mg C $ha^{-1}$ $yr^{-1}$, respectively). Further studies are needed to resolve these contrasting results.

**Objectives and Research Questions**

Emissions from tropical peatlands has never been estimated using the field measurements on the change in NEP. In addition I could not find any publications conducted on measuring the impact of degradation and conversion of tropical peat swamp forests (PSF) on NPP and NEP. In order to understand the role of peat swamp forest ecosystems on sequestration and emissions of greenhouse gases (GHG), it is crucial to determine the C losses resulting from PSF degradation into logged PSF (LPSF) and conversion into early seral (ES) and oil palm plantations (OP). This study is among the first that included intensive field measurements of NPP and NEP in different tropical peatland cover types. This will be a follow up of my estimate on C losses from LUC using C stock change approach (Chapter 3, this dissertation).

My main objective of this study was to estimate the changes in NPP, $CO_2$ fluxes and NEP resulting from PSF disturbance by logging (LPSF), fire (ES) and land conversion (oil palm). My specific research questions included: What are the NPP and soil $CO_2$ fluxes of intact, undisturbed peat swamp forests? How do they differ due to logging? What is the NPP and soil $CO_2$ fluxes of ES and OP that are on sites previously occupied by PSF? What are the changes of NEP caused by logging, logging and fire (ES) and from land conversion, logging and fire in OP? And finally, how do these compare to the NPP, soil $CO_2$ fluxes and NEP estimated from other ecosystems?

My hypotheses were: a. NPP of intact peat swamp forests will be lower than those of tropical mangrove and lowland forests, because there is limited nutrient in peatlands' soils (Moore, 1987; Moore *et al.*, 2002); b. Considering its waterlogged environment (Rieley *et al.*, 2008; Murdiyarso *et al.*, 2013), the heterotrophic respiration of intact peat swamp forest will be lower than the tropical lowland forests but higher than the tropical mangrove; c. Logging and land use changes will significantly decrease NPP and increase heterotrophic respiration of tropical peat swamp forests, as those human induced disturbances had significantly reduced ecosystem carbon stocks of the forests (this dissertation, chapter 3); d. Logging, draining and land clearing will significantly increase heterotrophic respiration of tropical peat swamp forests, as those disturbances had exposed peat to oxidation process (this dissertation, chapter 3); e. Logging and land use changes will significantly decrease NEP of tropical peat swamp forest, because those interventions had increased heterotrophic respiration (Comeau *et al.*, 2013; Novita, 2016).

## METHODS

### Study site

The study area was located in Pematang Gadung, Ketapang, West Kalimantan, Indonesia (Figure 4.1). The Pematang Gadung is a coastal peat dome (34,651 ha) between the Pawan and Pesaguhan Rivers that flow on the northern and the southern end of the peat dome, respectively. These two rivers run to the Karimata strait between Sumatra and Borneo islands. The rainfall in the region averages 2000 mm per year with the majority falling during the months of November to July. The mean annual temperature is 27.5°C. Elevation ranges from 11-22 m above sea level.

I sampled 6 forests (3 relatively intact - peat swamp forests/PSF and 3 disturbed forests - logged peat swamp forests/LPSF) were slightly and heavily disturbed, respectively, by logging activities. They had a similar mean canopy height of about 15 m and occurred near or towards around the center of the peat dome and well away (>1 km) from roads. In addition to the forests, I sampled three early seral (ES) and three oil palm (OP) smallholder plantations. The OP plantations were surrounded by the ES and LPSF. The early seral sites had been logged in the past and had been subjected to many fires that eliminated the overstory trees canopy. They were currently dominated by ferns and grasses. Based upon observation on satellite imageries and interviews with local people, the forests were logged since about 25 years before sampling (in 1988). Early seral sites were first formed from the logged forests that were cleared and burned about 19 years before sampling. The three oil palm plantations were three, four and five years old. They had been established on ES sites following burning for land clearing construction of small drainage canals around their perimeters.

*Insert Figure 4.1.*

### Field sampling

I selected research sites based on field observations, discussions with local experts and analyses of Landsat images. Considerations include availability of PSF and other land cover types that were previously converted from the PSF, as well as the sites relative position within the peat dome. I quantified the ecosystem NPP and soil $CO_2$ fluxes of 12 different peatland sites including three PSF sites, three LPSF sites, three ES sites, and three OP sites. In order to ensure the sequential changes of land cover types (from forests to ES and OP), I paired each forest site with the others in a close distance. I sampled three groups of cover types (i.e. intact forest, logged forest, early seral, and oil palm).

Within each PSF, LPSF, ES, and OP site, six plots were established 30 m apart along a 150 m transect (Murdiyarso *et al.*, 2009; Kauffman & Donato, 2012), to measure the tree diameter that was needed to extrapolate my tree diameter growth model. In each of ES sites, additional six plots were also established 7 m apart along a 35 m transect on the similar direction to the other land cover types. These additional plots were set specifically to measure NPP on ES.

**Plant production/Net Primary Production**

In this study, NPP is defined as the sum of annual tree growth (above and belowground) and litterfall production.

***Forests***

<u>Aboveground NPP</u>

At each site a 35 m transect was established, 10 m away from the main transect where carbon stocks were measured (chapters 2 and 3). Trees were randomly selected along the transect for determination of growth. Using measurement tape, tree diameter was measured at 1.3 m aboveground (breast height) and tree (dendrometer) bands was then installed at the measurement point (Moser *et al.*, 2014).

In total, 120 tree bands were installed in the three sites of PSF and three sites of LPSF. On each tree, diameter growth was measured for a one year time interval using a digital caliper with 0.01 mm precision. Based upon data from these trees I developed an allometric equation using linear regression to estimate annual tree growth based upon the tree dbh at time 0. The model was used to predict the tree dbh data at the end of year 1. I then applied this model using the dbh of all trees within all the six plots of each site. Tree growth was then calculated by subtracting the tree biomass from time 0 by the predicted biomass at year 1. Aboveground tree biomass was determined using allometric equations of peat swamp forests (Manuri *et al.*, 2014). The allometric equation (Table 4.1) was developed in Sumatra and Borneo islands for peat swamp forest trees 2–167 cm dbh.

To determine litterfall, six litterfall-traps were established every 7 m apart along the same transect. With a radius of 0.27 m, each trap were positioned a meter above ground and tied to surrounding trees. Litterfall samples were collected, two times during wet season (November and December 2015) and four times during dry seasons (September and October of 2014 and of 2015). Samples were transported to laboratory, dried at 60°C to constant mass, and then weighed. Laboratory analysis was conducted at analytical laboratory where C and N were determined using the LECO Analyzer. Branch fall production was estimated as 9.89% of the litterfall annual production (Chimner & Ewel, 2005).

*Insert Table 4.1*

Belowground NPP

Coarse root production of all the forests trees was estimated using allometric equation derived from a critical analyses of root : shoot ratio in terrestrial biomass (Table 4.1; Mokany *et al.*, 2006). Fine root production was estimated as 12% of the sum of tree, coarse root and litterfall annual production (Chimner & Ewel, 2005).

Annual NPP of forest trees (PSF and LPSF) was calculated by summing the aboveground and belowground NPP. This calculation captured the annual production associated with tree growth, coarse and fine root growth, and litter and branch fall production. The forest annual NPP were reported as potential C sequestration, or $CO_2$ equivalents (C-$CO_2$)—obtained by multiplying C values by 3.67, the molecular ratio of $CO_2$ to C.

***Oil palm plantations***

In a transect established in a similar manner to those in the forests, the height to the apical meristem of all oil palm trees was measured at all OP sites (the base of their young leaves). The height was re-measured two years later. The annual height growth of oil palm trees was calculated by subtracting the initial tree height from the tree height at year 2, divided by two. Annual biomass growth for OP trees was estimated by applying the annual height growth into an allometric equation (Table 4.1; Dewi *et al.*, 2010). The equation was developed in Sumatera and Kalimantan islands used for oil palm trees < 1- to 8 m height on peatlands (Dewi *et al.*, 2010).

Pruned frond biomass was estimated as 75.3% of frond production that is 68.8% of the tree biomass growth (Henson & Dolmat, 2003). Dead root biomass was estimated as 71.7% of root production that is 14.2% of the tree biomass growth (Henson & Dolmat, 2003).

Annual NPP of OP sites was quantified by summing the tree production with the dead root and pruned frond (litter) production.

***Early seral***

The transect and plot design for fern and grass dominated ES sites differed from those for forests and oil palms. In each of the three ES sites, six plots were established in 7 m intervals. Each plot was one $m^2$ where all aboveground standing herbaceous biomass and litterfall were harvested. These ES plots were burned in September, 2014, which enabled us to estimate annual aboveground NPP of ES in September 2015. Standing mass and litterfall were sampled using destructive sampling. Samples were collected and weighed in the field, sub-sampled, transported to laboratory, dried at 60°C to constant mass, and then weighed. Laboratory analyses were conducted at the analytical laboratory at Bogor Agricultural University, Bogor, Indonesia. In the laboratory, the concentration of C and N were determined using the dry combustion method (induction furnace) with a LECO Analyzer.

Root annual production was estimated as 110% of total leaf and litterfall production/aboveground NPP (Scurlock & Olson, 2012). This value was derived from their long period of monitoring study (1939-1996) on tropical grassland ecosystems.

**Ecosystem respiration: soil and heterotrophic respiration**

$CO_2$ emissions from soils were measured intermittently for 2 months in 2014 (August and September) and 10 months in 2015 (all months but February and April), on all land cover types. At each site two transects of 35 m were established to measure $CO_2$ emissions (soil respiration). Those transects were located about 10 m away from the NPP transect (Appendix Figure 4). A board walk was constructed on each transect in order to avoid disturbance on peat surface while measurements were taking place. 12 measurement points were systematically established 3.5 m apart in each transect (24 points in total). Eighteen points were used to measure total soil respiration (autotrophic and heterotrophic sources) and 6 for only heterotrophic respiration (trenching, excluding roots). Trenching was used to cut and severe existing roots, and a barrier was installed to inhibit root growth (Hanson *et al.*, 2000). At each of the six trenched plots, a 200 cm circular plot was established by cutting the peat to 50 cm depth (Jassal & Black 2006) with a machete. The inside wall of the trench was lined with a very fine mesh aluminum screening and the trench was backfilled in order to minimized disturbance. When plants were found growing within the trenched plot, they removed to prevent any new root growth that would influence the soil $CO_2$ emissions.

Soil $CO_2$ respiration was measured using a portable infrared gas analyzer EGM-4 (PP Systems, USA) connected with a closed soil respiration chamber to peat surface. The $CO_2$ emissions (mg $m^{-2}$ $h^{-1}$) were calculated from the linear change with time of gas concentration (Jauhiainen *et al.*, 2005). Soil $CO_2$ concentration were automatically recorded every 4.5 second intervals for about two minutes. In each site, the respiration measurements were done between 3 pm until 6 pm. Only one or two sites could be measured in a day, in order to have similar timing of sampling in all sites.

**Water table and peat surface temperature**

Environmental factors were also measured during soil respiration measurements. Water table depth was measured using perforated PVC tubes (10 cm diameter, 2 m long) inserted into the peat. In the forests, these six tubes were positioned below the litterfall traps. In ES and OP sites, they were established 7 m apart along the 35 m transect that was parallel with the NPP transect (10 m away). Water level was measured once a month, at the same time of $CO_2$ flux measurement. Soil temperature at 10 cm depth was measured using a temperature probe sensor connected to the EGM 4 (PP System, USA), adjacent to the $CO_2$ flux measurement point.

**Statistical analyses**

The normality distribution of research data among classes of ecosystems (land uses), seasonal rainfall, biomass sources and primary production sources, was tested using Saphiro-Wilks and Kolmogorov-Smirnov tests. Site differences in the mean values of variables, (e.g., NPP and soil respiration), within the same land cover were tested using t-test. Mann-Whitney U test was performed when the data were not normally distributed. Differences in NPP, $CO_2$ flux and NEP s among land cover types were tested with analysis of variance (ANOVA), when the data is normally distributed. If the ANOVA was significant, a least significant difference (LSD) test was performed to determine which means were significantly different. Kruskal-Wallis H test was used for non-normally distributed data. Regression analyses was used to model the growth of forest trees using diameter at breast height data. Statistical analyses was conducted using IBM SPSS software version 20.

## RESULTS

### Water table and peat surface temperature

There were differences in the depth to the water table and soil temperatures between land cover types (Table 4.2; Appendix Figure 5). The lower water table at the OP sites was likely due to the presence of trenches and canals in close proximity. The mean annual water table depth in OP was 78.3 cm in contrast to the 50 cm or less depth for the water level at other ecosystems (PSF, LPSF and ES), which were located further from canals. Mean seasonal difference of water table depth in OP between dry season (August to October) and wet season (November to July) was lower than other ecosystems ($p < 0.05$).

The OP and ES sites were open and had limited shade, thus more sunlight reached the peat soil surface. The mean soil temperature on these two ecosystems were 30.5°C and 29.5°C, respectively, and higher than the soil temperature at PSF and LPSF (27.2°C and 27.0°C, respectively). Seasonal differences of soil temperature in ES between dry season and wet season was significantly higher than other ecosystems ($p < 0.05$).

*Insert Table 4.2*

**Net Primary Production of peatland ecosystems**

***PSF and LPSF***

Stem diameter (dbh) growth model using dbh data

I managed to obtain data from 118 out of 120 dendrometer bands that were installed in the forests . I lost two tree bands to through logging by local people. Measured tree diameter of sampled trees PSF and LPSF was similar and averaged at 10.6 cm. This value was similar to the mean value of tree diameter from all of the 314 $m^2$ forest plots (11.5 cm).

The allometric equation using dbh at time 0 to predict annual growth ($r^2$=0.98) was used to estimate the increment growth of all trees in the 314 $m^2$ of forest plots (Figure 4.2).

*Insert Figure 4.2*

Annual increment of big and small trees

Growth increment of trees was similar between the PSF and the LPSF averaging 0.21 cm over one year (Table 4.3). On bigger trees (dbh > 5 cm), aboveground (wood and leaves) biomass production in LPSF (3.2 Mg C $ha^{-1}yr^{-1}$) was lower than in PSF (4.6 Mg C $ha^{-1}yr^{-1}$; $p < 0.05$). Belowground (coarse root) biomass production in LPSF (0.7 Mg C $ha^{-1}yr^{-1}$) was lower than in PSF (1 Mg C $ha^{-1}yr^{-1}$; $p < 0.05$). Both in PSF and LPSF, aboveground biomass production (4.6 Mg C $ha^{-1}yr^{-1}$ and 3.2 Mg C $ha^{-1}yr^{-1}$, respectively) was higher than the belowground biomass (1 Mg C $ha^{-1}yr^{-1}$ and 0.7 Mg C $ha^{-1}yr^{-1}$, respectively; $p < 0.05$).

*Insert Table 4.3*

Similar to the larger trees, smaller trees (dbh < 5 cm) in LPSF produced less aboveground and belowground biomass than those in PSF ($p < 0.05$). In logged forest there was a lower productivity of both aboveground and belowground (biomass in LPSF by 0.3 Mg C $ha^{-1}yr^{-1}$ and 0.1 Mg C $ha^{-1}yr^{-1}$, respectively (Table 4.4). Aboveground biomass production was higher than the belowground production in both PSF and LPSF by 0.4 Mg C $ha^{-1}yr^{-1}$ and 0.2 Mg C $ha^{-1}yr^{-1}$, respectively ($p = 0.043$).

*Insert Table 4. 4*

Litterfall

Annual production of litterfall or necromass (leaves, flower and small branches) did not differ significantly ($p = 1.0$) between LPSF (5.2 Mg C $ha^{-1}yr^{-1}$) and PSF (5.2 Mg C $ha^{-1}yr^{-1}$; Table 4.5). Litterfall production in PSF and LPSF during dry months (August – October; 2.5 and 2.6 Mg C $ha^{-1}$, respectively) and wet months (November – July; 2.7 Mg C $ha^{-1}$) was also similar in both forest ecosystems ($p = 0.7$).

*Insert Table 4. 5*

Fine root production

Fine root production showed higher production by 0.7 Mg C-$CO_2$ $ha^{-1}yr^{-1}$ (0.2 Mg C $ha^{-1}yr^{-1}$) than LPSF ($p$=0.10; Table 4.6). Total plant productivity was lower in LPSF than PSF by 7.9 Mg C-$CO_2$ $ha^{-1}yr^{-1}$. In PSF, aboveground biomass accounted for 40%, litterfall accounted for 39% and fine and coarse roots accounted for 11% and 10%, respectively, of total production. In LPSF, aboveground biomass accounted for 33%, litterfall accounted for 47% and root (fine and coarse) accounted for 11% and 9%, respectively, of total productivity.

*Insert Table 4.6*

***Early seral communities***

In the early seral ecosystem, total biomass production was 10.8 ± 1.3 Mg C $ha^{-1}yr^{-1}$ (Table 4.7). Of this production, belowground biomass (root), litter and aboveground biomass (leaves) accounted for 53%, 17% and 30%, respectively. Belowground biomass was higher than litter mass and aboveground biomass ($p < 0.05$, respectively). Belowground biomass source dominated the NPP in ES ecosystem.

*Insert Table 4.7*

***Oil palm plantations***

Total annual NPP in oil palm plantations was 3.7 Mg C $ha^{-1}yr^{-1}$ (Table 4.8). Belowground biomass (root), litter/necromass (pruned fronds) and aboveground biomass (tree) contributed 6%, 32% and 62%, of the NPP, respectively. Roots were lower in production than the fronds (Mann-Whitney, p-value = 0.02) and the above ground growth (Mann-Whitney, p-value = 0.03). Aboveground biomass production source dominated NPP in OP ecosystem.

*Insert Table 4.8*

**NPP among peatland ecosystems**

PSF had the highest aboveground biomass productivity ($p = 0.05$). Aboveground growth was measured at 19.3 Mg $CO_2$ $ha^{-1}yr^{-1}$ in forests. Aboveground growth for LPSF, ES and OP was 13.5 Mg $CO_2$ $ha^{-1}yr^{-1}$, 12.1 Mg $CO_2$ $ha^{-1}yr^{-1}$, and 8.4 Mg $CO_2$ $ha^{-1}yr^{-1}$, respectively (Figure 4.3).

Among all land cover types, ES (20.9 Mg $CO_2$ $ha^{-1}yr^{-1}$) was estimated to have the highest production of root biomass ($p = 0.05$). Root producitivity in PSF, LPSF and OP was 10 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, 7.6 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, and 0.9 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively.

Litterfall in PSF and LPSF were similar (19.1 Mg $CO_2$ $ha^{-1}yr^{-1}$ and 19.2 Mg $CO_2$ $ha^{-1}yr^{-1}$, respectively), and significantly higher ($p = 0.05$) than litterfall in ES and OP (6.7 Mg $CO_2$ $ha^{-1}yr^{-1}$ and 4.3 Mg $CO_2$ $ha^{-1}yr^{-1}$, respectively).

The NPP of peat forests was significantly greater than any other cover type (p-value = 0.05; 48.5 Mg $CO_2$ $ha^{-1}yr^{-1}$). The ecosystem NPP of LPSF, ES and OP was 40.6 Mg $CO_2$ $ha^{-1}yr^{-1}$, 39.8 Mg $CO_2$ $ha^{-1}yr^{-1}$, 13.6 Mg $CO_2$ $ha^{-1}yr^{-1}$, respectively.

*Insert Figure 4.3*

**Annual ecosystem respiration**

Heterotrophic respiration was lower in ES sites than LPSF ($p = 0.05$) or OP ($p = 0.05$) by 10 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ and 8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively (Table 4.9). Similarly, total soil respiration in ES (40.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) was lower than in PSF (48.5 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, $p = 0.046$), LPSF (50.2 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, $p = 0.021$) and OP (47.5 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, $p = 0.075$). All land cover types were similar in their autotrophic respiration. In addition, I found no significant correlation ($p > 0.05$; $r^2 < 0.2$) between respiration (heterotrophic and total soil) and environmental factors such as soil temperature and water level.

*Insert Table 4.9*

Autotrophic respiration ranged from 9.3 to 10.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ and did not differ among the ecosystems. Autotrophic respiration during wet months (4.7 and 3.2 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) was significantly lower ($p < 0.05$) than dry months (16.3 and 17.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) in LPSF and OP, respectively (Table 4.10). In contrast, heterotrophic respiration during wet months (45.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) was significantly higher than dry months (28.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) in OP ($p = 0.001$).

During wet months, total soil respiration of OP was the highest among ecosystems (48.9 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$). Heterotrophic respiration of PSF (36.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) was significantly lower than LPSF and OP (42.2 and 45.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; $p < 0.1$). Total and heterotrophic respiration of ES (38.8 and 29.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) were also significantly lower than OP (48.9 and 45.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; $p < 0.05$).

During dry months, total soil respiration in forests ranged from 53.4 to 54.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ and was higher than those in non-forest sites that ranged from 43.5 to 45.5 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$. Heterotrophic respiration of OP (28.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) was significantly lower than LPSF (38.4 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; $p = 0.006$) and PSF (39.0 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; $p = 0.06$).

*Insert Table 4.10*

**Net Ecosystem Productivity**

NEP of intact forest was 10.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ or 2.94 Mg C $ha^{-1}$ $yr^{-1}$. This is the amount of carbon being sequestered on site each year. In contrast, respiration exceeded NPP in oil palm such that the NEP of oil palm was – 25.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ or - 6.85 Mg C $ha^{-1}$ $yr^{-1.}$ This suggests that these plantations are significant sources of greenhouse gas emissions. Logged forests were weak sources of greenhouse gas emissions with a slightly negative NEP, i.e., – 0.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$. The difference in NEP between intact forest and oil palm was 35.9 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, and between intact and logged forest was 10.9 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$. These differences represent the missed potential carbon sequestration and important numbers of relevance in carbon trading.

The NEP of logged forest and oil palm plantation was lower than PSF (Table 4. 11) ($p=$ 0.056 and 0.001). In contrast the NEP of ES was similar to that of the PSF ($p = 0.8$). In addition, NEP was significantly correlated with the NPP ($p = 0.001$), but not with the heterotrophic respiration ($p=0.08$; Figure 4.4).

*Insert Table 4. 11*

*Insert Figure 4. 4*

**DISCUSSION**

**How land use change alters ecosystems from net sinks to sources of carbon in tropical peatland ecosystems**

The NPP in the intact forests exceeded that in other ecosystems by more than 8 Mg $CO_2$ $ha^{-1}yr^{-1}$. Logged peat forest, early seral and oil palm plantation were significantly lower in NPP than intact peat forests (Table 4. 11). Loss of trees from logging and land clearing had resulted in significant decreases of primary production in degraded peat landscapes.

In the early seral sites that were dominated by grasses and ferns, productivity was similar to the logged peat forest. As I assumed that my early seral sites are comparable to the grassland ecosystem, they may typically have high turnover rates of aboveground and belowground biomass (Long *et al.*, 1989). However, the NPP of early seral sites in this study (40 Mg $CO_2$ $ha^{-1}yr^{-1}$) was higher than studies of grassland ecosystems in Thailand (Kamnalrut, 2015) and the Ivory Coast (Menaut *et al.*, 1979), which were 34 and 36 Mg $CO_2$ $ha^{-1}yr^{-1}$, respectively.

Oil palm plantations that had been deforested and burned previously had the lowest NPP. In contrast to early seral, which also had been deforested and burned recurrently, oil palm showed lower productivity of aboveground and belowground biomass, as well as litterfall (Table 4.6 and 4.7). This may be explained by the peatlands' unsuitable growing conditions for oil palm as an agricultural crops (Basuki & Sheil, 2005; Lamade & Bouillet, 2005; Wijedasa *et al.*, 2016). Limited nutrient availability and high water table are not met with oil palm's growing requirements.

Tropical climates with adequate sunlight, temperatures and moisture availability throughout the year facilitate high productivity rates. For example NPP is twice as high in PSF compared to temperate forests of Pacific Northwest, USA (13.2 vs. 6.5 Mg C $ha^{-1}yr^{-1}$; Waring *et al.*, 2013). The NPP of the intact peat forest measured in this study (13.2 Mg C $ha^{-1}yr^{-1}$) was also higher than those reported from tropical rain forests, e.g., 2.5 and 5.5 Mg C $ha^{-1}yr^{-1}$ (Lamade & Bouillet, 2005; Proctor, 2013) and tropical mangrove forests, e.g., 9.8 Mg C $ha^{-1}yr^{-1}$ (Menaut *et al.*, 1979). However, it was similar with that reported from Indonesian mangrove (12.9 Mg C $ha^{-1}yr^{-1}$; Arifanti, 2017) and lower than that reported from Amazonian tropical forests, e.g., 16.9 Mg C $ha^{-1}yr^{-1}$ (Girardin *et al.*, 2010; Malhi, 2012).

NPP of tropical peat swamp forests was higher than tropical rainforests and mangrove forests. As these ecosystems have similar climates, it would be important to determine which factors result in higher rates of NPP in peat forests. High carbon use efficiency (CUE; ratio between NPP and GPP) of peat forests likely contribute to its higher productivity than other tropical ecosystem, as also found in freshwater marsh of California (Rocha & Goulden, 2009). My study suggests that tropical peat forest are among the most productive ecosystems in term of primary productivity (Figure 4.4).

*Insert Figure 4.4*

My results showed that oil palm plantation had the lowest NPP among other peatland ecosystems. The NPP in the oil palm plantations of this study (3.7 Mg C $ha^{-1}yr^{-1}$) were about a fifth of that from a review by Lamade & Bouillet (2005) of oil palm on mineral soils and a third of that reported by Melling et al. (2008) from Malaysia. This difference may be due to the difference in sites and methods among these studies. It may also be due to the low intensity of management and the young oil palm (1-5 years) in my smallholder plantation sites, the limited nutrient availability, saturated condition and low load-bearing capacity of peatland soils (Page *et al.*, 2011a).

Total soil respiration in peatland ecosystems of this study ranged from 40 to 50 Mg $CO_2$ $ha^{-1}yr^{-1}$, and heterotrophic respiration ranged from 31 to 41 Mg $CO_2$ $ha^{-1}yr^{-1}$ (Table 4.9). Significantly lower total soil and heterotrophic respiration was found in early seral than in intact forests. But similar total soil and heterotrophic respiration were detected between the intact forest and those in logged forest and oil palm plantation. I suspect that the lower heterotrophic respiration in early seral may due to the loss of labile - non-recalcitrant forms of organic carbon as a result of recurrent peat fires, respiration and dissolved losses in early seral ecosystem (Hirano *et al.*, 2014).

Soil respiration (48.5 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) of the intact forests in this study was similar to that reported in a review of South East Asia peatlands (Hergoualc'h & Verchot, 2011), but lower than those reports from Sumatera (59 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Comeau *et al.*, 2013), Kalimantan (55 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Novita, 2016) and Sarawak (77 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Melling *et al.*, 2005). These differences may had been affected by the use of different methodologies in measuring the soil respiration (portable EGM vs gas sampling), as well as the inherent differences in peat characteristics including soil microbial community and peat carbon quality (Jaatinen *et al.*, 2008), and forest condition (structure, composition, water table depth etc.). These results suggest that soil respiration of tropical peat forest is highly variable, site specific and likely high in annual variation (Valentini *et al.*, 2000).

The total soil respiration of logged forest (50.2 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) in my study area was much lower than those reported from logged forest in Sumatra (68 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Comeau *et al.*, 2013). Soil respiration in my early seral (30 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) was also lower than those early seral in Sumatra that is 60 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ (Husnain *et al.*, 2014). Similarly, my OP soil respiration (47.5 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) was lower than previous studies in Sarawak (55 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Melling *et al.*, 2005) and Sumatera plantation (104 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Comeau *et al.*, 2013), but similar to a study in Kalimantan (44 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Novita, 2016). Those differences may had been influenced by the difference in methodology applied, peat depth and by the variation in the spatial and temporal total soil respiration.

Mean annual soil temperature was higher and water table depth was lower in oil palm plantation than in intact peat forest. These similar to other studies in tropical peatlands (Melling *et al.*, 2005; Comeau *et al.*, 2013, Novita, 2016). However I did not find significant relationship between soil temperatures or water table depth to their soil respiration. This is in contrast to other studies who reported an effect of water table on $CO_2$ respiration (Comeau *et al.*, 2013; Hirano *et al.*, 2014; Novita, 2016). On the other hand, my finding was in conform with other studies from South East Asia (Hergoualc'h & Verchot, 2011) and from northern peatland forests (Mäkiranta *et al.*, 2009). Further research is needed in order to understand why contrasting results were found.

In comparison with other ecosystems, heterotrophic respiration of intact peat forest in this study was lower than the tropical rain forest (138 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Yoda, 1971 in Komiyama *et al.*, 2008), logged peat forests in Jambi (68 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Comeau *et al.*, 2013), and oil palm plantation in Jambi (104 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Comeau *et al.*, 2013) and Sarawak (55 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Melling *et al.*, 2005). Heterotrophic respiration in peat forest was higher than the mangrove forests in Australia (20 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Alongi *et al.*, 2000) and Thailand (8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Alongi *et al.*, 2001; Komiyama *et al.*, 2008).

My results are similar to that of Novita (2016) who found that land use change did not impact heterotrophic respiration in tropical peat forests landscapes. However other studies have suggested that land use change decreases (Melling *et al.*, 2005) or increases heterotrophic respiration (Comeau *et al.*, 2013). I found that land use change has decreased peat forest potential to sequester carbon by lowering its primary productivity rather than increasing its soil respiration.

**Effect of land use change on net ecosystem production**

Ecosystems are net carbon sinks when NEP is positive. Intact peat forest is a net carbon sink (10.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$; Table 4. 11) that has been attributed by significantly higher NPP (48.5 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) than logged peat forests, early seral and oil palm. ES sites were also carbon sinks (9.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) and this is attributed to its low heterotrophic respiration (30.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$), despite of its lower NPP than intact and logged peat forests. In contrast, logged peat forests and oil palm plantations are net sources of greenhouse gases (-0.1 and -25.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively). This is due to a low NPP (40.6 and 13.6 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) and high rate of heterotrophic respiration (Figure 4.5).

*Insert Figure 4.5*

Logging and conversion to oil palm on peat forest results in a loss of potential carbon sequestration as much as 10.9 and 35.9 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively (Table 4. 11). Changes in NEP are due to differences in NPP rather than in heterotrophic respiration.

The NEP of early seral sites was similar to the intact peat forest, with lower heterotrophic respiration than other ecosystems. Moreover, its NPP was 39.8 Mg $CO_2$ $ha^{-1}yr^{-1}$, close to the NPP of logged forests. Belowground NPP accounted for 53% (21.1 Mg $CO_2$ $ha^{-1}yr^{-1}$), of the total which was highest among of all sampled sites. As I did not directly measured this belowground NPP, the high value could also be due to differences in my methodology. Nevertheless, these suggest that early seral's high NEP is related to a lower heterotrophic respiration coupled with a relatively high belowground NPP.

The low heterotrophic respiration in early seral may had been reflective of effects of peat fires that burned the sites out in September 2014. The fires may had reduced microbial communities and burnt fresh carbon compounds out from the peat surface that in turn limiting decomposition process and heterotrophic respiration (Page *et al.*, 2004; Limpens *et al.*, 2008; Hirano *et al.*, 2014).

Despite of its positive annual NEP, early seral ecosystems have very high $CO_2$ emission potential from peat fires. I estimated the carbon losses from conversion of peat forest to early seral may reach an estimated 4,259 Mg $CO_2$ $ha^{-1}$ for 25 years, which involve peat fires (chapter 3, this dissertation). Combining these data, early seral sites are actually a significant net carbon emitter (-142 Mg $CO_2$ $ha^{-1}yr^{-1}$).

Regarding their annual NEP values, logged forest was a weak carbon emitter while oil palm was a strong one. Conversion of peat forest to the logged forest and oil palm was estimated, i.e., 1,982 and 3,176 Mg $CO_2$ $ha^{-1}$ for 25 years, respectively (chapter 3, this dissertation). Combining their NEP values with C losses from conversion process, logged forests and oil palm plantations are both significant net carbon emitter (-22 and -80 Mg $CO_2$ $ha^{-1}yr^{-1}$, respectively; Table 4.12).

*Insert Table 4.12*

I found that PSF's NEP in this study were lower than NEP in the tropical mangroves (Golley *et al.*, 1962; Alongi *et al.*, 2001; Alongi & Mukhopadhyay, 2015; Arifanti, 2017) but higher than the Siberian peat pine forests (Schulze *et al.*, 2002; Figure 4.5). High NEP of mangrove ecosystems has been attributed by its high NPP due to its nutrient-rich ecosystem and low heterotrophic respiration due to its tidal environment (Komiyama *et al.*, 2008; Arifanti, 2017). The low NEP of Siberian peat forests has been attributed to its lower NPP due to its limited growing season (Waring *et al.*, 2013). Again this supports my argument that tree production is the major driver of the changes on ecosystem NEP.

In contrast with the zero NEP of peat oil palm in Malaysia (Melling, L., Kah Joo Goh, Beauvais, C., Hatano, 2008), I found that oil palm in my study sites emit high amount of $CO_2$ (NEP = - 25.1 Mg $CO_2$ $ha^{-1}yr^{-1}$). My study estimated lower annual productivity of oil palm plantation (13.6 Mg $CO_2$ $ha^{-1}yr^{-1}$) than the previous study (44 Mg $CO_2$ $ha^{-1}yr^{-1}$). This difference may be due to the difference in the methods that were used among these studies. Nevertheless, it suggests that peat oil palm is more likely to be a carbon emitter than a carbon sink.

*Insert Figure 4.6*

**Implications for tropical peatland management**

Combining my results on carbon losses (Chapter 3, this dissertation) and NEP in response to land use changes, I could estimate the number of years that will be needed to re-accumulate the carbon through restoration activity. I found out that the mean potential carbon losses from PSF conversion to LPSF, ES and OP was 1,982, 4,259 and 3,176 Mg C-$CO_2$ $ha^{-1}$, respectively, and the NEP of intact PSF was 10.8 Mg $CO_2$ $ha^{-1}yr^{-1}$. Assuming that those converted sites are restored, then it will take at least 184, 394 and 294 years for the restored PSF to compensate the carbon losses in their previous LPSF, ES and OP land uses, respectively. It is best to conserve intact peat swamp forests that we have left than to restore the degraded forests.

Tropical peat swamp forests sequester carbon because of their high annual productivity rates that exceed their relatively high respiration rates. Degradation and conversion (land use changes) of peat swamp forests significantly reduced their productivity. My results support recent reports that tropical peatlands in Indonesia are now net sources of carbon (Dommain *et al.*, 2014), as there are 4 times more degraded peat forest than the intact forest. Moreover, intact peat swamp forest is less than 7% of all peatland areas in main Indonesia's islands (Miettinen *et al.*, 2016).

Intact tropical peat swamp forests is an effective carbon sink ecosystem that had been largely unknown on its rate in sequestering carbon. Recent model (HPMTrop) based estimation on peat accumulation rate in tropical peat swamp forests suggested lower values, i.e., 0.3 and 0.59 Mg C $ha^{-1}$ $yr^{-1}$ (Kurnianto *et al.*, 2015) than my results on NEP and NECB (3.7 and 2.3 Mg C $ha^{-1}$ $yr^{-1}$, respectively). This difference likely due to the different methodologies applied, spatial and temporal variation. It may be too early to conclude that the previous estimates was underestimating actual carbon accumulation rate in the tropical peat swamp forests. My result suggests that at current situation the intact peat forests are sequestering atmospheric $CO_2$ at faster rate than the previous estimate.

In 2015 there were more than three million hectares of oil palm plantations and almost one million hectares of degraded grass lands/early seral (ES) in South East Asia (Miettinen *et al.*, 2016). Using my estimates of oil palm's NEP (- 25.1 Mg $CO_2$ $ha^{-1}yr^{-1}$), the 3 million ha of oil palm will emit significant amounts of $CO_2$ into the atmosphere, as much as 75.3 Tg $CO_2$ $yr^{-1}$, unless clear management steps are applied to reduce this emissions. On the other hand, my results on early seral NEP (9.1 Mg $CO_2$ $ha^{-1}yr^{-1}$) suggested that allowing grasses and ferns to regrow and cover the peat surface of the 3 million ha of OP may reduce the emissions by about 27 Tg $CO_2$ $yr^{-1}$.

A million hectares of early seral lands on peatlands of South East Asia could actually sequester carbon especially if allowed to regrow and recover into forests. However, this ecosystem is currently largely unmanaged and may be the most fire prone cover type of the region (Page *et al.*, 2009; Blackham *et al.*, 2014). Recurrent fires in this cover type altered early seral as a net carbon sink to be a significant carbon source. This is especially clear if we look at the loss of carbon stocks from peat forest conversion into early seral ecosystem, which amounted to 125 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ (chapter 3, this dissertation).

Fire in tropical peatlands is unlikely a common natural process. Most ignitions are from humans and rarely are fuels dry enough to burn in natural forests. However, my results show that LUC significantly lower the water table and increased soil temperatures, thus increasing fire susceptibility (see also Usup *et al.*, 2004). Along with LUC, fire is a significant threat to the productivity of peatland ecosystems. A single event of uncontrolled peat fire may emit as much as 1000 – 1600 Mg $CO_2$ $ha^{-1}$ (Hergoualc'h & Verchot, 2011). This is a value that equals to the NEP of peat forests for more than a century. The presence of fires to clear peatlands for OP and agricultural activities (Page *et al.*, 2009; Carlson *et al.*, 2012) should be halted in order to reduce carbon emissions.

Logging and conversion to early seral and oil palm plantation on peat forest results in a loss of potential carbon sequestration as much as 10.9, 1.7 and 35.9 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively. These are the sum of the difference in NEP between intact peat forest (10.8 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) and each of logged peat forest (-0.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$), early seral (9.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) and oil palm (-25.1 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$). If we combine those NEP values with the mean loss of C per year from stock change measurements on logged peat forests, early serals and oil palms (chapter 3, this dissertation) and other sources of C loss (Table 4.12), we will have the potential C emission, i.e., 22, 142, and 80 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, which we could claim in a mitigation activity.

The social cost of carbon (SCC) is a measure, in US dollars (USD), of the long-term damage done by a ton of carbon dioxide ($CO_2$) emissions in a given year (Interagency Working Group on Social Cost of Greenhouse Gases, 2016). This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a $CO_2$ reduction). Assuming that the social cost of carbon is \$ 31 per Mg $CO_2$ (Nordhaus, 2017), the annual emissions of converting intact peat forests to logged forests, early serals and oil palm plantation equal to \$ 682, \$ 4,402 and \$ 2,480 per hectare. These are the annual social cost that should be compensated for avoiding (or invoking) the degradation and conversion of each hectare of intact peat forests.

My estimate on annual carbon emission of forest conversion to logged peat forest, early seral and oil palm (22, 142 and 80 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, respectively) are much higher than current default values (19 and 35 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) of IPCC (2014). This difference likely related to different methodologies applied. My values represent combined C emissions from LUC (carbon stock difference approach) and ongoing differences in NEP. In contrast, the IPCC values represent either historical (peat subsidence approach) or present ($CO_2$ fluxes) sources, excluding peat fires' impact. I argue that current IPCC default values of emission factors for drained organic soil are underestimating actual carbon loss from land use changes.

Intact tropical peat swamp forests are among the most productive of terrestrial ecosystems, with an NPP exceeding that of many tropical rain forests and similar to the most productive mangrove ecosystems. However, land use change has significantly decreased its productivity. Protection and restoration of tropical peat swamp forest are urgently needed to prevent further loss of its carbon sinks potential and ultimately mitigating the climate change. Conserving intact peat swamp forests that we have left should be prioritized more than to restore the converted forests, as it would take hundreds of year to compensate the carbon loss from the conversion.

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**Figures**

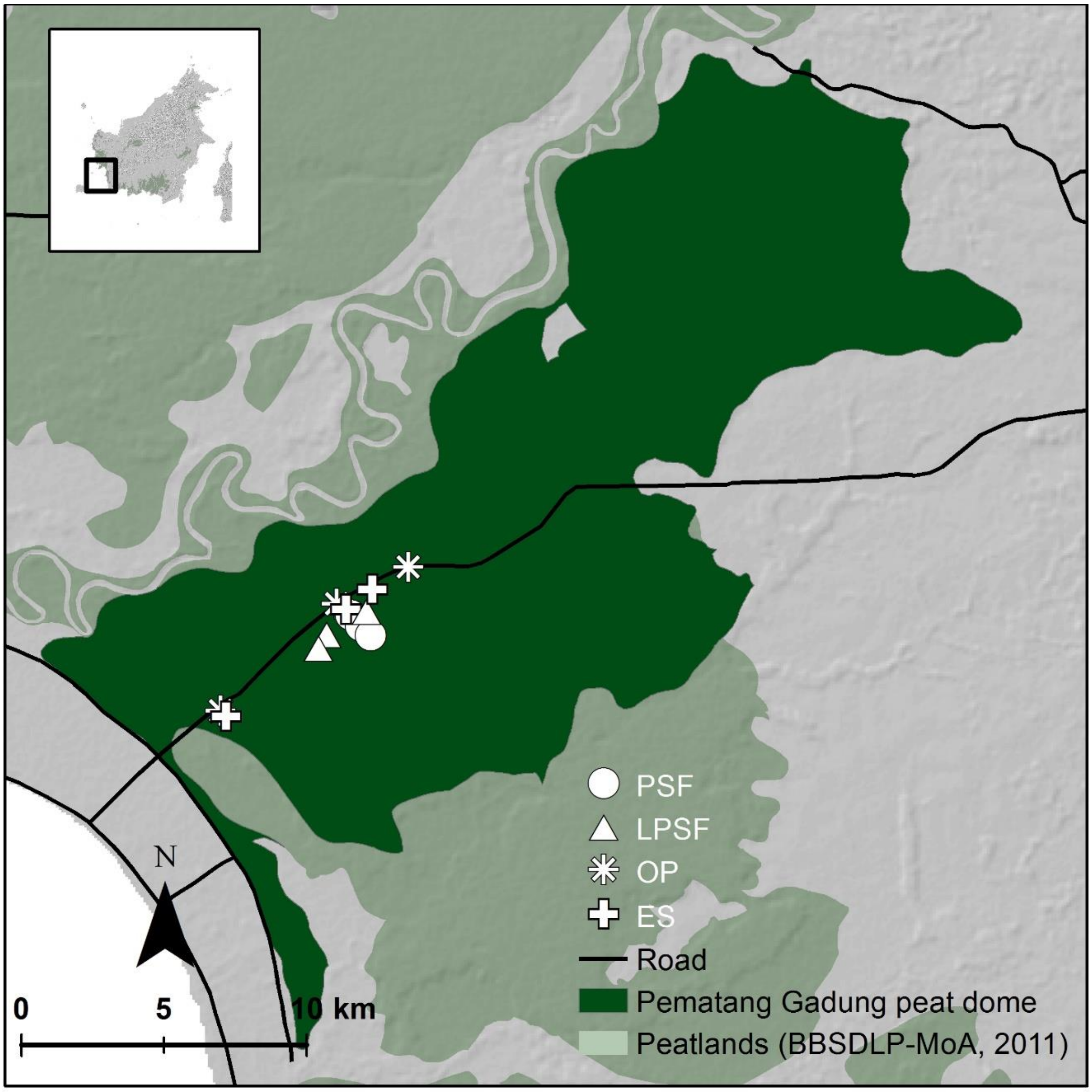


**Figure 4.1.** Plot locations (12 sites) within the study area, Pematang Gadung peat dome, Ketapang, West Kalimantan, Indonesia. Peat dome area (dark green) was delineated by BDSLDP - MoA (2011). White symbols represent the sample sites. Black line represents road. White areas represent the sea (Karimata Straits), light green areas represent the peatland areas. Grey areas represent the non-peat areas.

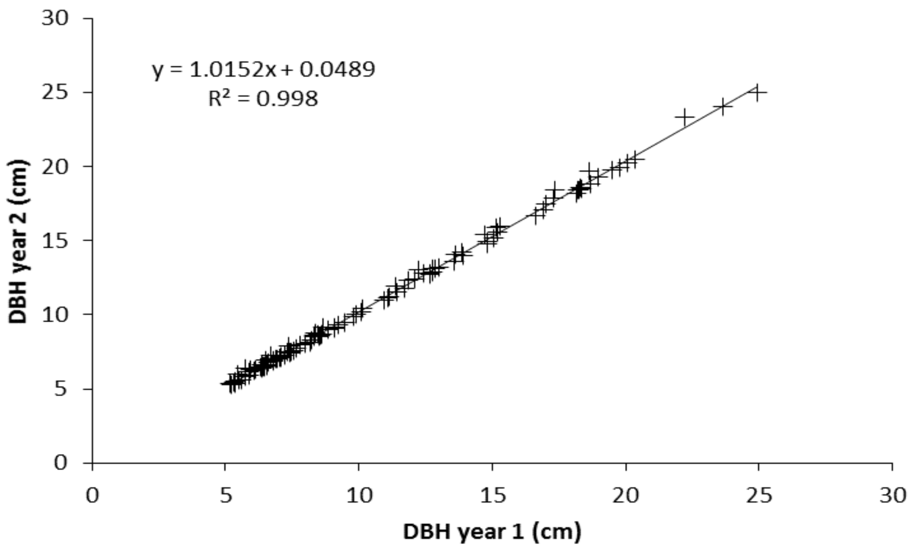


**Figure 4.2.** Linear regression model between tree diameters measured in year 1 and year 2 of 118 trees in forest areas (PSF and LPSF).

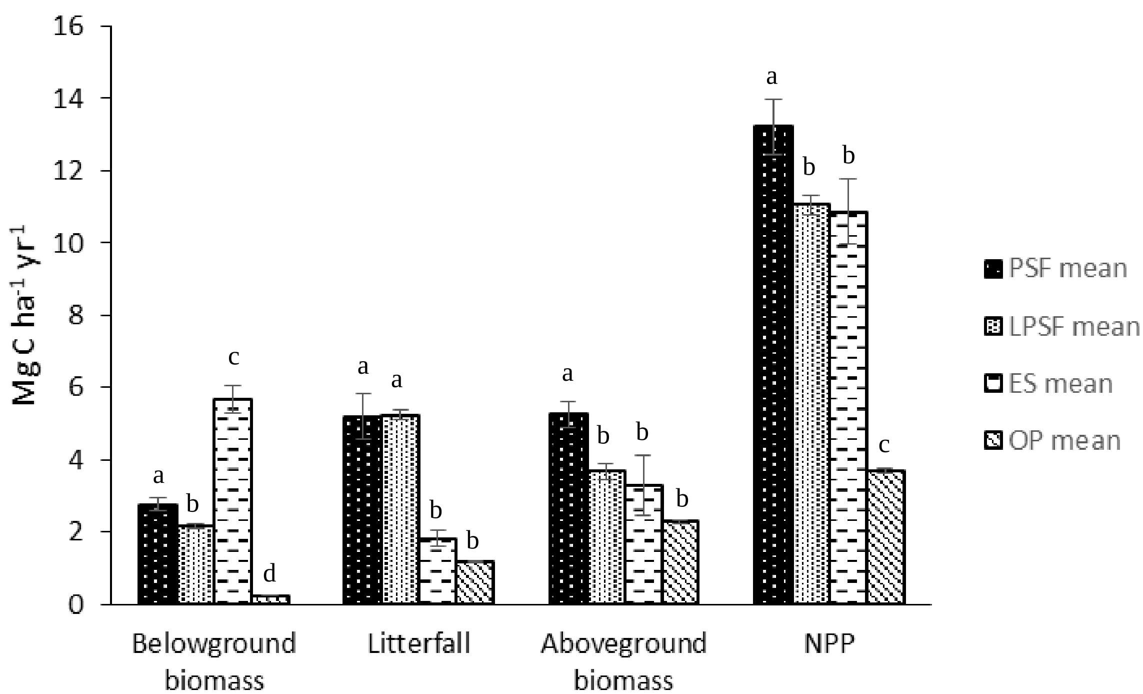


Figure 4.3. Productivity of belowground and aboveground biomass, litterfall, and NPP in intact and logged peat forest, early seral and oil palm plantation. Production of biomass and litterfall, and NPP reported as mean value. Error bars show ± SE of the production. Lower case letters represent statistical significance in productivity.

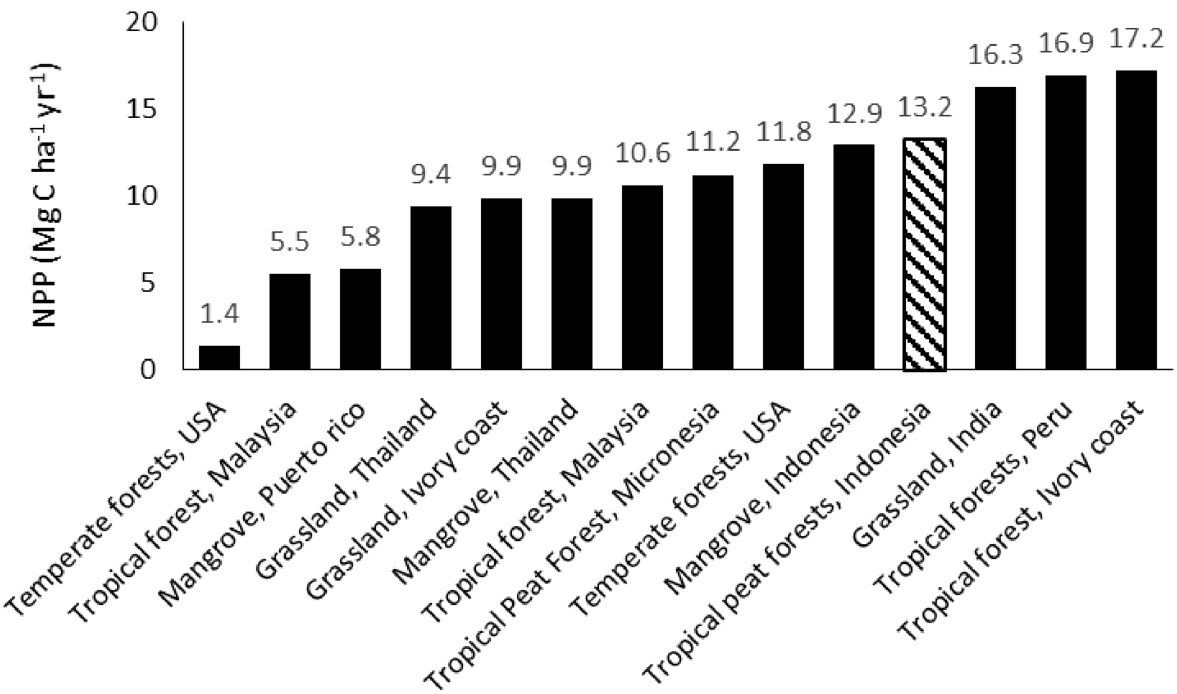


**Figure 4.4.** NPP among terrestrial ecosystems. Data for temperate forests are from (Waring *et al.*, 2013). Tropical forests are from (Clark & Brown, 2001; Girardin *et al.*, 2010; Proctor, 2013). Mangroves are from (Golley *et al.*, 1962; Komiyama *et al.*, 2008; Arifanti, 2017). Grassland are from (Menaut *et al.*, 1979; Kamnalrut, 2015). Tropical peat forests are from (Chimner & Ewel, 2005) and this study (represented with diagonal strips).

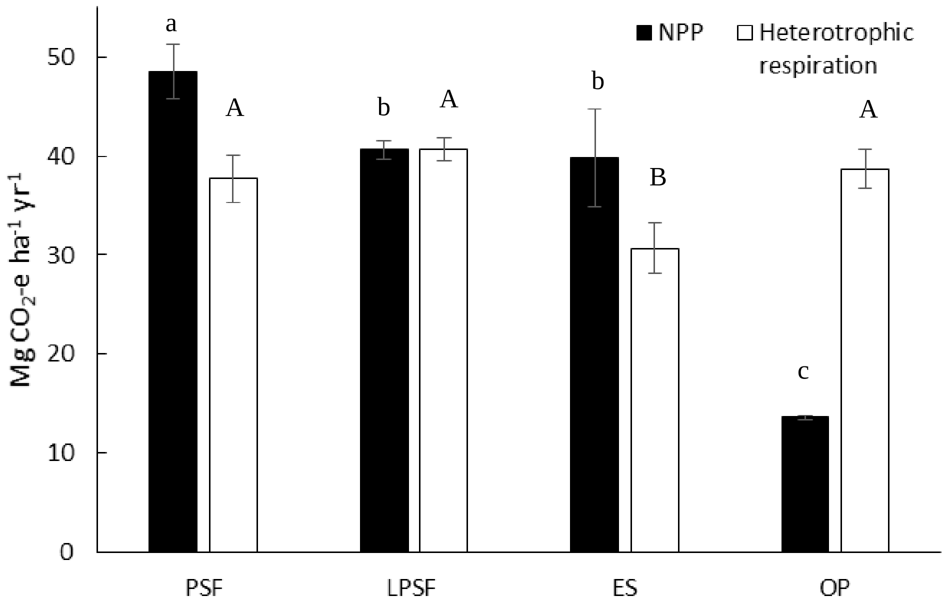


Figure 4.5. NPP and heterotrophic respiration in intact (PSF) and logged peat forest (LPSF), early seral (ES) and oil palm plantation (OP). NPP and respiration reported as mean value, while error bars are ± SE of production and respiration. Higher and lower case letters represent statistical significance in heterotrophic respiration and NPP, respectively.

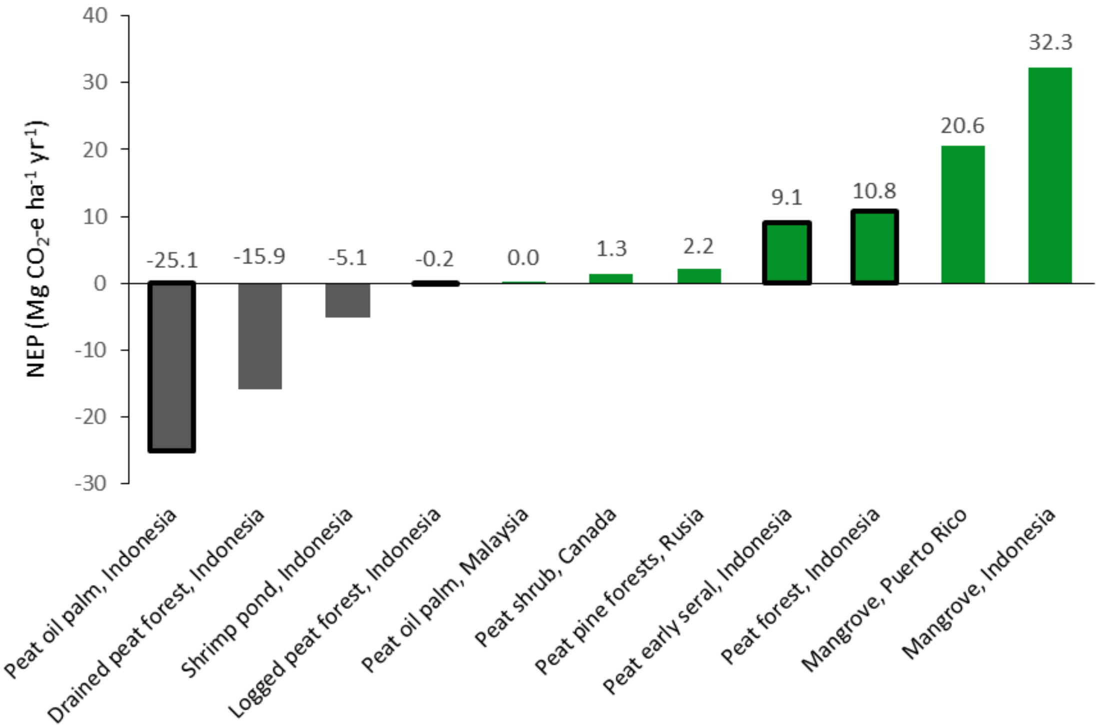


Figure 4.6. NEP among wetland ecosystems. Data for mangrove are from (Golley *et al.*, 1962; Arifanti, 2017). Shrimp pond is from (Arifanti, 2017). Peat oil palm are from (Melling, L., Kah Joo Goh, Beauvais, C., Hatano, 2008) and this study. Peat pine forest and drained peat forests are from (Schulze *et al.*, 2002; Hirano *et al.*, 2007). Peat shrub is from (Bubier *et al.*, 1999). Peat forest, logged peat forest, oil palm and early seral are from this study (bordered with black line).

**Tables**

Table 4.1. Equation utilized to determine biomass and carbon gain in peat forests, early seral and oil palm plantation

| Data | Equation | Reference | Results |
|---|---|---|---|
| Forests tree dbh (cm) | 0.136*Forest tree dbh^2.513 | Manuri et al., 2014 | Tree biomass |
| Forests tree biomass (kg) | 0.489*(Forest tree biomass^0.89) | Mokany et al., 2006 | Tree coarse root biomass |
| Forests litterfall (g) | 9.89%*Forest litterfall | Chimner and Ewel, 2005 | Branch fall production |
| Forests tree and root biomass, litterfall and branchfall (kg) | 12%*sum of forest tree, root, litterfall and branchfall | Chimner and Ewel, 2005 | Fine root production |
| Oil palm height (cm) | 0.0976*(Oil palm height) + 0.070 | Dewi et al., 2010 | Oil palm biomass |
| Oil palm biomass (kg) | 14.2%*Oil palm biomass | Henson and Dolmat, 2003 | Oil palm root production |
| Oil palm biomass (kg) | 68.8%*Oil palm biomass | Henson and Dolmat, 2003 | Oil palm frond production |
| ES leaf and litterfall (g) | 110%*ES leaf and litterfall | Scurlock and Olson, 2013 | ES root production |

Table 4.2. Water table depth and soil temperature (means± SE) of intact peat forest (PSF), logged peat forest (LPSF), early seral (ES) and oil palm (OP) during wet and dry months, and annually.

| | Water table depth level (cm) | | | Soil temperature (°C) | | |
|---|---|---|---|---|---|---|
| Ecosystem | Wet months | Dry months | Annual | Wet months | Dry months | Annual |
| PSF | 81 ± 13 | 21 ± 8 | 46 ± 6a | 27.1 ± 0.3 | 27.3 ± 0.5 | 27.2 ± 0.1a |
| LPSF | 74.3 ± 13 | 15 ± 9 | 40 ± 6a | 27.1 ± 0.6 | 27 ± 0.5 | 27.0 ± 0.1a |
| ES | 84 ± 21 | 26 ± 13 | 50 ± 7a | 28.8 ± 0.8 | 30 ± 0.8 | 29.5 ± 0.2b |
| OP | 105 ± 15 | 60 ± 13 | 78 ± 6b | 30.3 ± 0.8 | 30.6 ± 0.8 | 30.5 ± 1.6c |

Value followed by different lower case letter is significantly different ($p < 0.05$).

Table 4.3. Aboveground carbon mass (AGB) and belowground carbon mass (BGB) and the annual production in intact and logged peat forest (tree dbh > 5 cm). Aboveground and belowground pools and productivity reported as mean ± SE.

| Site | AGB Time 0 | AGB Yr1 | BGB Time 0 | BGB Yr1 | AGB production | BGB production | Total production |
|---|---|---|---|---|---|---|---|
| | (Mg C ha$^{-1}$) | | | | (Mg C ha$^{-1}$yr$^{-1}$) | | |
| PSF1 | 90.4 ± 10.2 | 94.6 ± 10.6 | 24.8 ± 2.5 | 25.8 ± 2.6 | 4.2 ± 0.4 | 1.0 ± 0.1 | 5.2 ± 0.5 |
| PSF2 | 102.0 ± 17.9 | 106.5 ± 18.6 | 25.7 ± 3.7 | 26.7 ± 3.8 | 4.5 ± 0.7 | 1.0 ± 0.1 | 5.6 ± 0.9 |
| PSF3 | 114.8 ± 12.8 | 119.9 ± 13.4 | 28.4 ± 2.4 | 29.5 ± 2.5 | 5.1 ± 0.5 | 1.1 ± 0.1 | 6.2 ± 0.6 |
| **PSF mean** | **102.4 ± 7** | **107 ± 7.3** | **26.3 ± 1.1** | **27.3 ± 1.1** | **4.6 ± 0.3** | **1 ± 0** | **5.7 ± 0.3** |
| LPSF1 | 61.2 ± 18.2 | 63.9 ± 18.9 | 15.1 ± 3.5 | 15.8 ± 3.6 | 2.7 ± 0.7 | 0.6 ± 0.1 | 3.3 ± 0.9 |
| LPSF2 | 78.0 ± 9.3 | 81.5 ± 9.7 | 20.2 ± 2.5 | 21.0 ± 2.6 | 3.5 ± 0.4 | 0.8 ± 0.1 | 4.3 ± 0.5 |
| LPSF3 | 78.0 ± 15.1 | 81.5 ± 15.7 | 20.2 ± 3.3 | 21.0 ± 3.4 | 3.5 ± 0.6 | 0.8 ± 0.1 | 4.3 ± 0.8 |
| **LPSF mean** | **72.4 ± 5.6** | **75.6 ± 5.9** | **18.5 ± 1.7** | **19.3 ± 1.7** | **3.2 ± 0.3** | **0.7 ± 0.1** | **4 ± 0.3** |

Table 4.4. Aboveground (AGB) and belowground carbon mass (BGB) and the annual production in intact and logged peat forest (tree dbh < 5 cm). Aboveground and belowground pools and total annual productivity reported as mean ± SE.

| Site | AGB Time | AGB Yr1 | BGB Time | BGB Yr1 | AGB production | BGB production | Total productivity |
|---|---|---|---|---|---|---|---|
| | (Mg C ha$^{-1}$) | | | | (Mg C ha$^{-1}$yr$^{-1}$) | | |
| PSF1 | 7 ± 1.1 | 7.6 ± 1.2 | 3.2 ± 0.5 | 3.4 ± 0.5 | 0.6 ± 0.1 | 0.3 ± 0 | 0.9 ± 0.1 |
| PSF2 | 5.8 ± 0.8 | 6.3 ± 0.8 | 2.7 ± 0.3 | 2.9 ± 0.4 | 0.5 ± 0.1 | 0.2 ± 0 | 0.7 ± 0.1 |
| PSF3 | 9.8 ± 2.4 | 10.7 ± 2.5 | 4.5 ± 1 | 4.9 ± 1.1 | 0.9 ± 0.2 | 0.4 ± 0.1 | 1.2 ± 0.2 |
| **PSF mean** | **7.5 ± 1.2** | **8.2 ± 1.3** | **3.5 ± 0.5** | **3.7 ± 0.6** | **0.7 ± 0.1** | **0.3 ± 0.1** | **0.9 ± 0.1** |
| LPSF1 | 4.4 ± 0.5 | 4.8 ± 0.5 | 2.1 ± 0.2 | 2.3 ± 0.3 | 0.4 ± 0 | 0.2 ± 0 | 0.6 ± 0.1 |
| LPSF2 | 4.7 ± 1.8 | 5.1 ± 1.9 | 2.2 ± 0.8 | 2.3 ± 0.8 | 0.4 ± 0.1 | 0.2 ± 0.1 | 0.6 ± 0.2 |
| LPSF3 | 4.7 ± 0.6 | 5.1 ± 0.6 | 2.2 ± 0.3 | 2.3 ± 0.3 | 0.4 ± 0 | 0.2 ± 0 | 0.6 ± 0.1 |
| **LPSF mean** | **4.6 ± 0.1** | **5 ± 0.1** | **2.2 ± 0** | **2.3 ± 0** | **0.4 ± 0** | **0.2 ± 0** | **0.6 ± 0** |

Table 4.5. Production of litterfall (leaves, flowers and small branches) in intact and logged peat forest. Biomass production of litterfall during dry and wet months (August to October and November to July, respectively), and annually reported as mean ± SE. Potential sequestered $CO_2$ presented on the NPP[1] column.

| Site | Dry months litterfall | Wet months litterfall | NPP | NPP[1] |
|---|---|---|---|---|
| | ---------------------Mg C $ha^{-1}yr^{-1}$ | | ------------------- | Mg $CO_2$ $ha^{-1}yr^{-1}$ |
| PSF1 | 3.3 ± 0.2 | 2.9 ± 1.4 | 6.2 ± 1.5 | 22.6 ± 5.4 |
| PSF2 | 2.1 ± 0.4 | 1.9 ± 0.3 | 4 ± 0.5 | 14.8 ± 2 |
| PSF3 | 2.1 ± 0.3 | 3.3 ± 0.9 | 5.4 ± 1 | 19.8 ± 3.7 |
| **PSF mean** | **2.5 ± 0.4** | **2.7 ± 0.4** | **5.2 ± 0.6** | **19.1 ± 2.3** |
| LPSF1 | 2.8 ± 0.2 | 2.7 ± 0.5 | 5.4 ± 0.6 | 20 ± 2.1 |
| LPSF2 | 2.6 ± 0.4 | 2.4 ± 0.2 | 5 ± 0.5 | 18.2 ± 1.8 |
| LPSF3 | 2.4 ± 0.3 | 2.9 ± 0.7 | 5.3 ± 0.9 | 19.5 ± 3.3 |
| **LPSF mean** | **2.6 ± 0.1** | **2.7 ± 0.1** | **5.2 ± 0.1** | **19.2 ± 0.5** |

Table 4.6. Aboveground biomass, litterfall, and root production (fine and coarse root) in intact and logged peat forest. Potential sequestered carbon through biomass production reported as mean ± SE, or otherwise as mean only.

| | AGB | Litterfall | BGB (Fine root) | BGB (Coarse root) | NPP |
|---|---|---|---|---|---|
| Site | ---------------------------- | | Mg C $ha^{-1}yr^{-1}$ | ---------------------------- | |
| PSF1 | 4.8 ± 0.4 | 6.2 ± 1.5 | 1.5 | 1.3 ± 0.1 | 13.7 |
| PSF2 | 5 ± 0.7 | 4 ± 0.5 | 1.2 | 1.3 ± 0.1 | 11.6 |
| PSF3 | 5.9 ± 0.5 | 5.4 ± 1 | 1.6 | 1.5 ± 0.1 | 14.4 |
| **PSF mean** | **5.3 ± 0.4** | **5.2 ± 0.6** | **1.4 ± 0.1** | **1.3 ± 0.1** | **13.2 ± 0.8** |
| LPSF1 | 3.2 ± 0.8 | 5.5 ± 0.6 | 1.2 | 0.8 ± 0.1 | 10.6 |
| LPSF2 | 3.9 ± 0.5 | 5 ± 0.5 | 1.2 | 1 ± 0.1 | 11.1 |
| LPSF3 | 3.9 ± 0.7 | 5.3 ± 0.9 | 1.3 | 1 ± 0.1 | 11.5 |
| **LPSF mean** | **3.7 ± 0.2** | **5.2 ± 0.1** | **1.2 ± 0** | **0.9 ± 0.1** | **11.1 ± 0.3** |

Table 4.7. Belowground biomass, litterfall and aboveground biomass in early seral ecosystem. Biomass, litterfall and NPP reported as mean ± SE. Annual sequestered $CO_2$ presented on the NPP[1] column.

| | Belowground biomass | Litterfall | Aboveground biomass | NPP | NPP[1] |
|---|---|---|---|---|---|
| Site | ---------------------------Mg C $ha^{-1}yr^{-1}$ | | | --------------------------- | Mg C-$CO_2$ $ha^{-1}yr^{-1}$ |
| ES1 | 4.5 ± 0.5 | 2.1 ± 0.3 | 1.9 ± 0.2 | 8.5 ± 0.9 | 31.3 ± 3.3 |
| ES2 | 6.9 ± 1.9 | 1.4 ± 0.4 | 4.8 ± 1.5 | 13.1 ± 3.5 | 48.1 ± 13 |
| ES3 | 5.7 ± 0.8 | 2.0 ± 0.3 | 3.2 ± 0.5 | 10.9 ± 1.5 | 39.9 ± 5.5 |
| **ES mean** | **5.7 ± 0.7** | **1.8 ± 0.2** | **3.3 ± 0.8** | **10.8 ± 1.3** | **39.8 ± 4.9** |

Table 4.8. Belowground biomass (BGB), litterfall, aboveground biomass (AGB) and NPP of oil palm plantation. Biomass and necromass production, and NPP reported as mean ± SE. Annual sequestered $CO_2$ presented on the NPP[1] column.

| Site | BGB | Litterfall | AGB | NPP | NPP[1] |
|---|---|---|---|---|---|
| | ---------------- (Mg C $ha^{-1}$ $yr^{-1}$) --------------- | | | | (Mg C-$CO_2$ $ha^{-1}$ $yr^{-1}$) |
| **OP1** | 0.2 ± 0.0 | 1.2 ± 0.1 | 2.4 ± 0.2 | 3.8 ± 0.4 | 14.1 ± 1.4 |
| **OP2** | 0.2 ± 0.1 | 1.2 ± 0.3 | 2.3 ± 0.6 | 3.7 ± 1.0 | 13.4 ± 3.5 |
| **OP3** | 0.2 ± 0.0 | 1.2 ± 0.1 | 2.3 ± 0.2 | 3.7 ± 0.3 | 13.4 ± 1.0 |
| **OP mean** | 0.2 ± 0.0 | 1.2 ± 0.0 | 2.3 ± 0.0 | 3.7 ± 0.1 | 13.6 ± 0.2 |

Table 4.9. Heterothropic, autothropic and total respiration, along with water table depth and soil temperature in intact and logged peat forest, early seral and oil palm plantation. Respiration, water table depth and soil termperature. Data are mean ± one SE.

| | Heterotrophic respiration | Autotrophic respiration | Total soil respiration | Water table depth | Soil temperature |
|---|---|---|---|---|---|
| Site | ---------------Mg $CO_2$ $ha^{-1}$ $yr^{-1}$--------------- | | | cm | °C |
| PSF1 | 40.0 ± 5.8 | 5.9 ± 2.9 | 45.9 ± 5.5 | 44.3 ± 10.4 | 27.1 ± 0.1 |
| PSF2 | 40.1 ± 5.3 | 13.9 ± 4.1 | 54.0 ± 5.7 | 48.4 ± 10.4 | 27.3 ± 0.2 |
| PSF3 | 32.9 ± 4.5 | 12.8 ± 2.3 | 45.6 ± 4.3 | 45.3 ± 10.1 | 27.2 ± 0.3 |
| **PSF mean** | **37.7 ± 2.4** | **10.8 ± 2.5** | **48.5 ± 2.7** | **46 ± 20.1** | **27.2 ± 0.4** |
| LPSF1 | 43.0 ± 5.4 | 10.9 ± 4.6 | 53.9 ± 5.3 | 39.9 ± 10.5 | 27 ± 0.2 |
| LPSF2 | 39.6 ± 5.1 | 6.1 ± 4.2 | 45.6 ± 4.9 | 34 ± 9.9 | 26.8 ± 0.2 |
| LPSF3 | 39.4 ± 4.3 | 11.6 ± 3.4 | 51.0 ± 5.4 | 45.1 ± 10.6 | 27.3 ± 0.3 |
| **LPSF mean** | **40.7 ± 1.2** | **9.5 ± 1.7** | **50.2 ± 2.4** | **39.7 ± 20.3** | **27 ± 0.5** |
| ES1 | 26.0 ± 2.5 | 14.9 ± 4.1 | 39.6 ± 4.3 | 59.8 ± 13 | 30.5 ± 0.5 |
| ES2 | 31.3 ± 4.0 | 6.1 ± 1.2 | 37.5 ± 4.2 | 40.4 ± 12.5 | 29.1 ± 0.3 |
| ES3 | 34.6 ± 2.0 | 10.7 ± 5.8 | 45.3 ± 5.8 | 50.7 ± 9.9 | 28.9 ± 0.3 |
| **ES mean** | **30.7 ± 2.5** | **10.6 ± 2.5** | **40.8 ± 2.3** | **50.3 ± 23.5** | **29.5 ± 0.8** |
| OP1 | 42.2 ± 7.0 | 8.6 ± 5.4 | 49.3 ± 4.3 | 88.4 ± 10.3 | 31.5 ± 0.3 |
| OP2 | 38.5 ± 3.3 | 5.9 ± 3.2 | 44.4 ± 3.5 | 74.4 ± 9.1 | 30 ± 0.3 |
| OP3 | 35.4 ± 3.6 | 13.3 ± 6.0 | 48.7 ± 4.9 | 72.2 ± 9.3 | 30 ± 0.4 |
| **OP mean** | **38.7 ± 2.0** | **9.3 ± 2.2** | **47.5 ± 1.6** | **78.3 ± 19.1** | **30.5 ± 0.8** |

Table 4.10. Heterotrophic, autotrophic and total respirations by dry and wet months in intact and logged peat forest, early seral and oil palm plantation. Respiration reported as mean ± SE.

| | Ecosystem respiration | | | | | |
|---|---|---|---|---|---|---|
| | Dry months (August to October) | | | Wet months (November to July) | | |
| | Heterotrophic | Autotrophic | Total | Heterotrophic | Autotrophic | Total |
| Site | ----------------------------------Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ | | | ---------------------------------- | | |
| PSF1 | 41.2 ± 6.3 | 9.9 ± 4.2 | 51.1 ± 6.5 | 39.2 ± 5.9 | 3.0 ± 1.1 | 42.2 ± 5.0 |
| PSF2 | 40.2 ± 5.3 | 18.9 ± 5.1 | 59.2 ± 7.4 | 40.1 ± 5.6 | 10.2 ± 3.2 | 50.3 ± 4.6 |
| PSF3 | 35.5 ± 4.2 | 14.5 ± 3.5 | 50.0 ± 3.5 | 31.0 ± 4.9 | 11.5 ± 1.2 | 42.5 ± 4.9 |
| **PSF mean** | **39.0 ± 10.1** | **14.4 ± 8.3** | **53.4 ± 11.5** | **36.7 ± 10.8** | **8.3 ± 4.5** | **45.0 ± 9.4** |
| LPSF1 | 42.4 ± 2.9 | 17.9 ± 6.3 | 60.2 ± 5.3 | 43.5 ± 7.0 | 5.9 ± 2.5 | 49.4 ± 5.3 |
| LPSF2 | 36.7 ± 2.4 | 14.3 ± 4.5 | 51.0 ± 5.7 | 41.6 ± 6.6 | 0.2 ± 3.2 | 41.8 ± 4.4 |
| LPSF3 | 36.2 ± 2.1 | 16.8 ± 5.0 | 53.0 ± 6.8 | 41.7 ± 5.4 | 7.9 ± 1.1 | 49.5 ± 4.7 |
| **LPSF mean** | **38.4 ± 4.9** | **16.3 ± 9.9** | **54.7 ± 11.3** | **42.2 ± 12.1** | **4.7 ± 5.0** | **46.9 ± 9.4** |
| ES1 | 27.5 ± 3.3 | 13.6 ± 6.2 | 37.9 ± 5.8 | 25.0 ± 2.1 | 15.9 ± 2.1 | 40.9 ± 3.4 |
| ES2 | 30.8 ± 4.8 | 8.4 ± 1.2 | 39.2 ± 4.9 | 31.8 ± 3.6 | 4.5 ± 1.1 | 36.2 ± 4.1 |
| ES3 | 37.6 ± 2.1 | 15.8 ± 9.1 | 53.4 ± 8.3 | 32.4 ± 1.9 | 7.0 ± 2.0 | 39.4 ± 2.7 |
| **ES Mean** | **31.9 ± 7.1** | **12.6 ± 12** | **43.5 ± 12.7** | **29.7 ± 5.4** | **9.1 ± 4.5** | **38.8 ± 6.6** |
| OP1 | 30.1 ± 2.1 | 18.7 ± 4.3 | 45.3 ± 3.6 | 50.8 ± 8.3 | 1.4 ± 5.4 | 52.2 ± 4.8 |
| OP2 | 31.1 ± 3.0 | 10.4 ± 4.3 | 41.5 ± 4.7 | 43.8 ± 2.6 | 2.7 ± 2.0 | 46.5 ± 2.5 |
| OP3 | 25.3 ± 2.9 | 24.4 ± 7.0 | 49.7 ± 7.8 | 42.6 ± 2.5 | 5.4 ± 4.2 | 48.0 ± 2.1 |
| **OP Mean** | **28.8 ± 5.2** | **17.8 ± 10.5** | **45.5 ± 10.6** | **45.7 ± 10.1** | **3.2 ± 7.9** | **48.9 ± 6.5** |

Table 4.11. NPP, NEP and heterotrophic respiration in intact and logged peat forest, early seral and oil palm plantation, which were reported as mean ± SE whenever possible.

| Site | Total NPP | Heterotrophic respiration | NEP |
|---|---|---|---|
| | -----------------Mg $CO_2$ $ha^{-1}$ $yr^{-1}$ | ------------------- | |
| PSF1 | 50.4 | 40.0 ± 5.8 | 10.4 |
| PSF2 | 42.4 | 40.1 ± 5.3 | 2.3 |
| PSF3 | 52.8 | 32.9 ± 4.5 | 19.9 |
| **PSF mean** | **48.5 ± 2.8** | **37.7 ± 2.4** | **10.8 ± 5.1** |
| LPSF1 | 38.8 | 43.0 ± 5.4 | -4.2 |
| LPSF2 | 40.7 | 39.6 ± 5.1 | 1.1 |
| LPSF3 | 42.2 | 39.4 ± 4.3 | 2.8 |
| **LPSF mean** | **40.6 ± 1.0** | **40.7 ± 1.2** | **-0.1 ± 2.1** |
| ES1 | 31.3 ± 12.8 | 26 ± 2.5 | 5.3 |
| ES2 | 48.1 ± 19.7 | 31.3 ± 4.0 | 16.8 |
| ES3 | 39.9 ± 16.3 | 34.6 ± 2.0 | 5.3 |
| **ES mean** | **39.8 ± 4.9** | **30.7 ± 2.5** | **9.1 ± 3.8** |
| OP1 | 14.1 ± 1.4 | 42.2 ± 7.0 | -28.1 |
| OP2 | 13.4 ± 3.5 | 38.5 ± 3.3 | -25.1 |
| OP3 | 13.4 ± 1.0 | 35.4 ± 3.6 | -22.0 |
| **OP mean** | **13.6 ± 0.2** | **38.7 ± 2.0** | **-25.1 ± 1.8** |

Table 4.12. Annual carbon gain (NPP), carbon losses (respiration, aboveground C stocks, fire, dissolved organic carbon, methane), NEP, NECB (net ecosystem carbon balance) and annual emission in intact and logged peat forest, early seral and oil palm plantation.

| | Carbon gain | --------------Carbon loss | --------------- | | | | | |
|---|---|---|---|---|---|---|---|---|
| Site | NPP | Hetero-trophic respiration | Land use change | Dissolved organic carbon[1] | $CH_4$[2] | NEP[3] | NECB[4] | Annual emission[5] |
| | ---------------------------------------------Mg CO2-e | ------------------------------------------ | | | | | | |
| PSF | 48.5 | 37.7 | 0 | 2.31 | 0.11 | 10.8 | 8.4 | 0 |
| LPSF | 40.6 | 40.7 | 75 | 3.70 | 0.11 | -0.1 | -79.3 | -88 |
| ES | 39.8 | 30.7 | 176 | 3.67 | 0.07 | 9.1 | -170.3 | -179 |
| OP | 13.6 | 38.7 | 95 | 6.97 | 0.00 | -25.1 | -127.0 | -135 |

[1](Cook *et al.*, 2017); [2] (Hergoualc'h & Verchot, 2011); [3] NEP represent the difference between NPP and heterotrophic respiration; [4] NECB represent the net carbon gain and carbon loss; [5] Annual emission represent the net NECB between certain land cover type and intact forest.

# Chapter V

# Conclusion

## RESEARCH QUESTIONS AND ANSWERS

Tropical peat swamp forests are threatened by degradation and conversion at alarming rate. Logging, drainage canals and peat fires have been significant vectors of land use/land cover change that have degraded the ecosystem structures and functions, especially their carbon sink role. Yet, there is lack of information regarding their carbon stocks and changes related to land use/land cover change. Considering the threats of ongoing global warming to humanity and the significant role of peat swamp forest conversion on global GHG emission rate, information on potential greenhouse gas emissions and net ecosystem productivity associated with peat swamp forest conversion and degradation are crucially needed. These information will support better strategies and decisions on climate change mitigation approaches such as REDD+ scheme. This information are relevant to many tropical countries that are struggling to reach their target in reducing national emission as proposed during the last COP 21 in Paris. Indonesia is one among those countries that target to cut its national emissions by 29% - 41% in 2030, through emissions reduction from deforestation and forest degradation.

I provide new data and information of carbon dynamics from deep peat swamp forests in response to logging activities and conversion to early seral and oil palm plantations. My research was among the first that combines intensive field measurements of carbon stocks to provide estimates of the changes in ecosystem C stocks and emissions with land use/land cover change. This study was a pioneer in estimating the change in NPP and NEP of peat swamp forest associated with the land conversion. My study was the first comprehensive chrono-sequential estimate of ecosystem carbon stocks and potential $CO_2$ emissions from intact and logged peat swamp forest, early seral and oil palm plantations in tropical peatlands. In addition, I provide an update on emissions factor of the conversion of the intact tropical peat swamp forest to logged forest, early seral and oil palm plantations. My findings on NEP provides insight to increase the accuracy of recent dynamic model in estimating the rate of peat accumulation in tropical peat swamp forests.

1) What are the carbon stocks of the peat swamp forests (PSF) of the Pematang Gadung peat dome?

The PSF sites have higher total aboveground C stocks (158 Mg C $ha^{-1}$) than the LPSF sites (93 Mg C $ha^{-1}$). Aboveground C stocks comprise of tree and snag (and their roots), woody debris and litter. Tree C in PSF ranges from 82 to 113 Mg $ha^{-1}$ and was higher than in LPSF that ranges from 43 to 75. Tree roots C in PSF ranges from 24 to 30 Mg $ha^{-1}$ and was higher than in LPSF that ranges from 12 to 21 Mg/ha. Woody debris C in PSF ranges from 19 to 33 Mg/ha and was higher than in LPSF that ranges from 6 to 20 Mg/ha. Mean understorey and litter in PSF ranges from 5 to 10 Mg $ha^{-1}$ and was higher than in LPSF that ranges from 3 to 6 Mg $ha^{-1}$. The PSF soil carbon stocks in this study ranged from 3,650 to 5,442 Mg C $ha^{-1}$ with a mean of 4,243 Mg C $ha^{-1}$, which is substantially higher than the global mean suggested by Page (2011).

Not surprisingly, the ecosystem carbon stocks of PSF sites (4,401 Mg C/ha) has the highest carbon stocks among terrestrial ecosystem. In contrast with Alongi (2014) tropical PSF of this study sites has 4 and 3 times more of C density than Mangrove and Boreal peatland, respectively. Thus it has significant potential contribution for carbon sink, but on the other hand also for GHG emissions.

2) What are the potential emissions that could arise from degradation of PSF to LPSF, and from conversion of PSF to ES and OP?

PSF sites had higher total aboveground carbon stocks (158 Mg C $ha^{-1}$) than the LPSF (93 Mg C $ha^{-1}$), ES (12 Mg C $ha^{-1}$) and OP sites (8 Mg C $ha^{-1}$). Tree, roots, woody debris and litter C stocks in PSF were higher than those in LPSF, ES and OP. The mean ecosystem carbon stock for the PSF sites was 4,401 Mg C $ha^{-1}$. Ecosystem C stocks of LPSF, ES and OP was 3,768, 3,147, and 3,442 Mg C $ha^{-1}$, respectively. PSF stocks (4,401 Mg C $ha^{-1}$) was significantly higher than those degraded sites. At all sites, soils comprised > 96% of the mean ecosystem carbon stock. The conversion of PSF to LPSF was estimated to result in a net loss of 1,982 Mg $CO_2$ $ha^{-1}$. On the other hand, the conversion of PSF to ES was estimated to result in a total ecosystem net loss of 4,259 Mg $CO_2$ $ha^{-1}$. While the conversion of PSF to OP is estimated to result in a total ecosystem net loss of 3,176 Mg $CO_2$ $ha^{-1}$.

These results confirm that land use/land cover change significantly impacted ecosystem carbon stocks, emitting significant amount of $CO_2$ from tropical peatland ecosystems to the atmosphere. The tropical peatlands need urgent and significant efforts in conservation and restoration, to regain its function as a C sink and mitigate climate change.

**3)** What are the changes of NPP and NEP caused by logging, logging and fire (ES) and from land conversion, logging and fire in OP?

Based on my measurement on NPP and soil respirations in one year period, I found that logged peat swamp forest, early seral and oil palm plantation have significantly lower NPP (11.1 Mg C $ha^{-1}$ $yr^{-1}$, 10.9 Mg C $ha^{-1}$ $yr^{-1}$ and 3.7 Mg C $ha^{-1}$ $yr^{-1}$, respectively) than PSF (13.2 Mg $CO_2$-e $ha^{-1}$ $yr^{-1}$). ES showed lower heterotrophic respiration (30.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$) than PSF, LPSF and OP (37.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, 40.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$, 38.7 Mg $CO_2$ $ha^{-1}$ $yr^{-1}$**,** respectively)**.** LPSF and OP were net carbon sources; they have negative mean NEP values (-0.1 Mg $CO_2$-e $ha^{-1}$ $yr^{-1}$ and -25.1 Mg $CO_2$-e $ha^{-1}$ $yr^{-1}$, respectively). In contrast PSF and ES were net carbon sinks (10.8 Mg $CO_2$-e $ha^{-1}$ $yr^{-1}$ and 9.1 $CO_2$-e $ha^{-1}$ $yr^{-1}$, respectively). PSF is among the most productive of terrestrial ecosystems, with an NPP exceeding that of many tropical rain forests and similar to the most productive mangrove ecosystems. I learned that land use decreases productivity of the LPSF and OP sites. The ES had a similar NEP to the PSF, but frequent fires in this ecosystem likely offset carbon gains during the fire intervals. Land use change and forest degradation has shifted tropical PSFs from net carbon sinks to net carbon sources.

## IMPLICATIONS

My results on carbon stocks, soil GHG emissions and net ecosystem productivity should improve understanding about carbon dynamics in tropical peatlands. This study provides new knowledge of: a. how carbon stocks are impacted by logging, drainage and peat fires; b. how GHG emissions from tropical peatlands are effected by land use and land cover change; and c. How the net ecosystem productivity is evolved through different land uses/land covers.

This study provides empirical data to support not only tropical countries, but ultimately the IPCC in improving the accuracy of emission estimate from the degradation and conversion of tropical peat swamp forests.

Tropical peat swamp forest, in its intact state, is a net carbon sink. While degradation and conversion of the remaining peat swamp forests should be halted, the million hectares of degraded tropical peatlands should be restored in order to reduce significant GHG emissions from forestry and agricultural sectors. My study suggests that supporting degraded peat forest to regenerate, avoiding peat fires, and allowing fern and grass to grow under oil palm canopy, may enhance their net ecosystem productivity.

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# APPENDICES

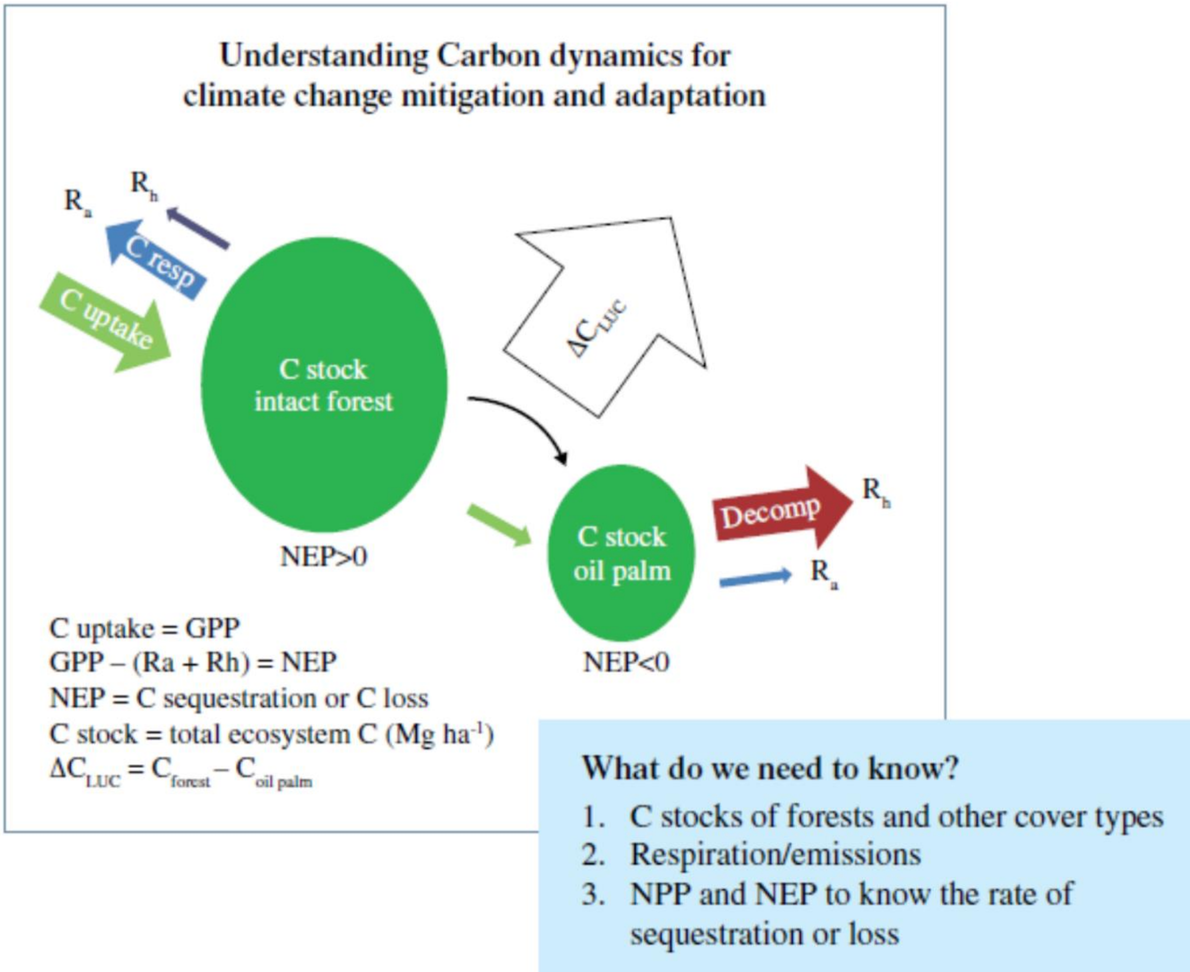


Figure 1. Conceptual framework of carbon dynamic in response to land use/cover change in tropical peatland ecosystems (Kauffman *et al.*, 2016). Estimating carbon gain or loss through carbon stock change approach and gain-loss approach (IPCC, 2006b).

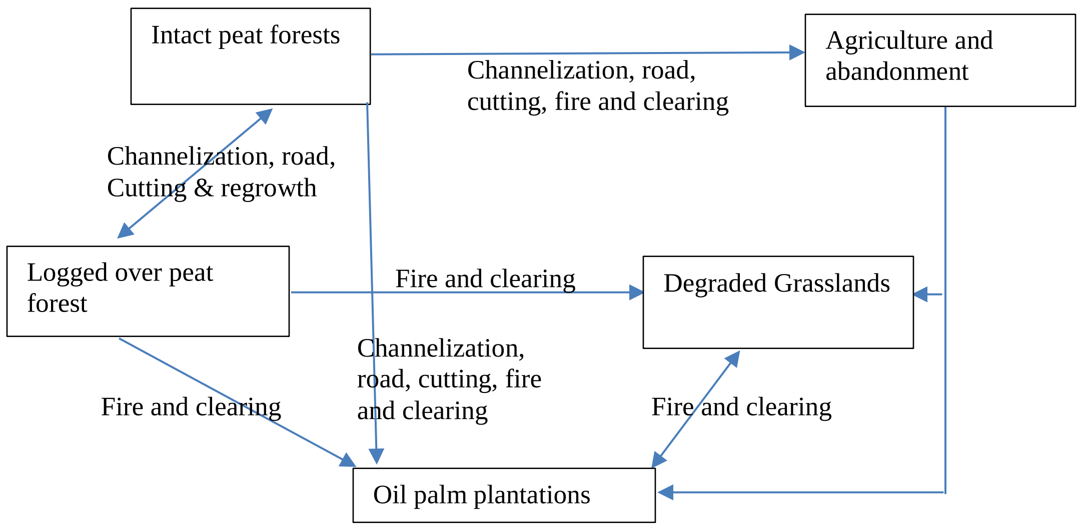


Figure 2. Conceptual model of land use leading to forest degradation and conversion to early seral and oil palm plantations in the research area

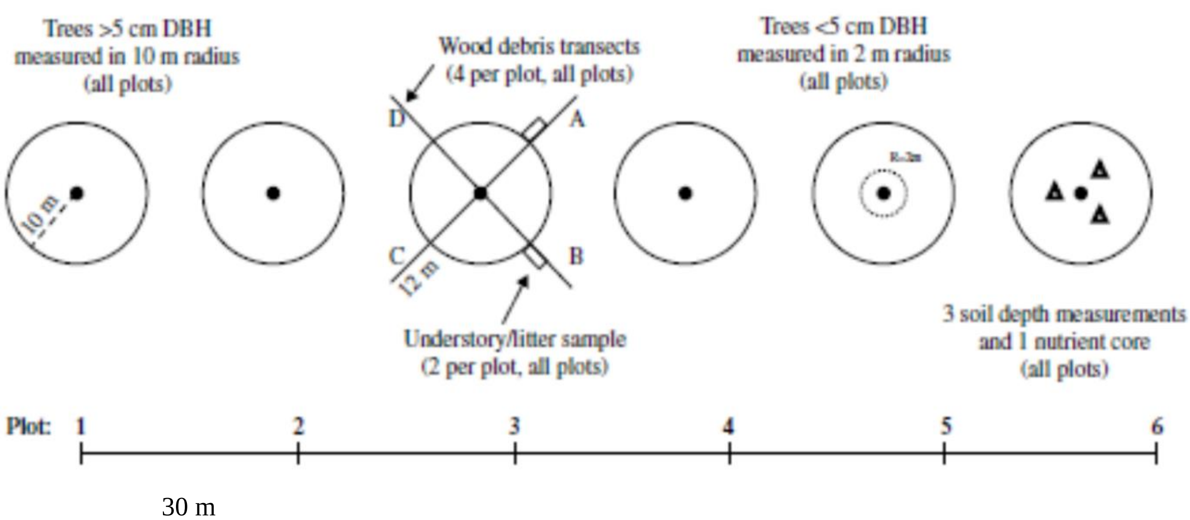


Figure 3. Transect and plot design to measured aboveground and belowground carbon pools,and sample peat (Kauffman *et al.*, 2016). Estimating carbon sequestration or emission through carbon stock change approach (IPCC, 2006).

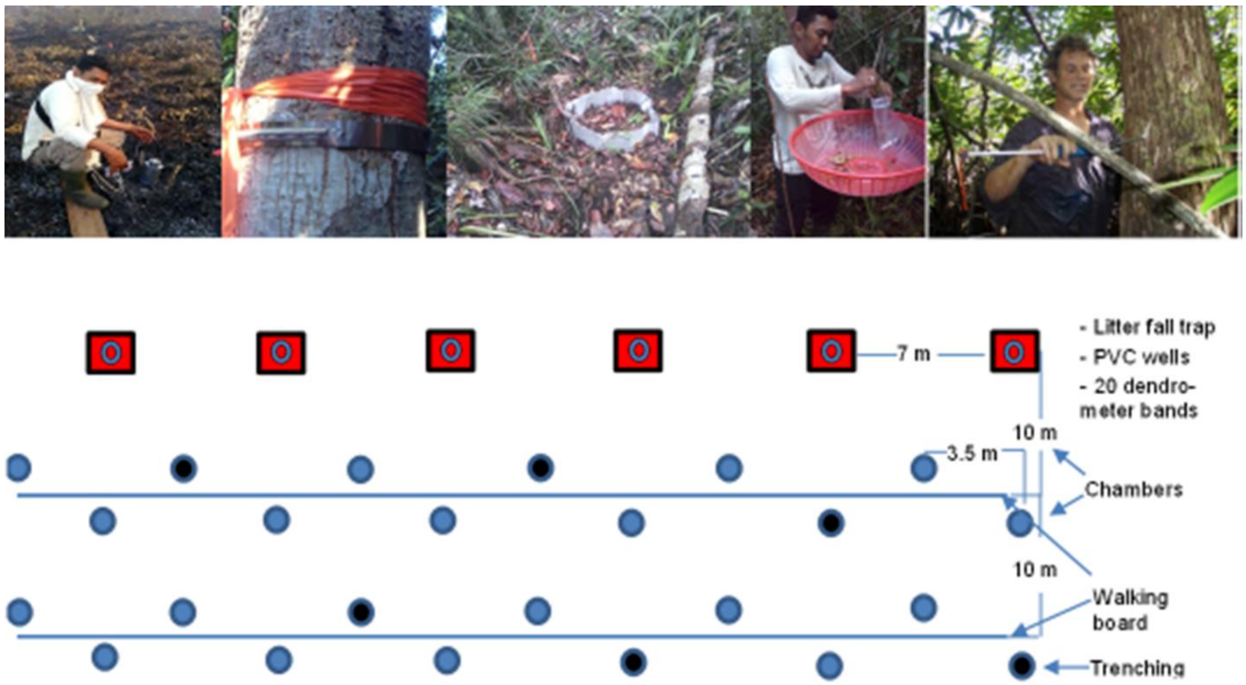


Figure 4. Transect and plot design to measured NPP (using dendrometer band) and heterotrophic respiration (using EGM-4). Estimating carbon sequestration or emission through gain-loss approach (IPCC, 2006).

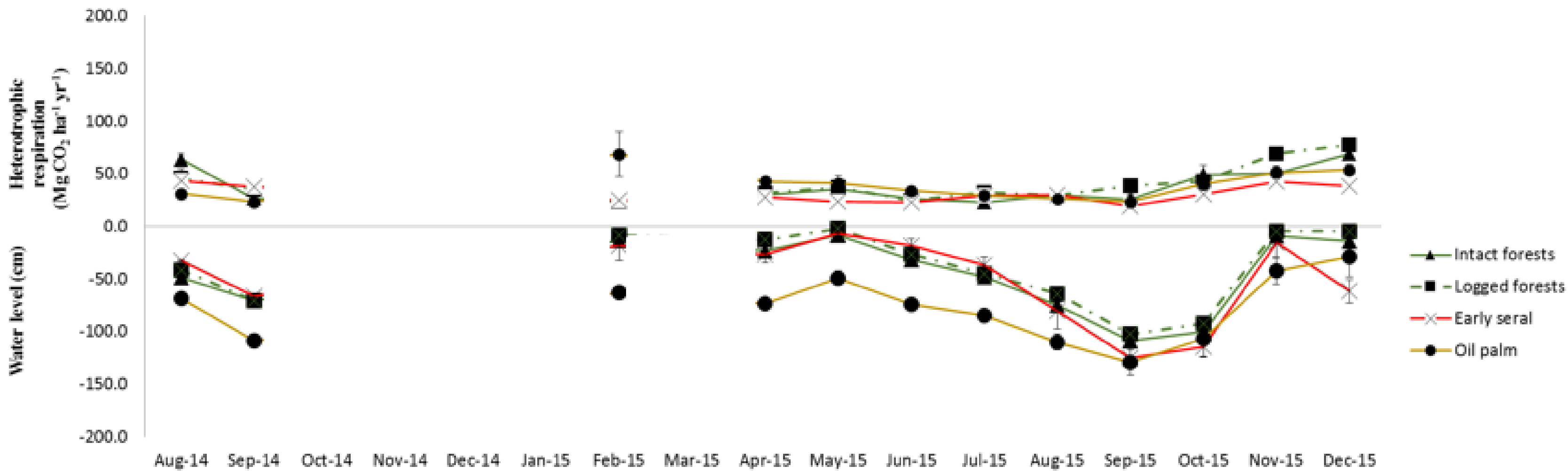


**Figure 5.** Heterotrophic respiration and water level trend from August 2014 to December 2015. Dry months is represented by data from August, September and October (5 months). Wet months are represented by data from February to July, and November to December period (7 months).