Assessing stand characteristics in relation to natural and anthropogenic disturbances and environmental factors in regenerating forest in East Kalimantan, Indonesia

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Summary

Tropical forests sequester and store vast amounts of carbon that can be emitted into the atmosphere as carbon dioxide, a greenhouse gas that has been linked to climate change. There is global interest in reducing the amount of carbon emitted into the atmosphere, and one of the main ways to do this is to slow degradation and deforestation. Forest degradation and deforestation can be caused by natural and anthropogenic disturbances or environmental factors. Currently, due to increasing global demands of products that are grown in areas covered by tropical forest, such as palm oil, it is important to study the surrounding forest to further understand how a variety of factors and disturbances may relate to the degradation and regeneration of forests. These relationships may help plantations make more conscious decisions of which forest to convert to plantation, they may aid in the conservation of forest that has high potential to regenerate, and they may help in assessing national and global carbon storage for initiatives that encourage the reduction of carbon emissions.

This research found that different categorizations of disturbance based on historical data or based on remote sensing and categorizations based on flooding regime and soil types as environmental factors have different relationships with the forest stand characteristics aboveground biomass (AGB), diameter at breast height (1.3 m, dbh) and stand density. Historically more severely disturbed forest seems to have lower AGB and smaller overall dbhs. Forest categorized by remote sensing seems to have more differences in the structural characteristics of dbh and stand density than AGB. Increased flooding frequency seems to be related to increased AGB, dbh and stand density. Soil types appear to relate to degraded forest differently from research suggesting that increased soil fertility relates to increased productivity and therefore increased AGB and dbh. In the degraded forests of this research, the least fertile soil, peat, which was also the least prone to erosion, had the most AGB. Furthermore, the oil palm stands contain significantly less AGB than any of the surrounding forest. Further understanding and consciousness of secondary regenerating forests are crucial in the deceleration of greenhouse gas emissions.

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Abbreviations and Terminology

ALOS PALSAR	Advanced Land Observing Satellite – Phased Array L-band Synthetic Aperture Radar
AGB	Aboveground biomass
dbh	Diameter at breast height (1.3m)
DC	Degraded forest Closed canopy
DO	Degraded forest Open canopy
HC	High forest Closed canopy
Large dbh	Trees with a dbh ≥ 10 cm
Small dbh	Trees with a dbh ≥1 cm and < 10 cm
REA	PT REA Plantations
REAKON	PT REA Conservation Department
UN-REDD	The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries

1 INTRODUCTION

1.1 Background Information

1.1.1 Forests & Climate Change

Forests are one of the most important ecosystems providing a variety of goods and services. Provisioning services or goods from forests include timber and fuel wood from tree biomass, and non-wood products, including herbaceous and edible plants. Supporting services include soil formation and nutrient cycling, along with others that serve as socio-cultural services. Regulatory services include water regimes, climate regulation, and carbon storage and sequestration (Diaz *et al.*, 2005). The benefits and services that forests provide are usually considered as 'public goods,' which are disregarded in many decision-making processes where they are not properly represented (Ecosystem Services, 2010; Nasi *et al.*, 2002).

The importance of regulatory services are often selected as focus points for international agreements such as the Kyoto Protocol (1998), which focuses on carbon storage in mitigating the release of greenhouse gases into the atmosphere, which is linked to the United Nations Framework Convention on Climate Change (UNFCCC). Forests can act as carbon sinks, through the process of photosynthesis or carbon sequestration, which is an important service as it contributes to the mitigation of greenhouse gas effects that can influence global climate change (Gibbs *et al.*, 2007). Aboveground biomass (AGB), including wood products and trees, and belowground biomass, is roughly half made up of carbon. Carbon sinks are defined by the fact that over time more carbon is being accumulated by the resource than being emitted by it. The flow of carbon in and out of forest resources depends on different biological processes. The carbon can be continually sequestered in trees and other life forms until they reach a saturation stage, and can be released back into the atmosphere due to natural decay or disturbance events such as fires and anthropogenic factors such as logging (US EPA, 2007).

The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation (UN-REDD) and REDD+ programs are working towards creating incentives for developing countries to decrease deforestation and forest degradation in efforts to reduce global greenhouse gas emissions. Ideally for REDD+, a monetary value or credit would be assigned for the amount of carbon stored in forests, encouraging developing countries with high carbon stocks to reduce emissions by conserving the remaining forest. This would not only aim to deter the effects of greenhouse gas emissions on climate change, but also help conservation efforts direct more attention to the environmental services of natural forests while promoting funds for pro-poor development encouraging equity and poverty alleviation in these areas (Gibbs *et al.*, 2007; UN-REDD Programme, 2009).

1.1.2 Forest Degradation

A variety of natural and anthropogenic disturbances lead to deforestation and forest degradation including fire events, flooding, logging and conversion of land for agriculture. Definitions of forest degradation vary, but in general involve the reduction of a forests ability to provide goods and services, or a negative alteration of the structure or function of the site (Assessing forest degradation, 2011). Continuous forest degradation could be globally detrimental as the loss of the ecosystem goods and services could lead to environmental, social and economic problems.

Wildfires can be devastating to forest ecosystems as they are unconfined and can spread quickly. Most wildfires in Indonesia are generated by fires from anthropogenic activities, but are intensified in periods of drought (Piadjati, 2002). Severe fire events have heavily degraded the forests of Kalimantan, with occurrences becoming more frequent in the past three decades (Piadjati, 2002). Major fire events occurring in 1982-83, 1991, 1994, and most recently 1997-98 have occurred after long drought events coinciding with the El Niño-

Southern Oscillation (ENSO) (Hoffman *et al*., 1999). An estimated 5.2 million hectares of forest have been degraded by fire in East Kalimantan in just the most recent 1997-98 fires alone, with a majority of this area having been logged-over forest prior to the fires (Piadjati, 2002). Fires degrade forests by directly burning living and dead AGB, but many trees remain standing once the fire has passed, and larger trees are sometime able to survive the fire event. These events can also negatively affect the seedbanks in the top layers of soil further reducing the ability of the primary species to recover (Nieuwstadt *et al*., 2001). The change in species composition due to degradation of the seedbanks of primary species can decrease biodiversity and subsequently decrease productivity that has been linked to biodiversity (Diaz *et al*., 2005). Silk *et al*. (2010) have found that frequent fires in Bornean forests can change the species composition of the forest and can even lead to species extinctions.

Flooding is generally assumed to have a negative affect on the total AGB as excessive flooding can reduce the growth of roots and impair total growth of trees (Lopez & Kursar, 2003). Flooding can also lead to soil anoxia, which restricts optimal nutrient flow to the trees and can negatively alter plant functions (Lopez & Kursar, 2003). Furthermore, flooding has been known to increase mortality by uprooting trees, particularly where trees have shallow roots and are continuously water logged in long rainy seasons (Nishimura, 2003).

Logging, both legally and illegally, is another main driver of deforestation in Indonesia. Some reports suggest that over 180 million cubic meters of large logs had been removed from East Kalimantan forests between 1969 and 2001 (Siegert *et al*., 2001), and that around 40 million hectares of Indonesian forest had been logged over in the last four decades of the 20th century (Priadjati, 2002). It is particularly devastating for forests not only because the aboveground biomass is physically being removed, but also because of the processes that occur after forests are logged. Common logging machinery compacts and displaces topsoil, which invokes erosion and creates open areas in the understory (Nieuwstadt, 2001; Pinard & Cropper, 2000). After logging, areas are also more susceptible to drought and fire because the opened up understory leads to drying of the remaining trees and fallen wood that act as fuel, plus further degradation and loss of biodiversity (Sundaland, 2007). By reducing the area of primary forest, logging also leaves the remaining primary forest more fragmented and vulnerable to edge effects that will further degrade the untouched area. Berry *et al*. (2010) have calculated that logging and its side effects reduce the aboveground biomass in Northern Borneo by about 50%. The degradation associated with logging can negatively influence the potential for the area to regenerate biomass and subsequently the rate at which the forest can accumulate carbon (Pinard & Cropper, 2000). Furthermore, after an area has been logged it is often converted to other land use types such as agriculture and plantations, or pastureland (Chazdon, 2003). In Indonesia, the lowland dipterocarp forest is heavily extracted due to globally increasing demands of wood products, with the roads for the removal constantly expanding and further enhancing deforestation and forest degradation (Sundaland, 2007).

Land conversion referring to elimination of forest to make space for agricultural land is also a main source of deforestation in Indonesia, which is the extreme form of forest degradation. This process can occur locally from shifting cultivation in which communities will clear forested areas for the cultivation of crops for their own use, but the larger pressure comes from the production of commercial agricultural products such as rice, rubber, palm oil, coconut and wood pulp (Langner, 2009). Increasing global demand for these products has accelerated the rate of land conversion in the past two decades. Between 1990 and 2010 in Indonesia, the area of land covered by oil palm plantations alone is recorded to have increased by 600% to cover 7.8 Mha (Carlson *et al*., 2012). There is concern that this practice is not only reducing the viable forest habitats for people and animals that rely on their products, but is also releasing significant amounts of carbon into the atmosphere further influencing climate change (Carlson *et al*., 2012).

Soil properties and soil structure are also considered to be important indicators in forest degradation, but are less commonly analyzed. Soil erosion can lead to decreased soil fertility and forest degradation as fertility is linked to productivity. The loss of soil enhances degradation because not only are the nutrients and organic matter in the removed soil lost, but the remaining deeper layers are less fertile and more dense, which makes germination and root expansion more difficult (Assessing forest degradation, 2011; Lamb, 2001).

The FAO has initialized the development of a universal set of criteria for defining, identifying and assessing forest degradation. The four main criteria selected as quantifiable indicators of degradation are; 1) forest biological diversity, 2) biomass, growing stock and carbon, 3) productive functions, and 4) protective functions (Assessing forest degradation, 2011). This research focuses on the biomass, growing stock and carbon criteria for indicating forest degradation due to the nature of the measurement taken as described in the methodologies. These measurements were the most straightforward indicators of degradation without a botanist in the field to assess biodiversity and without assessing other ecosystem services.

Baraloto *et al*. (2011) have created a framework (Figure 1) for assessing the relationship between AGB and forest characteristics such as diameter at breast height (dbh, 1.3 m) and stand density. This framework is useful for this research to further examine the relationship of these factors in the context of different types of disturbances or causes of degradation. Baraloto *et al*. (2011) acknowledge a hierarchical nature of relationships as some characteristics, such as dbh, are more directly related to the way AGB is calculated, while other characteristics such as soil fertility have a more indirect relationship with AGB.

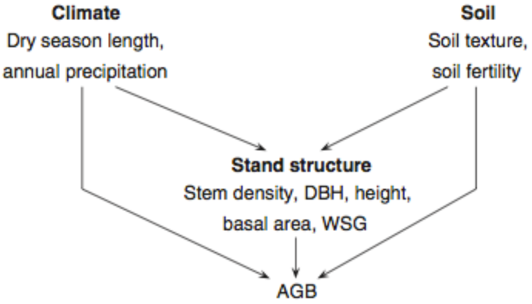


Figure 1. Framework for assessing the relationships between aboveground biomass (AGB) and stand and environmental descriptors as defined by Baraloto *et al*. (2011).

1.1.3 Forest Regeneration

Secondary forests broadly refer to forested areas that have been disturbed or degraded and may be recovering. The rate and ability of secondary forests to regenerate depends on multiple factors including the degree of soil erosion and availability of seed banks, proximity to primary forest, plus weather trends and droughts such as El Niño-Southern Oscillation that increases chances of fires (Chazdon, 1998; Lamb, 2011).

Multiple or frequent disturbances such as fire events and logging often decrease the resilience of the system and its ability to regenerate. When this is the case, secondary forests often take longer to regenerate, and community structure tends to change, leading to decreasing biodiversity and less long-living primary forest species. The change in community structure to a more degraded state is also often associated with less AGB overall, fewer large trees, more weeds and vines, and a more open canopy (Lamb, 2011). Disturbances such as logging and fire also have a positive feedback effect where logging can lead to higher mortality rates of trees during subsequent fire events, after which the trees are likely to be salvage felled (Nieuwstadt *et al*., 2001). Furthermore, when logging is followed by multiple fires or intense erosion, the forest may not recover at all and will degrade into grasslands (Lamb, 2011). Nonetheless, regenerating forests are widespread throughout Indonesia, and under workable conditions can and do regenerate while providing habitats for local wildlife, and water and greenhouse gas regulatory services (Lamb, 2011).

Although there are limitations to forest regeneration, tropical secondary forests are quite resilient. Without further disturbances, Lamb (2011) assumes that secondary forests are often able to regenerate to a more or less undisturbed state after 80 years, at which point it can be very difficult to differentiate between primary and secondary forests. Some studies have shown that the number of individuals and species richness of regenerating secondary forest is able to recover to pre-logged levels after 15 years (Chazdon, 2003). Cannon *et al.* (1998) suggest that with selective logging, species richness can remain high and recover to that of unlogged forests within a decade. This research found that in Kalimantan, species in the *Dipterocarpaceae* family were still the dominant species eight years post logging in an area where all of the stands with a dbh > 20 cm were removed. Other studies have calculated that after an initial logging disturbance, aboveground biomass can accumulate 1.8% of the lost biomass per year on average (Berry *et al.*, 2010). If this rate of accumulation were upheld throughout the regeneration process, the forest would recover within 60-65 years, but generally the biomass and carbon accumulation rates decrease as the forest matures so it would probably take longer than this estimate. As secondary tropical forests are relatively resilient in their recovery after single logging events, some scientists argue that these secondary forests should be considered for conservation rather than conversion to a different land-use type (Berry *et al.*, 2010; Cannon, 1998).

1.1.4 Oil Palm

The propagation of oil palm plantations is one of the leading sources of deforestation in Indonesia, but due to global increasing demands for food and fuel that contain palm oil, are not viewed entirely as destructive. Palm oil is used mainly in foods and biofuels, and the oil palm is one of the world's most rapidly expanding crops (Fitzherbert *et al.*, 2008). In 2008, the Roundtable on Sustainable Palm Oil (RSPO) was created with founders such as WWF in order to promote better palm oil production practices throughout the supply chain that consider the producers, the environment, and the local people. 41% of all RSPO certified palm oil is produced in Indonesia, with over 400,000 hectares of certified production area (Market Updates, 2009). Combined with the companies that are not part of the RSPO, there are six million hectares of oil palm plantations in Indonesia alone, with another four million hectares planned for expansion in the next three years due to increasing demands (The RSPO NPP, 2012).

With the increasing demand for palm oil, plantation expansions will undoubtedly lead to further degradation of the surrounding environment. One of the new recommendations introduced in January 2012 for RSPO certified palm oil is the New Planting Procedure (NPP). This procedure aims to increase transparency of plantation expansions and to make the selection process of potential plantation land more environmentally friendly. This process takes into consideration the conservation of primary forest and land with a high conservation value (HCV) when selecting where to expand oil palm cultivation and subsequently change the land use type. Areas with HCV include land that is valuable for the ecosystem, such as supporting endangered species, but also culturally valuable, such as burial grounds (Hager, 2002). When using the NPP, companies aim to select areas to expand their plantations that will be the least damaging socially and environmentally (The RSPO NPP, 2012). With further knowledge of the effects of different disturbances on forest degradation and regeneration, the NPP will be more easily practiced and regulated. Under these conditions, expanding plantation areas could be considered an anthropogenic form of regeneration if the site is too heavily degraded to continue as forest.

1.2 Problem Definition

Secondary forests in Indonesia are currently not considered for their conservation value compared to primary forests, and are often awarded as concession land for agriculture such as oil palm plantations (Fitzherbert *et al.*, 2008; Indonesian decree to halt primary forest loss, 2011). Furthermore, the New Planting Procedure recommended by the RSPO does not consider the values of secondary forest when assessing land to make environmentally sound decisions regarding plantation expansion. Studies have suggested that the additional emitted carbon that is sequestered by regenerating biomass should receive further attention as conservation value of logged forest (Berry *et al.*, 2010; Cannon *et al.*, 1998). The Indonesian Government has set national goals to reduce emissions by 26% by 2020 in relation to emissions from land use and land use change (Luttrell *et al.*, 2011). This will incorporate the tools derived from REDD+, but it would also be beneficial to consider the potential conservation of regenerating post-logged forests that accumulate carbon and not only focus on primary forest conservation. Currently, there is a knowledge gap regarding the relationship between disturbances related to forest degradation and forest stand characteristics that may act as indicators of regeneration, more specifically in East Kalimantan, Indonesia. Studying AGB and stand structures of degraded forests to further understand the relationship between AGB, stand characteristics, and different disturbance regimes can help provide a tool for Indonesia to assess the current state of its forest and monitor change. Furthermore, these indicators could be used to support field or satellite data used to assess the state of the forest and carbon variations on a national and global scale. This in turn would support Indonesia in reaching its carbon emissions goals, but also encourage oil palm companies to further investigate their concession areas and make more educated decisions for plantation expansion.

1.3 Research Aim

The first aim of this research is to assess the relationship between three forest characteristics; AGB, diameter at breast height (dbh, 1.3 m) and stand density, and different influencing factors of degradation. This aims to assess the forest characteristics on a landscape level and make comparisons between sampling sites for forests that have had different disturbance levels based on historical or satellite date, or different environmental characteristics such as flooding frequency and soil type that may lead to additional degradation.

This second aim seeks to directly compare AGB between regenerating forests and oil palm plantations, and therefore also carbon storage of the different land cover types. As 50% of above ground biomass is assumed to be carbon (Chave *et al*., 2005; Gibbs *et al*., 2007), the biomass measurements aim to assess the amount of carbon stored in concession stands to support logging and plantation companies to make informed decisions about plantation expansion while maintaining a goal of reducing greenhouse gas emissions.

1.4 Research Questions

1. Do aboveground biomass, stand density and the distribution of the dbh of trees differ significantly between areas with different levels of degradation?

    a. Degradation based on historical data on disturbance levels: relatively moderate vs. relatively heavy disturbance histories
    b. Degradation based on remote sensing data stratified in the following categories: degraded forest open canopy, degraded forest closed canopy, high forest closed canopy based on remote sensing data

2. Do aboveground biomass, stand density and the distribution of the dbh of trees differ significantly between areas with different environmental factors?

    a. With regards to flooding frequency
    b. With regards to soil type

3. How does the AGB and carbon of oil palm plantations compare to that of the surrounding secondary forest?

1.5 Hypotheses

1a. Do aboveground biomass, stand density and the distribution of the dbh of trees differ significantly between areas with different levels of degradation based on historical data on disturbance levels: relatively moderate vs. relatively heavy disturbance histories?

In general, the reoccurrence of disturbances such as logging reduces the regeneration time and ability to recover after each disturbance (Lamb, 2011). I expect that this will also hold true for the areas measured for this research, and that the regenerating forests after more disturbances, will have lower total aboveground biomass. Regeneration partially depends on the intensity and number of the disturbances. Trees can repopulate more easily if there are saplings or stumps left by the disturbance, such as with logging, which can leave behind viable individuals that can regenerate and already have an established root system (Lamb, 2011). Fire on the other hand can severely diminish the seed bank in the soil slowing regrowth of the original forest species (Lamb, 2011). I expect that the plots in the relatively moderately disturbed areas will have a higher overall AGB than those in the heavily disturbed areas due to the higher number and severity of disturbances there. For similar reasons, I also expect that the mean dbh will be higher for moderately disturbed plots. This is also because less severe and frequent disturbances may have allowed for the survival of more very large trees than heavier disturbances. Dbh is used in most allometric equations to calculate AGB, so I assume that they will have similar relationships with the moderately and heavily disturbed areas, and that moderately disturbed areas will have more trees with the largest dbhs than the heavily disturbed areas rather than just having more small dbh (dbh < 10 cm) trees that increase the AGB.

Furthermore, as lianas and vines are more resilient to recurring disturbances (Lamb, 2011), I expect that the density of the small dbh trees will be proportionately higher for those plots in the more heavily disturbed areas than in the moderately disturbed plots. Multiple logging and fire events can also leave the canopy more open and less densely populated, but with more vines and lianas (Lamb, 2011; Pinnard & Cropper, 2000). I expect that tree density in the more heavily disturbed sites will be relatively higher for small dbh trees, while large dbh (dbh ≥ 10 cm) tree density may be similar or slightly higher for more moderately disturbed sites. I expect that the density may be higher for large dbh trees in moderately disturbed sites because more large dbh trees may have survived the less frequent disturbances, while in the heavily disturbed site where fewer large dbh trees remain there may not have been enough time for the trees in the area to grow to have dbh > 10 cm.

1b. Do aboveground biomass, stand density and the distribution of the dbh of trees differ significantly between areas with different levels of degradation based on remote sensing data stratified in the following categories: degraded forest open canopy, degraded forest closed canopy, high forest closed canopy based on remote sensing data?

The SarVision, 2010 vegetation structural type map used considers several land cover types based on satellite imagery for the entire island of Borneo. The land cover types chosen for this research each have an expected level of biomass. The degraded forest open canopy is expected to have relatively medium biomass levels, the high forest closed canopy is expected to have high biomass levels, and the degraded forest closed canopy is expected to have high to medium biomass levels (Hoekman *et al*., 2009). I expect to see that the biomass levels measured in the field and calculated for this research follow these expectations. While all forests are degraded, I also expect that the land cover types with more closed canopies will have more large dbh trees than the forest with an open canopy. Furthermore, I expect that degraded forest open canopy will have higher small dbh tree densities as lianas and vines can become dominant where gaps in the canopy have been created by disturbance (Gehring *et al*., 2004).

2a. Do aboveground biomass, stand density and the distribution of the dbh of trees differ significantly between areas with different environmental factors with regards to flooding frequency?

As the data for this research has been divided into flood frequency categories of never or rarely flooded and seasonally flooded, I expect that the AGB will follow the general trend in tropical forests where flooded forests have less biomass than forests that rarely flood. Lopez and Kursar (2003) suggest that seasonal flooding not only reduces aboveground biomass, but also root and overall growth of trees. This could be due to the soil anoxia caused by flooding which diminishes the trees ability to function maximally (Lopez & Kursar, 2003). Due to this, I also expect that dbh and stand density will be lower in seasonally flooded plots than in plots that are rarely or never are flooded.

2b. Do aboveground biomass, stand density and the distribution of the dbh of trees differ significantly between areas with different environmental factors with regards to soil type?

The effect of soil types and their nutrient contents on AGB in tropical forests is a debated topic. There are arguments for fertile soils leading to higher AGB because of fewer nutrient limitations, but there are also arguments for lower biomass with higher turnover rates and mortality on very fertile soils in tropical forests (Paoli *et al*., 2008; Russo *et al*., 2005). While increased fertility is often correlated with higher mortality rates (Russo *et al*., 2005), the trend in Borneo seems to support the former argument, with a gradient of soils textures and fertility affecting both AGB and stand density (Paoli *et al*., 2008). The observed soil types for this research are peat, silt loam, and clay loam, and they are suggested to increase in fertility roughly in this order (Russo *et al*., 2005; Louck, 2012). Due to prior research, I expect that AGB will be relatively higher as the soil fertility increases, but also because this research focuses on regenerating forests after major disturbances rather than long-lived primary stands. Due to this, the assumption is that mortality correlated with increased soil fertility will not play as major of a role on biomass as for older stands. Furthermore, soil fertility also seems to be correlated with stand density. Baraloto *et al*. (2011) found that infertile sandy soils have higher small stem density while more fertile clay soils have larger overall trees, suggesting that clay soil plots will have higher dbhs. Paoli *et al*. (2008) found that soil type may not affect forest structure as much as AGB, but also suggests that tree density was lower on richer soils. Based on these findings, I expect to find that tree density decreases as soil fertility increases.

3. How does the AGB and carbon of oil palm plantations compare to that of the surrounding secondary forest?

I expect to find that secondary forests have a significantly higher ability to accumulate biomass and subsequently sequester carbon than oil palm plantations. This is supported by Lamb (2011) and by research performed by Morel *et al*. (2011). Morel *et al*. (2011) used ALOS PALSAR satellite data to estimate aboveground biomass for oil palm plantations and other land use types that had undergone different intensities of disturbance in northern Borneo. They found that both immature and mature oil palm plantations accumulated significantly less carbon than almost all of the other land-cover types including unlogged forest and a selection of logged forest that had been logged between 4 to 40 years prior. The values given by Morel *et al*. (2011) for oil palm plantation biomass are an average value of the biomass over the lifetime of the plantation. I will assess biomass at a single point in time, but I do still expect that the regenerating forests will have a significantly higher biomass than oil palm plantations. Furthermore, although these results come from satellite sensing, I assume that aboveground biomass calculations would produce similar biomass proportions.

2 METHODOLOGIES

2.1 Study Area

PT REA Kaltim Plantations (0º 14’ 57.8” N, 116º 18’ 24.6” E)

This research was conducted between April and June, 2012 in collaboration with REAKON, an oil palm company in East-Kalimantan, Indonesia on the island of Borneo (Figure 2). PT REA is a RSPO certified company meaning that they uphold the most sustainable industry practices. PT REA is comprised of eight supply base plantations in East Kalimantan province that are processed at one of their two mills. They note that the New Planting Procedures are recognized in this company and will be followed when identifying land for expansion of planting (Ogg, 2011). The oil palms planted at PT REA are *Elaeis guineensis*, originally from Costa Rica and begin to produce fruit around 18 months old. The palms begin to produce harvestable fruit at around 2 years and are harvested at this time, or when the fruit reaches a weight of 3kg (Kusneti, 2012).

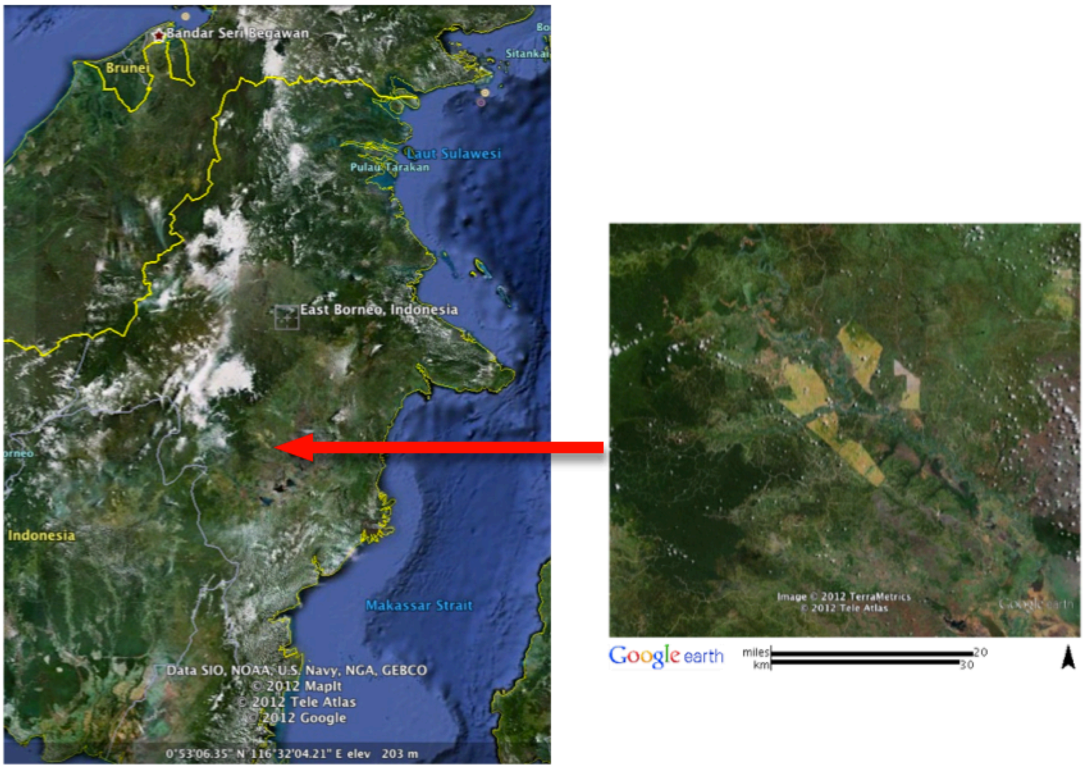


Figure 2. Location of PT REA oil palm plantations in East Kalimantan (PT REA, 2012)

The plantation estates lie on both sides of the Belayan River in the Kutai Kartanegara District of East Kalimantan, where planting first began in 1995. The land was designated as Conversion Forest before it was obtained by PT REA from the government, and had all been logged at least once since the early 1970s. The Belayan River is a major tributary to the Mahakam River where the soil variety includes shale, sandstone, some coal seams, karst limestone and some peat swamps. The annual rainfall in this area is between 2500-3000 mm with no clear dry season, but it is also heavily affected by the El Niño Southern Oscillation (ENSO) system when over an 18 month period the area may receive only 30% of its normal rain (Whitmore & Mackenzie, 1995).

2.2 Above Ground Biomass (AGB) Measurements

2.2.1 Site Selection

Sampling sites were selected based on the type of vegetation cover present according to the vegetation structural type map of SarVision (Hoekman *et al*., 2009), the known fire intensity acquired from a fire classification map (Hoffman *et al*., 1999), the distribution of forest in the vicinity, and other land history information acquired through interviews with PT REA staff and local experts and land surveys. The sample plots were selected using Geographic Information System (GIS), while taking into account accessibility and how representative it was of the surrounding land.

Based on historical land data, sites were selected in areas with a relatively moderate number of past disturbances (South of the Belayan River) and a relatively heavy number of past disturbances (North of the Belayan River). The categories of forest cover that were selected from the SarVision map are degraded forest open canopy, high forest closed canopy, and degraded forest closed canopy (Hoekman *et al*., 2009). These land cover categories were the three categories that relate to forest in the area that is not permanently inundated or swamp land. The areas were also selected according to the fire classification map (Hoffman *et al*., 1999), which indicates fire disturbance intensity during the 1997-98 fires. The aim was to find sites within the <25% fire damage areas from this time period to keep this disturbance intensity by fire minimal and constant for all plots measured. Based on these maps, and the information provided by the Whitmore and Mackenzie, 1995 and Wulffraat 2008 and 2009 surveys, 19 locations comprising 36 forest plots were selected throughout the PT REA concession area and nearby land. The breakdown of how many plots were measured in each of the categories can be seen in Table 1, with a visual of the distribution of the plots depicted in Figure 3. Most of the sites were selected in the Conservation Areas within the PT REA concession area, but some were in land adjacent to Conservation Areas or oil palm plantation. This difference is neglectable as previous research in the area shows that there is no significant difference in the AGB of forest managed as a Conservation Area by PT REA and not managed as a Conservation Area (Kies, 2011).

Six locations (12 plots) of plantation were also measured, 6 plots on either side of the Belayan River. Oil palms that had been planted in 1997-98 were measured as this was when the last major disturbance in the area occurred. They were measured to assess the biomass of a land conversion option in contrast to letting the forest regenerate naturally. The age of the oil palms will then be about the same age as the time the forest has had to start the recovery process since the last major disturbance event.

	Degraded forest open canopy	High forest closed canopy	Degraded forest closed canopy
Heavily Disturbed (19 plots)	6 plots	7 plots	6 plots
Moderately Disturbed (17 plots)	4 plots	7 plots	6 plots
Plantation	South bank: 6 plots	North bank: 6 plots	
Total: 48 plots		**36 forest plots & 12 plantation plots**	

Table 1. Overview of distribution of plot locations

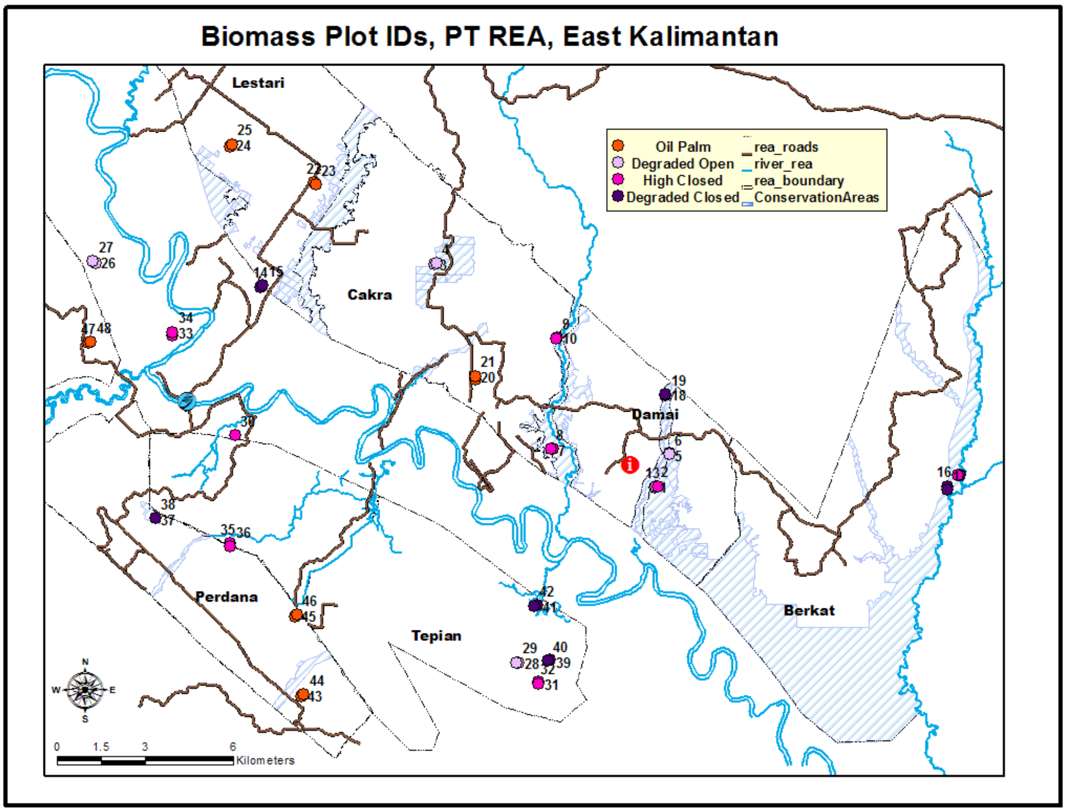


Figure 3. Locations of plots, orange dots represent plantation plots, light pink are degraded forest open canopy, pink are high forest closed canopy and purple dots are degraded forest closed canopy.

2.2.2 Categorization of Sites

The following four factors were chosen as categories in which to assess AGB, diameter at breast height (dbh, 1.3 m), and stand density. These categories are either based on disturbance levels as decided either by historical data or satellite data, or based on environmental factors that could lead to degradation. These were chosen as they can all be related to degradation and regeneration or the growth of forest.

Historical Disturbance: Logging and Fire events

One of the variables considered in plot selection as mentioned above was the relative level of disturbance based on historical data. The North and South banks of the Belayan River have different land use histories and frequencies of disturbances. According to a survey by Whitmore and Mackenzie in 1995, the North bank was extensively logged starting in the 1970s and subsequently more vulnerable to fire. In the large fire of 1983 58% of the North bank was destroyed, 45% of which had been logged. After the fire, this area was logged again and many trees smaller than the minimum were removed leaving much exposed subsoil and a depleted seedbank. This area was burned again in the 1997-98 fires and was selectively logged as the area was converted into oil palm plantation (Hoffman *et al.*, 1999; Whitmore & Mackenzie, 1995). Further WWF surveys in 2010 suggest that the forest is regenerating well in some areas on the North bank in and surrounding PT REA's concession areas, but there are many secondary tree species such as Macaranga, and still some heavily disturbed areas (Wulffraat, 2009).

The South bank of the Belayan River was not logged in the 1970s and much less severely damaged by the fire in 1983 in which only around 2% was burned. There was some secondary forest due to local shifting cultivation, and some logging after the big fire, but

Whitmore reported only seeing signs of removal of legal sized trees (Whitmore & Mackenzie, 1995). WWF surveys of the current conservation areas within PT REA in 2008 report finding areas in the south bank with good canopy and some peat forest, along with areas designated as community forest land where local people can take wood products (Wulffraat, 2008). There are areas on both banks of the Belayan River that are currently very degraded and recovering more quickly, but the trend is that the North bank was more heavily and more frequently disturbed than the South bank throughout the 25 years prior to being obtained by PT REA. Based on this information, the sites on the North bank of the river are referred to as heavily disturbed areas and the sites on the South bank are referred to as moderately disturbed areas in the results and discussion.

Remote Sensing

Hoekman *et al.* (2009) have used ALOS PALSAR data to produce land cover maps of Borneo, which was another variable considered in the selection process of site locations. This radar data is suitable for collecting information about the region because it can receive information through clouds and smoke, and can detect land cover change over time. For this research three categories specified by Hoekman *et al.* (2009) were selected as mentioned previously as they are the forest categories that are not permanently flooded nor considered riparian zones. They were also chosen because this research focuses on degraded forests and each category chosen has a slightly different expected amount of biomass.

The categories are degraded forest open canopy (DO), high forest closed canopy 1 & 2 (HC), and degraded forest closed canopy (DC). DO is described by Hoekman *et al.* (2009) as secondary forest with a 10-30% canopy cover in mostly flat terrain with dry soils. This land cover type is expected to have a medium amount of AGB. HC is described as having a canopy cover of over 30% with either mountainous, well-drained *dipterocarp* forest or mixed peat swamp and heath forest where there is poorer drainage. HC is expected to have a relatively high AGB levels. DC is described as degraded forest with more than 30% closed canopy in mostly flat, dry terrain. This land cover type is expected to have medium to high AGB levels (Hoekman *et al.*, 2009).

Flooding Regimes

Flooding occurrence was not a variable used during the selection process of the sites, but was used to categorize the sites after the fieldwork was conducted based on observations in the field and local knowledge of flooding. The sites were located in one of two categories; never or rarely flooding, and seasonally flooded. Thirteen of the sites were found to never or rarely flood and the other 23 sites were found to have seasonal flooding, and no sites considered for this study were permanently inundated.

Soil Types

Soil types were also observed in the field and not used in the selection process of the sites. There were five soil types noted in the field, which have been further condensed into three categories for analysis. The original five categories observed were; sand/clay, clay, clay/silt, silt, and peat. The three categories used for the analysis were; clay loam, silt loam and peat. Loam soil is made up of a mixture of sand, silt and clay in relatively even amounts, but can also have higher concentrations of one of the components, such as clay or silt as seen in Figure 4 (Soil Characterization, 2011). Clay loam is comprised of the sand/clay and clay observed soils, and can be described as nutrient rich with relatively poor drainage and relatively not prone to erosion (Russo *et al.*, 2005). Silt loam is comprised of the clay/silt and silt observed soil types and has relatively better drainage than clay loam, but is more prone to erosion. Peat, the final category generally has low nutrients and a low pH because nutrients are primarily from local decomposing vegetation. Also because most of the water entering the system is from rainfall and not exiting through flooding, which also reduced the risk of erosion (Louck, 2012).

Figure 4. Diagram of loam and the soil types it consists of. Loam, in the middle of the pyramid consists of sand, clay and silt, while if there are higher concentrations of one or more of these components, the soil type can be shifted toward that corner of the soil pyramid. (Soil Characterization, 2011)

2.2.3 Aboveground Biomass Data Collection

Diameter at Breast Height (dbh, diameter at 1.3 m) and the height of trees was measured for the selected plots according to the methodology described by SarVision (Quinones, 2010). Within the 48 plots measured, a total of 7492 individual plants were measured with a dbh range from 1-136.6 cm and a height range from 0.75-35 m. For each site, 2 rectangular plots measuring 10 x 100 m were set up, with a smaller subplot of 3 x 50 m in each of the larger rectangles (Figure 5). Large dbh trees with a dbh of >10 cm were measured in the entire plot, and small dbh trees with a diameter of >1cm and <10 cm were recorded within the smaller subplot.

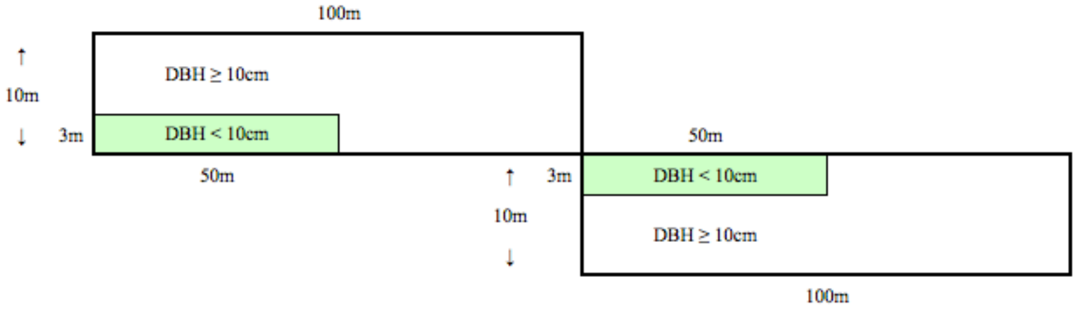


Figure 5. Plot design for data sampling

Although all locations were visually examined before the start of the measurements, due to some unexpected difficulties in measuring out 200 m for each location, there are some exceptions to this configuration. Under these circumstances, the two plots did not overlap, but instead share a portion of their borders so there are sections of the two plots that were directly adjacent to each other (plots 9, 10, 13, 30, 31 and 32 were the exceptions to the original plot design).

The dbh and height of woody biomass in the plots were measured for further calculations. Woody biomass was considered if it still had roots in the ground and was at least 2 m high, or if it was a dead fallen tree, including logged stumps measuring less than 2 m high. If the top of the tree was visible, the tree height was measured with a hypsometer, and if it was not clearly visible the height was estimated based on surrounding tree heights. If a tree had irregularities or buttressed roots at 1.3 m, the dbh was taken either 0.5 m above the irregularity or above the buttress. There were a few trees with buttresses too high to measure above, the diameter of these trees was measured at 1.3m, and the diameter above the buttress was calculated based on a significant correlation derived by Ngomanda *et al.* (2012) that dbh is on average 9.1% greater than the diameter above the buttress.

2.3 Allometric Equations

Allometric equations based on destructive sampling techniques have been used to calculate the AGB of trees from the dbh and height data collected. Dbh and height, or just dbh can be used to derive the AGB, both of which will be considered. Allometric relationships are typically developed for particular types of forests, such as equations described by Brown (1997) for forests with different amounts of annual rainfall, or the equations derived from Kenzo *et al.* (2009) for mixed lowland dipterocarp forests in Sarawak, Malaysian Borneo, that had been selectively logged within the past 20 years. They also differ between trees, palms, bamboos and lianas as the different groups have different relationships between parameters such as diameter and height and total biomass. The sum of biomass calculations from within one plot can be extrapolated into biomass in t/ha. As AGB is assumed to be roughly 50% carbon, these values can be converted into measurements of carbon stock in t/ha.

2.3.1 Living Trees

Brown (1997) used a database with trees from 3 tropical regions to create biomass regression equations for dry, moist and wet forests. Equation 1 below was derived for moist forests, or forests that receive between 1500-4000mm of rain per year with a very short to no dry season, and was based on a dataset of 170 trees with dbh range from 5-148 cm.

Equation 1. $B = \exp\{-2.134+2.530*\ln(d)\}$ $r^2 = 0.97$
$\rightarrow B = 0.118 * d^{2.53}$

B; biomass (kg), d; dbh (cm)

This equation is quite accurate until the dbh is around 160cm, after which the biomass calculated becomes rapidly overestimated due to the exponential nature of the equation (Brown, 1997). The maximum dbh of the data for this research is 136.6cm, so Equation 1 was suitable for all of the trees measured.

2.3.2 Necromass

Dead trees with branches are assessed with the same equations that apply to living trees. Dead trees without branches are considered to be either cylinders or truncated cones, and their biomass can be calculated based on the equations for these volumes.
If the dead tree is assumed to be cylindrical, the equations is based on:

$$V = \pi r^2 h$$

V; volume (cm^3), h; tree height or length (cm), r; radius (cm)

Based on this equation, Hairiah *et al*. (2001) have given Equation 2 below to calculate biomass;

Equation 2. $B = \pi d^2 h * g/40$

B; biomass (kg), h; height or length (m), d; dbh (cm), g; specific gravity of wood (g/cm^3)

If the dead tree has been measured to have different diameters at either end, the equation is based on the volume of a truncated cone.

$$V = 1/3 * \pi * h\,(R^2 + r^2 + R*r)$$

V; volume (cm^3), h; tree length (m), R; radius of one base (cm), r; radius of other base (cm)

Based on the volume equation above and the relationship of the volume of a cylinder and Equation 2, biomass was calculated for fallen trees with different size bases using Equation 3;

Equation 3. $B = 1/3 * \pi * h\,(D^2 + d^2 + D*d) * g/40$

B; biomass (kg), h; height or length (m), D; diameter of one base (cm), d; diameter of other base (cm), g; specific gravity of wood (g/cm^3)

The default specific gravity of wood, or wood density, is estimated at 0.5 g/cm^3, with a range of 0.3-0.8 g/cm^3 (Hairiah *et al*., 2001). For this research, 0.5 g/cm^3 was used to calculate the biomass of dead trees.

2.3.3 Palms

From a study where 25 individual palms were harvested and dried, Frangi and Lugo (1985) have developed allometric equations to calculate the biomass of palm trees. They have developed equations that use either the height of the stem (Equation 4) or the total height of the palm (Equation 5). In the field it was easier and more accurate to measure the stem height rather than the total height. If the height of the stem was available this value was used to calculate the biomass with Equation 4, but if it was not available the total height was used to calculate biomass with Equation 5.

Equation 4. $B = 7.7s + 4.5$ $r^2 = 0.90$
Equation 5. $B = 6.4h - 10$ $r^2 = 0.96$

B; biomass (kg), s; stem height (m), h; total height (m)

2.3.4 Lianas & Rattan

Gehring *et al*. (2004) have developed allometric equations for the biomass of lianas in primary and secondary tropical forests of central Amazonia. As measuring the length of lianas is difficult and less accurate than measuring the diameter in the field, they recommend to use an equation based on the diameter. Equation 6 is based on the harvesting of 561 individuals with a diameter range from 0.1-13.8cm and a length range of 20cm-48m.

Equation 6. $\ln(B) = -7.114 + 2.276*\ln(d)$ $r^2 = 0.73$
$\rightarrow B = 0.0008*d^{2.276}$

B; biomass (kg), d; diameter (cm)

Rattan, a climbing, non-branching palm is also considered a liana in its structure (Butler, 2012; Lianas, 2012; Watanabe, 2007). Equation 6 was also used to calculate the biomass of rattans.

2.3.5 Extrapolations

To find the total above ground biomass (TAGB) of each plot, the biomass (t/ha) of each individual in the small and large plots was summed. The biomass data for each plot was then converted from kg to t/ha by an extrapolation factor. To extrapolate the data for large dbh trees measured in the large plot:

Biomass (t/ha) = B/1000*10, or B/100
B; biomass within large plot (kg/1000m^2)

To extrapolate the data for all small dbh trees measured in the sub plot:

Biomass (t/ha) = B/1000*66.666, or B/15
B; biomass within subplot (kg/150m^2)

The stand density refers to a count of how many individuals were measured in the plots including live trees, dead trees, palms, lianas and rattans. To convert the stand density to coverage per hectare the values for the large dbh trees were multiplied by 10, and the small dbh trees were multiplied by 66.667.

2.4 Statistical Analysis

SPSS 20 was used to organize and analyze the data collected in the field. Both parametric and non-parametric tests were used depending on the distribution of the data. Data with a relatively normal distribution require the parametric ANOVA and independent sample t-tests, while data that had a skewed distribution required non-parametric Kruskal-Wallis and Mann-Whitney tests. The alpha value for two-tailed significance used was .05, except when using the Mann-Whitney tests as post hoc tests for the Kruskal-Wallis, when a Bonferroni correction was applied making the alpha value unique for the circumstances. The Bonferroni correction divides the alpha value by the number of comparisons being made when there are more than two categories being compared, but a pairwise calculation such as the Mann-Whitney test is being applied (Price, 2000).

3 RESULTS

Table 2 shows an overview of the data collected with the categorization for each plot, the total AGB (t/ha), the mean dbh (cm) for large dbh trees, and the total number of individual life forms measured. In total, 7139 individual life forms in temporary forest plots were measured, including living trees (68.3%), necromass (8.5%), palms (.1%), lianas (16.4%), and rattans (6.4%), and 267 oil palm trees in oil palm plantations. The AGB for forest plots ranged from 70.9 t/ha to 574 t/ha with a mean of 235.4 +/- 137.5 t/ha. The total AGB for oil palm plots measured ranged from 6 t/ha to 11.8 t/ha with a mean of 10.4 +/- 1.6 t/ha.

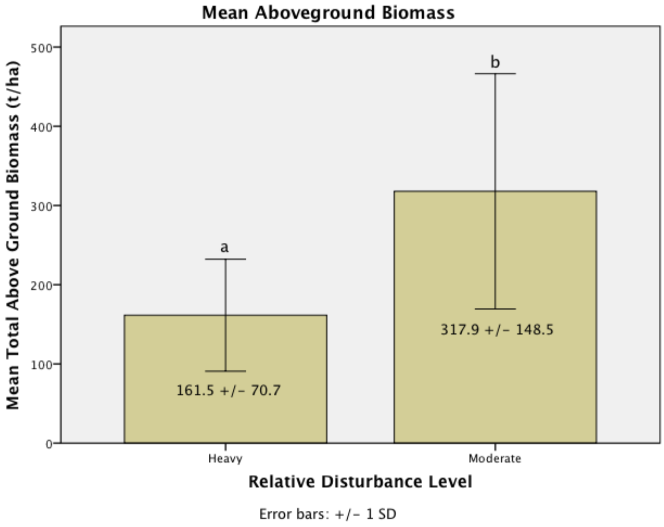
Plot	Relative Disturbance Level	Type of Vegetation/Land Cover	Flooding Frequency	Observed Soil Type	Total AGB (t/ha)	Mean dbh of trees > 10 cm (cm)	Total Number of Life Forms Measured
1	Heavy	Degraded Open	Never/Rarely	Clay Loam	81.104	14.651	106
2	Heavy	Degraded Open	Never/Rarely	Silt Loam	167.756	17.831	182
3	Heavy	Degraded Open	Never/Rarely	Clay Loam	225.371	19.193	202
4	Heavy	Degraded Open	Never/Rarely	Clay Loam	101.263	18.739	191
5	Heavy	Degraded Open	Seasonally	Silt Loam	89.477	17.773	102
6	Heavy	Degraded Open	Seasonally	Silt Loam	119.829	19.234	91
7	Heavy	High Closed	Seasonally	Clay Loam	214.817	15.657	257
8	Heavy	High Closed	Seasonally	Clay Loam	269.469	16.663	245
9	Heavy	High Closed	Never/Rarely	Silt Loam	70.904	13.008	199
10	Heavy	High Closed	Never/Rarely	Silt Loam	105.132	15.104	189
11	Heavy	High Closed	Seasonally	Silt Loam	113.161	14.853	217
12	Heavy	High Closed	Seasonally	Silt Loam	208.665	19.369	181
13	Heavy	High Closed	Never/Rarely	Clay Loam	115.075	14.012	161
14	Heavy	Degraded Closed	Seasonally	Clay Loam	336.944	18.493	171
15	Heavy	Degraded Closed	Seasonally	Clay Loam	164.804	16.380	210
16	Heavy	Degraded Closed	Seasonally	Silt Loam	214.623	16.427	262
17	Heavy	Degraded Closed	Seasonally	Silt Loam	195.109	16.482	252
18	Heavy	Degraded Closed	Never/Rarely	Clay Loam	151.654	18.109	135
19	Heavy	Degraded Closed	Never/Rarely	Clay Loam	124.198	18.772	305
20	Heavy	Oil Palm	Never/Rarely	Sand	10.330	81.709	22
21	Heavy	Oil Palm	Never/Rarely	Sand	11.746	78.765	23
22	Heavy	Oil Palm	Never/Rarely	Clay Loam	11.439	78.159	22
23	Heavy	Oil Palm	Never/Rarely	Clay Loam	10.978	79.443	21
24	Heavy	Oil Palm	Never/Rarely	Silt Loam	10.021	86.091	23
25	Heavy	Oil Palm	Never/Rarely	Silt Loam	6.008	68.613	24
26	Moderate	Degraded Open	Never/Rarely	Silt Loam	136.139	16.609	179
27	Moderate	Degraded Open	Never/Rarely	Silt Loam	129.118	17.405	189
28	Moderate	Degraded Open	Seasonally	Peat	266.562	17.203	233
29	Moderate	Degraded Open	Seasonally	Peat	201.108	14.994	175
30	Moderate	High Closed	Seasonally	Clay Loam	571.462	29.597	250
31	Moderate	High Closed	Seasonally	Peat	413.005	21.461	296
32	Moderate	High Closed	Seasonally	Peat	337.633	20.595	266
33	Moderate	High Closed	Seasonally	Silt Loam	340.037	19.237	169
34	Moderate	High Closed	Seasonally	Silt Loam	166.664	16.269	175
35	Moderate	High Closed	Seasonally	Silt Loam	363.607	18.277	266
36	Moderate	High Closed	Seasonally	Silt Loam	282.183	17.057	214
37	Moderate	Degraded Closed	Never/Rarely	Silt Loam	457.034	29.124	118
38	Moderate	Degraded Closed	Never/Rarely	Silt Loam	93.374	22.471	135
39	Moderate	Degraded Closed	Seasonally	Peat	439.564	23.019	250
40	Moderate	Degraded Closed	Seasonally	Peat	574.184	23.990	227
41	Moderate	Degraded Closed	Seasonally	Silt Loam	224.138	19.079	173
42	Moderate	Degraded Closed	Seasonally	Silt Loam	408.585	19.269	220
43	Moderate	Oil Palm	Never/Rarely	Clay Loam	11.470	70.286	22
44	Moderate	Oil Palm	Never/Rarely	Clay Loam	16.185	74.456	22
45	Moderate	Oil Palm	Never/Rarely	Clay Loam	30.283	58.779	21
46	Moderate	Oil Palm	Never/Rarely	Clay Loam	47.281	68.517	22
47	Moderate	Oil Palm	Never/Rarely	Clay Loam	17.713	69.511	23
48	Moderate	Oil Palm	Never/Rarely	Clay Loam	30.858	72.064	22

Table 2. Data overview for each plot.

3.1 Historical Disturbances

3.1.1 Aboveground Biomass (AGB)

Mann-Whitney tests show that the mean total AGB of moderately disturbed forests is significantly higher than in heavily disturbed forests (p=.001). Figure 6 shows the mean total AGB and mean AGB for large dbh trees for heavily and moderately disturbed plots with the mean +/- 1 standard deviation, and clearly shows that the AGB is higher in moderately disturbed plots. This supports hypothesis 1a, more disturbed forest will have lower overall AGB. This difference is also present for mean AGB of large dbh trees measured (p=.001), but not for the mean AGB of small dbh trees. The mean AGB of small dbh trees in heavily disturbed plots is 22 +/- 9.8 t/ha while the mean AGB of small dbh trees in moderately disturbed areas is 21.9 +/- 10.7 t/ha.



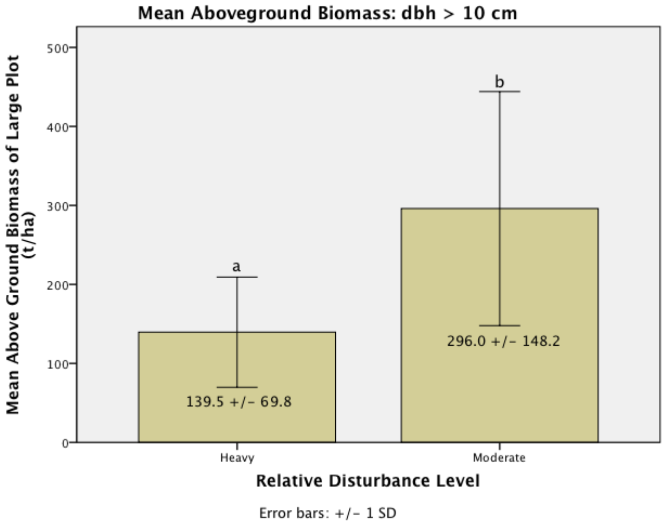


Figure 6. Mean AGB (t/ha) for plots in moderately (N=17) and heavily (N=19) disturbed forest. Top: Total AGB, moderately disturbed range is 93.4-574.2 t/ha, heavily disturbed range is 70.9-336.9 t/ha. Bottom: AGB of large dbh trees, moderately disturbed range is 71.3-557.8 t/ha, heavily disturbed range is 49.9-325.3 t/ha.

The distribution of total AGB for all of the plots measured is positively skewed, as is shown in the top graph of Figure 7. Figure 7 also shows the distribution of total AGB in heavily and moderately disturbed areas separately. The former resembles the total frequency distribution with a positively skewed shape, while the distribution of total AGB in moderately disturbed areas does not. In moderately disturbed areas, the total AGB seems to be more uniformly distributed throughout the range.

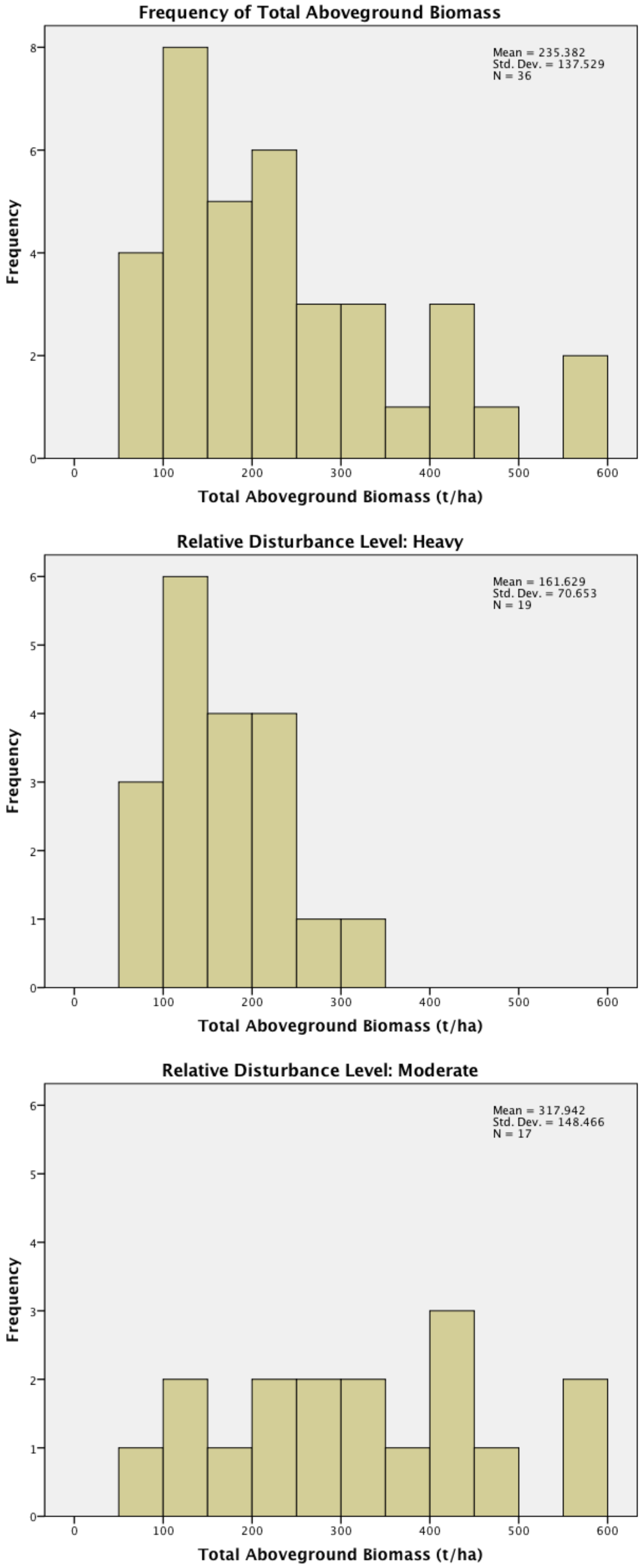


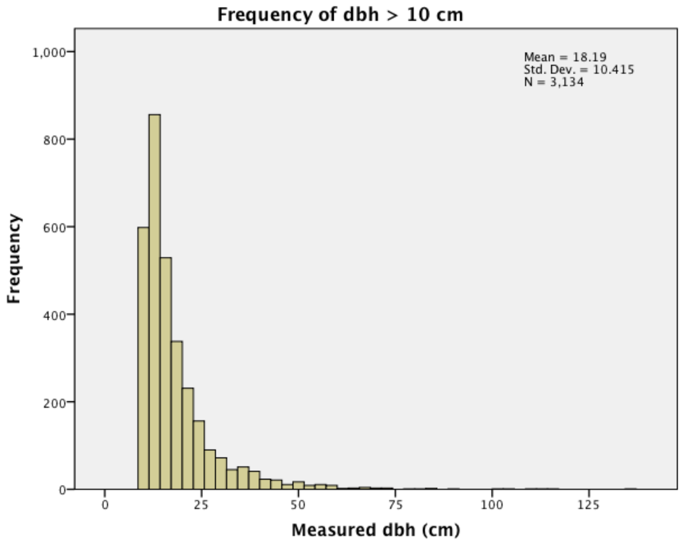
Figure 7. Distribution of total AGB (t/ha) for forest plots. Top: All forest plots, range: 70.9-574.2 t/ha. Middle: Plots in heavily disturbed areas, range: 70.9-336.9 t/ha. Bottom: Plots in moderately disturbed areas, range: 93.4-574.2 t/ha.

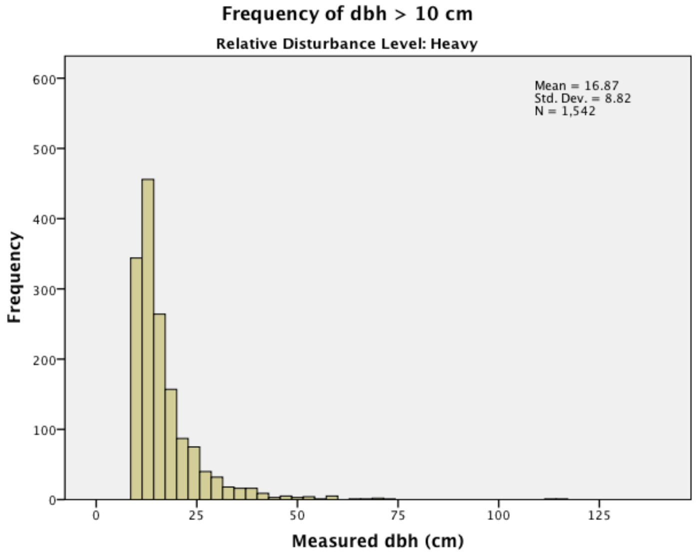
3.1.2 Diameter at breast height, 1.3 m (dbh)

The dbh for large dbh trees ranged from 10-136.6 cm, with an average of 18.2 +/- 10.4 cm. The minimum dbh here is 10 cm because this was the cutoff point between small dbh and large dbh trees. As small dbh trees were restricted to being between 1 and 10 cm, only the range and distribution of large dbh trees is considered in Figure 8 as there is more difference between the plots.

The frequency of dbh is positively skewed for all large dbh trees as seen in Figure 8, similarly to the distribution of total AGB. This distribution is similar for trees in heavily and moderately disturbed areas, although the mean is shifted slightly to the right for moderately disturbed plots. Mann-Whitney tests show that there is a significant difference (p=.000) between the two disturbance groups for the dbh of large dbh trees. This supports hypothesis 1a that dbh will be higher in moderately disturbed plots, and also that dbh will have a similar relationship with the disturbance levels as total AGB.

The median dbh for heavily disturbed plots is 14.1 cm, with a mean of 16.87 +/- 8.82 cm, and the median dbh for moderately disturbed plots is 15.7, with a mean of 19.47 +/- 11.62 cm. The greater difference between the median and mean of moderately disturbed plots shows that the distribution is more skewed suggesting that there are more trees with larger dbh. The difference in median is shown by a slight shift to the right for the moderately disturbed dbh distribution.





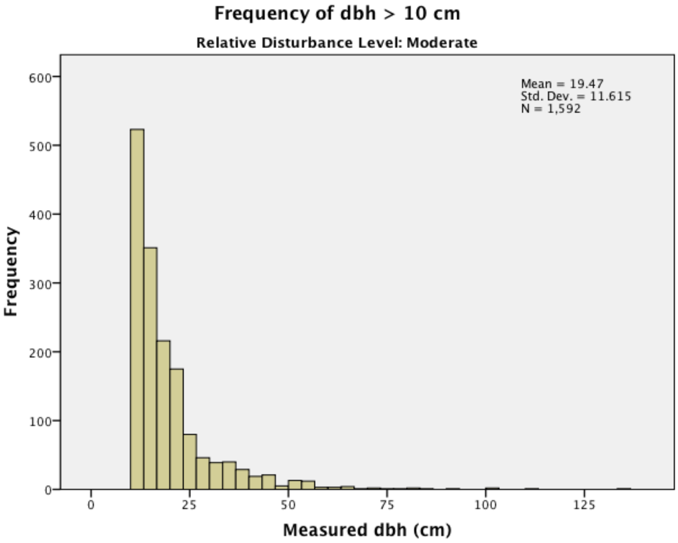


Figure 8. Distribution of dbh > 10 cm. Top: For all plots, range: 10-136.6 cm. Middle: For plots in heavily disturbed areas, range: 10-116.7 cm. Bottom: For plots in moderately disturbed areas, range: 10-136.6 cm.

To further assess the high dbhs that make up the top 10% of large dbh, all dbh >= 29.7 cm were considered. This helps to understand if the difference in large dbh trees in moderately and heavily disturbed plots can be linked to more large dbh trees in moderately disturbed areas, or if the trees there actually have higher dbhs. The distribution is also positively skewed, similar to the distribution of all large dbh. Mann-Whitney tests show that there is a significant difference (p=.040) of top 10% of dbh of large dbh trees between the heavily & moderately disturbed areas. Heavily disturbed plots had 110 trees in this range with a mean of 41.06 +/- 14.2 cm, and moderately disturbed plots had 203 trees in this range with a mean of 43.6 +/- 15.4 cm. There are more trees in this range for moderately disturbed plots than heavily, but this significant difference supports hypothesis 1a in that there are trees with larger dbhs in moderately disturbed plots, which would be expected because with fewer intense disturbance events, the large dbh trees may have a higher chance of survival.

3.1.3 Stand density

Tree stand density is not significantly different between plots in heavily disturbed areas and moderately disturbed areas as shown in Figure 9 above. There is also no significant difference between the two disturbance histories for density of large dbh trees or density of small dbh trees. Hypothesis 1a states that tree density of small dbh trees will be higher in the heavily disturbed areas, but the data reject this hypothesis as there is no significant difference, and the moderately disturbed plots actually have a slightly higher mean (93.7 +/- 33.3) than for the heavily disturbed plots (81.2 +/- 253.0). Hypothesis 1a also says that the density of large dbh trees will be similar or slightly higher for moderately disturbed areas than heavily disturbed areas. This is supported as the mean dbh of large dbh trees in moderately disturbed areas (93.7 +/- 33.3 cm) is slightly higher than the mean dbh of large dbh trees in heavily disturbed areas (81.2 +/- 25.0 cm), and there is no significant difference between the two groups.

Figure 9. Total tree density in heavily (N=19, range = 91-305 individuals) and moderately (N=17, range = 118-296 individuals) disturbed areas.

3.2 Remote Sensing

The land cover categories were considered while choosing the sites to be measured, so they are relatively evenly distributed throughout the heavily and moderately disturbed plots. Of the 36 plots, 28% were degraded forest open canopy, 39% were high forest closed canopy, and 33% were degraded forest closed canopy. Within each land cover category, high forest closed canopy (HC) and degraded forest closed canopy (DC) were each split evenly between heavily and moderately disturbed, and degraded forest open canopy (DO) had 60% of its distribution in heavily disturbed and 40% in moderately disturbed.

3.2.1 Aboveground Biomass (AGB)

Although there are large differences in the mean total AGB of each land cover category, a Kruskal-Wallis tests shows that there are no significant differences between the 3 categories (p=.084), as seen in Figure 10 below. Hypothesis 1b states that DO would have a medium AGB level, DC would have medium to high AGB levels, and HC would have high AGB levels, but that is not supported by the findings here. Hypothesis 1b also suggested that the forest types with closed canopies would have more total AGB, but this is also rejected, as there is no significant difference in AGB between any of the categories.

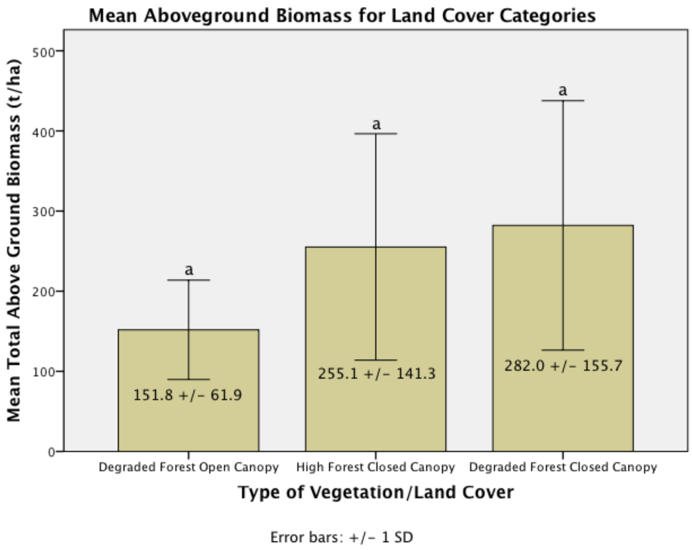
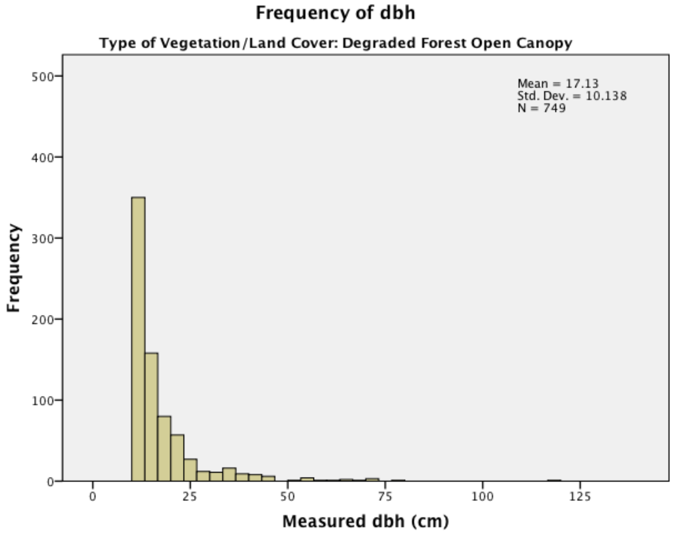


Figure 10. Mean total AGB (t/ha) for each of the three forest categories; Degraded forest open canopy (N=10, range: 57.3-215.6 t/ha), High forest closed canopy (N=14, range: 49.9-557.8 t/ha), and Degraded forest closed canopy (N=12, range: 71.3-555.8 t/ha).

3.2.2 Diameter at breast height, 1.3 m (dbh)

Although AGB is not significantly different between these three categories, the dbh are. A Kruskal-Wallis test shows that there is a significant difference between the dbh of these groups. Further Mann-Whitney tests show that there is a significant difference between the dbh of each group (p=.000) for each pair. The distributions of large dbhs for the three categories are all positively skewed, as shown in Figure 11.The median dbh of DO plots is 13.6 cm with a mean of 17.13 +/- 1-.14 cm, the median dbh of HC plots is 14.9 cm with a mean of 17.71 +/- 9.58 cm, and the median dbh of DC plots is 15.8 cm with a mean of 19.61 +/- 11.50 cm. The difference between the median and mean of DC plots is the greatest, along with having the greatest median and mean values suggesting that this category has more large dbh trees than the other land cover categories. This supports hypothesis 1b in that categories with closed canopies will have more large dbh trees than the category with an open canopy.



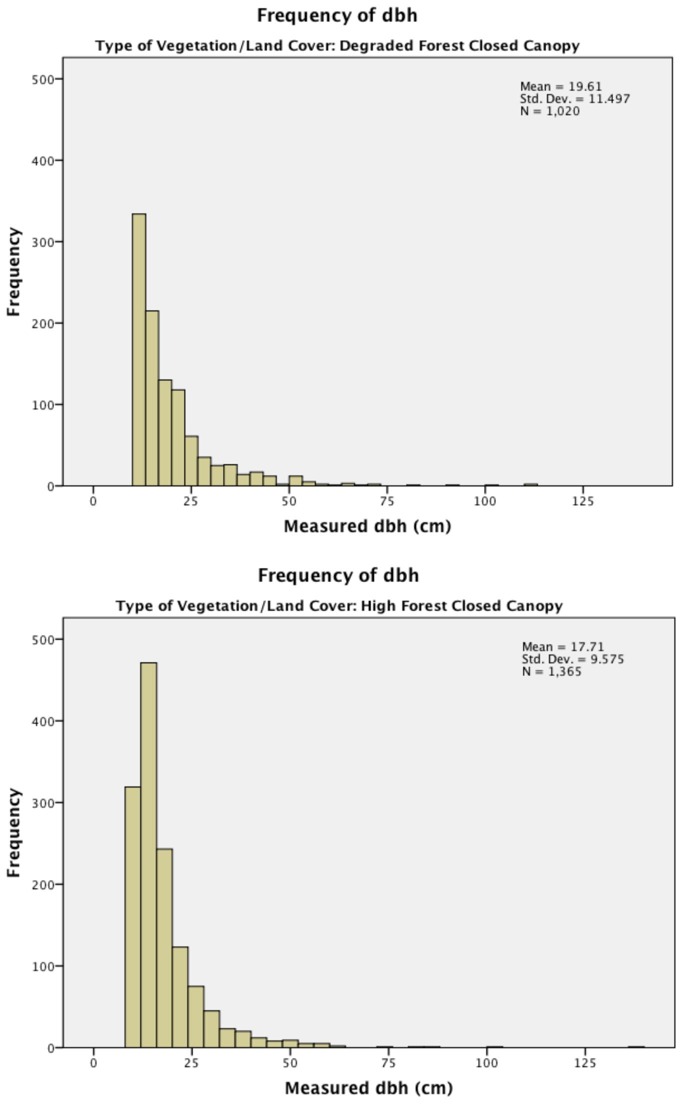


Figure 11. Distribution of dbh > 10 cm. Top: For plots in degraded forest open canopy, range: 10-116.7 cm. Middle: For plots in degraded forest closed canopy, range: 10-112.5 cm. Bottom: For plots in high forest closed canopy, range: 10-136.6 cm.

3.2.3 Stand density

Figure 12 shows that DO has the lowest mean stand density, HC has the highest mean stand density, and DC is not significantly different from either of the other two categories. An ANOVA and Tukey HSD post-hoc test assessing the differences between total tree density in forest cover categories suggest that there is a significant difference between the stand densities of DO and HC (p=.030). As large dbh and small dbh stand densities follow this trend, this rejects hypothesis 1b that states that DO will have a significantly higher small dbh stand density.

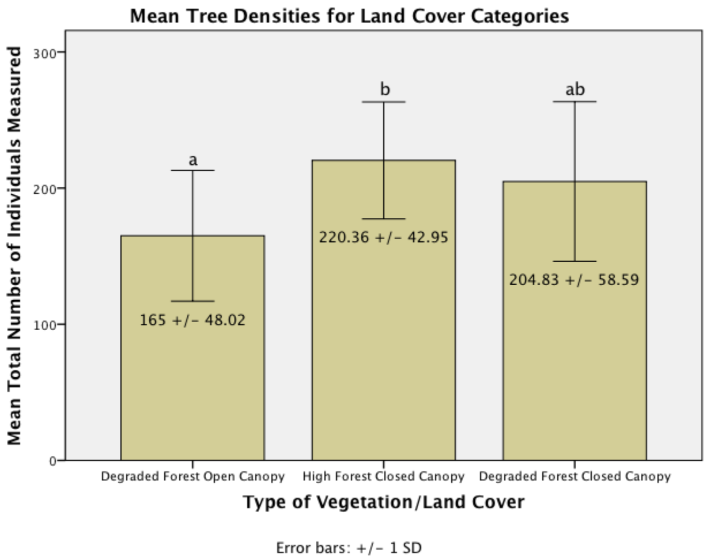


Figure 12. Mean total density for each of the land cover categories; Degraded forest open canopy (N=10, range: 91-233 individuals), High forest closed canopy (N=14, range: 161-296 individuals), and Degraded forest closed canopy (N=12, range: 118-305 individuals).

3.3 Flooding Regimes

2,257 large trees were measured in 23 plots that had seasonal flooding while 877 large trees were measured in 13 plots that never or rarely flooded.

3.3.1 Aboveground Biomass (AGB)

An independent sample t-test and Figure 13 below shows that the plots that flood seasonally have a higher average AGB than plots that rarely or never flood (p=.039). This rejects hypothesis 2a that flooded forests will have less biomass than rarely flooded forests.

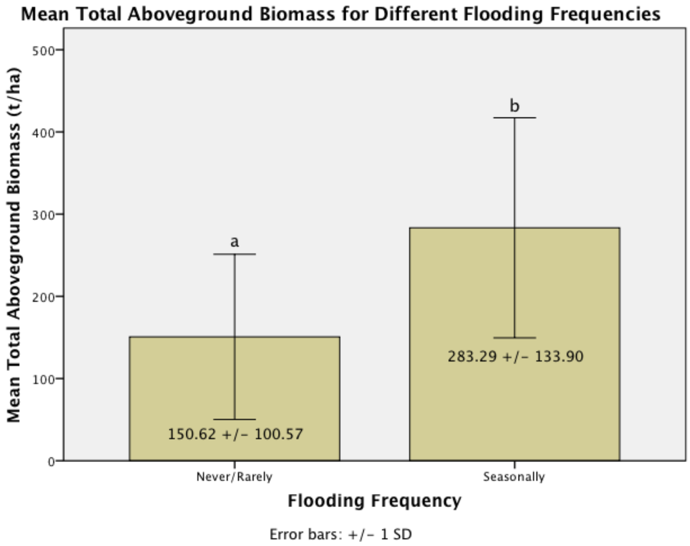


Figure 13. Mean total AGB (t/ha) for forest plots that never or rarely flood (N=13, range: 70.9-457.0 t/ha) and plots that seasonally (N=23, range: 89.5-574.2 t/ha) flood.

3.3.2 *Diameter at breast height, 1.3 m (dbh)*

A Mann-Whitney test comparing the median dbh for each group shows a significant difference between the two flooding frequencies (p=.000). The median dbh for plots that never or rarely flood is 14 cm and the mean dbh is 17.72 +/- 10.9 cm, while for seasonally flooded plots the median is 15 cm and the mean is 18.37 +/- 10.2 cm. Figure 14 shows that the distribution of dbh for seasonally flooded areas is shifted to the right compared to that of rarely flooded areas, and due to many more large trees being present in seasonally flooded areas, the peak of this distribution is much higher. It seems evident that the larger dbhs of trees in seasonally flooded plots contributes to the larger total AGB of seasonally flooded plots.

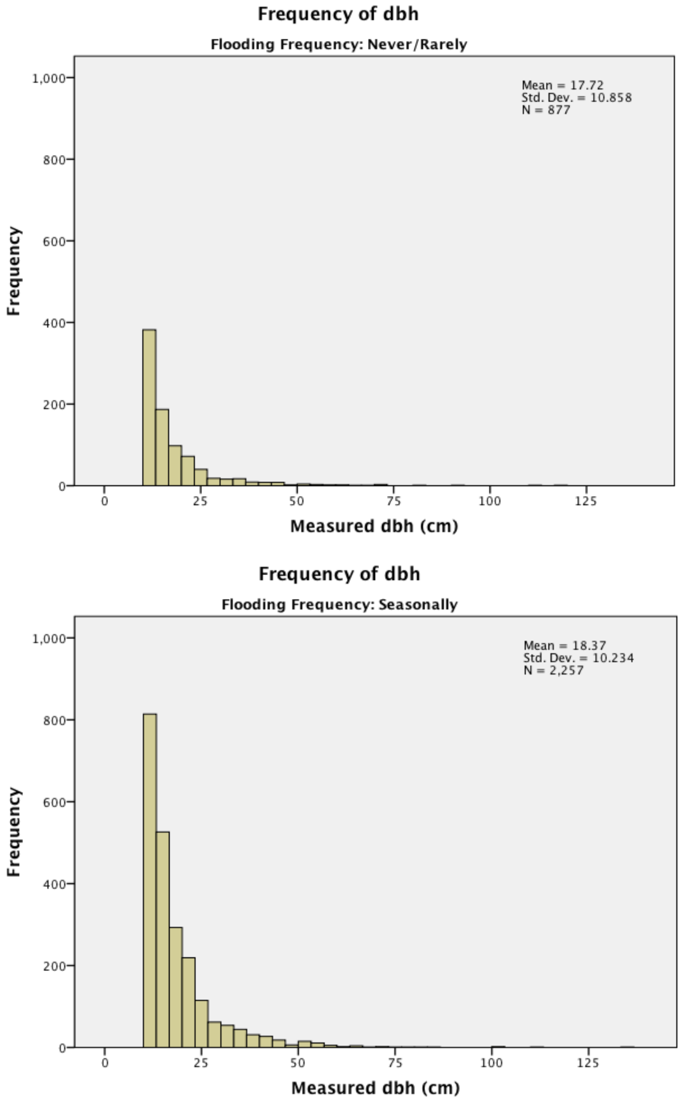
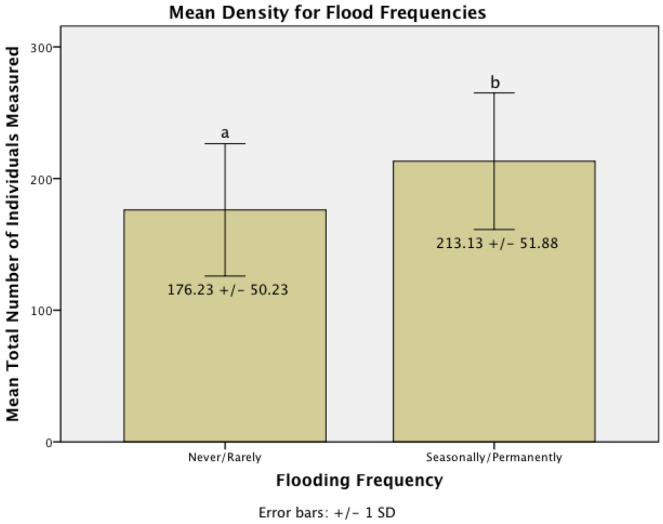


Figure 14. Distribution of large dbh trees. Top: For never or rarely flooded plots, range: 10-116.7 cm. Bottom: For seasonally flooded plots, range: 10-136.6 cm.

3.3.3 *Stand density*

The mean stand density of all trees is significantly higher in plots that seasonally flood than in plots that rarely or never flood (p=.043, two-tailed). The same is true for the stand density of large dbh trees, the density is higher for seasonally flooded areas (p=.001). There is no significant difference in stand density small dbh trees in rarely flooded plots (mean: 108.77 +/- 48.13) and those in seasonally flooded plots (mean: 115 +/- 46.56). This rejects hypothesis 2a that stand density will be lower in seasonally flooded areas.



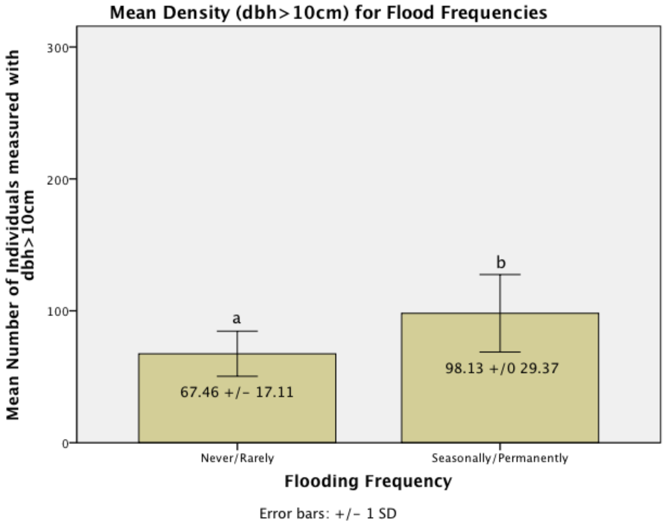


Figure 15. Mean densities of trees for plots that never or rarely flood (N=13) and plots that seasonally flood (N-23). Top: All trees, never/rarely flood range = 106-305 individuals, seasonally range = 91-296 individuals. Bottom: Large dbh trees, never/rarely flood range = 31-95 individuals, seasonally range = 39-150 individuals.

3.3.4 Spatial Distribution of Flooding

Out of 36 forest plots, 13 (36%) were considered to have rare flooding while 23 (64%) were considered to have seasonal flooding. The distribution of seasonally and rarely flooded plots with respect to relative disturbance and land cover categories vary. As flooding frequency was a parameter noted in the field and not a preliminary variable determining where plots were to be set up, this is to be expected.

In heavily disturbed plots the breakdown is relatively equal, 47% rarely or never flood while the remaining 53% seasonally flood. In moderately disturbed plots, about 24% of the plots rarely or never flood while a majority 76% seasonally flood. Upon further analysis, independent-sample t-test show total AGB is only statistically significantly different for plots in heavily disturbed areas (p=.039), and not in moderately disturbed areas. This suggests that flooding frequency more strongly relates to AGB in heavily disturbed areas. Furthermore, while moderately disturbed areas have a higher average AGB in all plots, there is only a significant difference in AGB between heavily and moderately disturbed areas for seasonally flooded plots (p=.002).

For the remote sensing land cover categories, degraded forest open canopy was comprised of 60% rarely flooding plots and 40% seasonally flooding plots, this is the only subcategory in which the overall majority of plots were rarely flooded. High forest closed canopy was comprised of 21% rarely flooded and 79% seasonally flooded plots, and degraded forest closed canopy was comprised of about 33% rarely flooded plots and 67% seasonally flooded plots.

3.4 Soil Types

3.4.1 Aboveground Biomass (AGB)

An ANOVA shows that the total AGB of plots with peat soil is significantly higher than in plots with clay loam (p=.049) and those in silt loam soils (p=.021), but that the total AGB in plots with clay loam and silt loam are not significantly different, which is also shown in Figure 16. This trend also holds for the AGB for large dbh trees, but is not evident for the AGB of the small dbh trees. This rejects hypothesis 2b that AGB increases with soil fertility and that peat soil will hold the lowest AGB amounts followed by silt loam and clay loam.

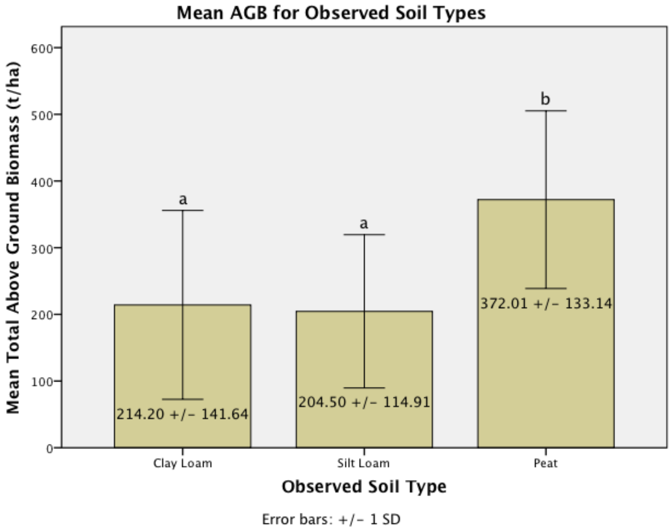


Figure 16. Mean total AGB (t/ha) for each category of observed soil type; clay loam N = 11, range = 81.1-571.5 t/ha, silt loam N = 19, range = 70.9-457.0 t/ha, peat N = 6, range = 201.1-574.2 t/ha.

3.4.2 Diameter at breast height, 1.3 m (dbh)

An initial Kruskal-Wallis test shows a significant difference in dbh among the soil types (p=.007), but further tests with a Bonferroni correction were applied to further assess the differences among the individual groups (3 groups; alpha level = .05/3=.017). The mean dbh for clay loam is 17.49 +/- 10.08 cm, silt loam has a mean of 17.89 +/- 9.94 cm, and peat has a mean dbh of 19.89 +/- 11.77 cm. The further tests show that there is no significant difference between the dbh of plots in clay loam and silt loam (p=.145), and with the Bonferroni correction there is no significant difference between peat and silt loam (p=.024), but plots in peat soil do have significantly larger dbhs than plots in clay loam (p=.002). This is not expected and does not follow the same trend as total AGB.

3.4.3 Stand density

There are no significant differences in the stand densities between plots with different soil types, but plots in peat have the highest mean density (241.17 +/- 40.86), then plots in clay loam (203 +/- 58.57), then plots in silt loam (184.89 +/- 49.2). This rejects hypothesis 2b that stand density decreases as soil fertility increases, as there is no significant difference.

3.4.4 Spatial Distribution of Soil Types

The soil types are not distributed evenly throughout the categories used in this research to assess regeneration. Similarly to flooding frequency, they were not used in selecting the sample sites, but rather observed and recorded in the field. There are no peat soils found in areas with relatively heavily disturbed histories, and a majority of plots were measured in silt loam soils overall. Of the 36 forest plots, 19 were measured in areas with silt loam soils, 11 in clay loam soils, and 6 in peat soils.

Within the heavily disturbed sites, around 53% were in clay loam and 47% in silt loam, while in the moderately disturbed sites about 6% were measured in clay loam soils, 59% in silt loam soils, and 35% in peat soils. Between plots with the same soil type in different disturbance levels, there are some differences in total AGB. Although there was only one clay loam plot in the moderately disturbed area compared to 10 in the heavily disturbed area, an independent sample t-test shows that there is a significant difference between total AGB of plots in clay loam between heavily and moderately disturbed sites (p=.001). There is also a significant difference in total AGB between silt loam plots in moderately and heavily disturbed areas (p=.021).

The soil types were more evenly spread throughout the remote sensing land cover categories with an even number of plots with peat soils in each category. Within plots characterized as degraded forest open canopy, 30% of the plots were in clay loam soils, 50% in silt loam, and 20% in peat soils. In the high forest closed canopy 29% were in clay loam, 57% in silt loam, and 14% in peat soils. In the degraded forest closed canopy 33% of the plots had clay loam soils, 50% had silt loam, and 17% had peat soils. According to an ANOVA, there were no significant differences in total AGB between plots of the same soil type in the different land cover categories.

Furthermore, there are no plots with peat soil in the plots that rarely or never flood. Plots with peat make up about 26% of the plots that flood seasonally. Silt loam plots make up just over 50% in areas that never or rarely flood and that seasonally flood (54% & 52% respectively), while clay loam plots make up about 46% of areas that never or rarely flood and 22% of areas that seasonally flood. An independent sample t-test shows that there is a significant difference in the total AGB of plots with clay loam soil between rarely or never flooded plots and seasonally flooded plots (p=.028), but not for silt loam soils.

3.5 Oil Palm

3.5.1 Aboveground Biomass (AGB)

Oil palm trees were measured that had been planted in 1997-1998, some of the earliest palms planted at the REA estates, helping to compare the AGB of land conversion to the AGB of forests that have been regenerating for about the same amount of time. A total of 267 palms were measured with a mean AGB of 10.36 +/- 1.6 t/ha.

The mean total AGB of forested plots is much higher than that of oil palm plots. A Mann-Whitney test shows that they are significantly different (p=.000), and Figure 17 clearly shows that the AGB of the oil palm measured is much lower than that of the AGB of forest.

Further analysis shows that the total AGB of oil palms measured is also significantly lower than all of the forest categories analyzed above including moderately and heavily disturbed plots, rarely and seasonally flooded plots, and silt loam, clay loam and peat soils. There is no significant difference between the total AGB of oil palm plots near heavily or moderately disturbed.

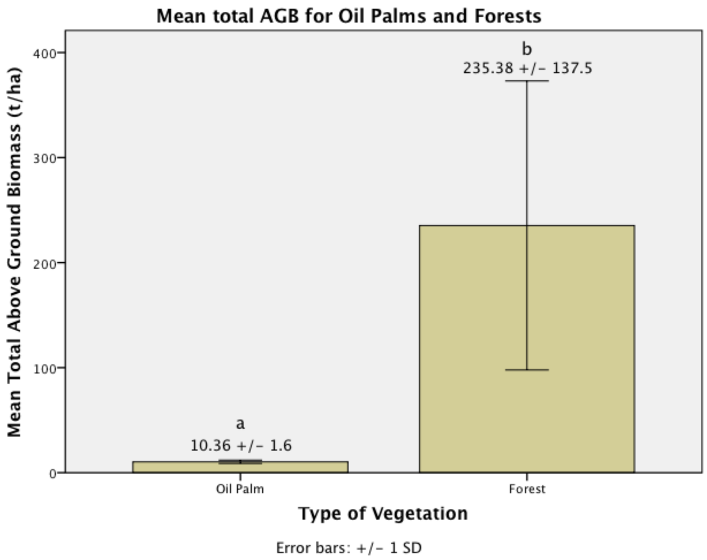


Figure 17. Mean total AGB of oil palm plots (N=12) and all forest plots (N=36).

4 DISCUSSION

4.1 Discussion of Results

Aboveground biomass (AGB) estimates from this study range from 70.9 to 574 t/ha, with a mean of 235.4 +/- 137.5 t/ha. Based on the assumption that half of forest AGB is carbon, the carbon storage of the forests measured ranges from 35.5 to 287 t/ha of carbon, with a mean carbon storage of 117.7 +/- 68.8 t/ha of carbon. Lamb (2011) estimates that recovering secondary tropical forest can reach about 100 t/ha of AGB within 15 years, which is within the range of AGB calculated for this research. Berry et al. (2010) measured secondary forest in Northern Borneo that had been heavily logged 18 years prior and calculated an average AGB of 177 +/- 14.4 t/ha, which can be equated to 88.5 +/- 7.2 t/ha of carbon. This is also within the range of AGB calculated for this research. While the range of AGB and carbon content are higher than these other estimates, this suggests that the results here are fairly in accord with other studies of similar forest.

4.1.1 Categorization of disturbance from historical data

Mean AGB is significantly higher in moderately disturbed areas than heavily disturbed areas, with the difference mainly related to a significant difference in the AGB of trees with a large dbh. Small dbh tree AGB is very similar in both disturbance levels. Hypothesis 1a which tests that AGB is significantly higher in moderately disturbed plots is supported, which is expected because more frequent and more severe disturbance events diminish an area's ability to regenerate and accumulate carbon or AGB (Lamb, 2011). Furthermore, fire events and logging can have a positive feedback effect on each other leading to further degradation of already disturbed sites, and lowering the overall AGB (Siegert *et al.*, 2001).

The distribution of total AGB is positively skewed, as can be expected with degraded forests where it is more frequent that a disturbed plot will have a lower biomass than a relatively high biomass. Heavily disturbed plots follow a similar distribution for AGB. While individual disturbances do not always clear the entire area, the more severe and the more frequent disturbances are, the less biomass is remaining (Nieuwstadt et al., 2001). In these areas that have been recovering without a major disturbance for the last 15 years have most likely accumulated AGB, but it may take another 65 years for AGB amounts to recover completely (Lamb, 2011). Therefore the majority of degraded plots have an AGB that falls on the low side of the distribution while there are a few plots that tail to the right due to remaining high AGB. In moderately disturbed areas, the total AGB seems to be more uniformly distributed throughout the range suggesting that there are less highly degraded plots, but maybe also that the moderately disturbed category has more of a range of disturbances. If many of the plots had the same amount of moderate level of disturbances, it might be expected that the distribution would be more normal, as the majority of plots would have slightly higher resiliency to disturbances than heavily degraded areas (Nieuwstadt et al., 2001).

Hypothesis 1a in which the mean diameter at breast height (dbh, 1.3 m) is tested is also supported, the dbh is significantly higher for moderately disturbed areas. As dbh is used in almost all (all except for palms) of the allometric equations from which AGB is derived, it is expected that dbh and AGB are both significantly higher in moderately disturbed areas. The distribution of dbhs for all plots is positively skewed, as are the dbh distributions for moderately and heavily disturbed areas separately. It is interesting that while dbh and AGB seem closely related, the distributions of AGB and dbh for moderately disturbed areas do not follow a similar trend. This suggests that dbh may be a more appropriate indicator for AGB in heavily disturbed forest than in moderately disturbed forest.

Furthermore, the trees with the largest 10% of all dbhs are also significantly higher in moderately disturbed areas than heavily disturbed areas. This suggests that the largest of the large dbh trees have bigger diameters and are more common in the moderately disturbed areas. The 15 years past the last major disturbance (until present time) would not have been enough time for a tree to grow this top 10% of large dbhs, but this proposes that there was a higher chance for survival and potentially less severe disturbances in the moderately disturbed areas as fire and selective logging individually do not lead to the complete loss of the canopy (Nieuwstadt et al., 2001).

There is no significant difference in mean tree stand density between plots with different historical disturbance levels. Hypothesis 1a that tests if stand density of large dbh trees is higher for moderately disturbed forests is rejected, and does not reflect the difference in AGB between the areas with different disturbance levels. Also, this rejects hypothesis 1a that small dbh tree density may be higher in heavily disturbed areas. This may be due to similar types of disturbances occurring in all plots. While disturbance severity and frequency were more intense in heavily degraded forest, all areas were subject to the same types of disturbances, so their regeneration patterns could be expected to be similar for stand density, such as a general reduction in stand density after excessive logging (Lamb, 2011), but not for the productivity and the ability of the individual trees, as is shown with the difference in dbhs.

When dividing the plots by historical disturbance history, there is a significant difference in AGB and dbh, but not in tree stand density, which suggests that dbh may be a better indicator for AGB than stand density. This is not surprising as dbh is used directly in calculating AGB, but it is expected that stand characteristics such as stand density have a direct relationship with AGB (Baraloto et al., 2011). There are around the same number of trees in each of the categories, but the larger dbhs of trees in moderately disturbed plots seems to be a major contributing factor to the higher AGB of moderately disturbed plots. This further suggests that stand density may not be a reliable indicator for total AGB or land use history.

4.1.2 Categorization of disturbance from remote sensing

There are no significant differences in mean total AGB between the remote sensing land cover categories, but the mean AGB is lowest for degraded forest open canopy (DO), then high forest closed canopy (HC), and highest for degraded forest open canopy (DC). Hypothesis 1b testing if DO would have a medium amount of biomass, degraded closed would have medium to high biomass, and high closed would have high biomass as noted in the legend for the remote sensing map used (Hoekman *et al.*, 2009) is rejected. As all forest analyzed here was degraded forest, it is not surprising that the AGB is not significantly different between the categories. Furthermore, as HC was predicted to have a medium to high level of AGB (Hoekman *et al.*, 2009), there is overlap in the amounts of AGB of the three categories.

Dbh of the large dbh trees is significantly different between all three land cover categories. DO has the lowest dbhs, followed by HC, and DC has the highest dbhs. Although the AGB are not significantly different between the categories, the dbhs do seem to reflect the relative AGB for each category, which is expected as the dbhs are directly used to calculate AGB. The allometric equations used for different life forms and the factors included in them, such as assumed wood density may have influenced the AGB, leading to no significant difference, while the dbhs that were directly measured are statistically different. It is also interesting to note that HC has the largest range of dbhs, with the largest tree measuring 136.6 cm around, but DC has the highest median and mean dbh, and the smallest range of dbhs with the largest tree measuring 112.5 cm around. Hypothesis 1b that the closed canopy forest would have larger dbh trees than the open canopy forest is supported, but the distribution of dbhs within these categories suggests that degraded forest has more large dbh trees than high forest.

Overall tree stand densities follow a different trend than dbh between the 3 categories, HC has a significantly higher stand density than DO, and the stand density of DC plots is not significantly different from DO or HC. Small dbh stand density and large dbh stand density have means that reflect the overall stand density, but there are no significant differences between land cover categories. These relationships support hypothesis 1b laid out for AGB based on the descriptions by Hoekman *et al.* (2009), but reject hypothesis 1b that tests if DO would have the highest small dbh stand density, presumably due to increased numbers of lianas and vines in the open canopy (Gehring *et al.*, 2004). This may be explained by the methodology, only woody biomass was measured here but not grasses and shrubs, and no trees under 2 m tall. Further analysis on the structure of the understorey may support the hypothesis, but small dbh vines and lianas that were measured were not significantly more dense in more degraded, open forest.

These findings further support that density may not be as strongly correlated with AGB as dbh is, and that dbh may be a better indicator of total biomass, which could directly reflect the equations used. Baraloto *et al.* (2011) suggests that AGB is indirectly affected by environmental changes, and directly affected by characteristics of the stand structure. The findings of this research suggest that environmental changes such as degradation relate to AGB more directly through dbh than density of the stand structure.

4.1.3 Categorization of disturbance from flooding regime

Mean total AGB is higher for plots that are seasonally flooded than for those that never or rarely flood. Hypothesis 2a that tests whether there will be higher amounts of AGB in never or rarely flooded areas due to flooding hindering the growth and productivity of trees (Lopez & Kursar, 2003) is rejected. This could be due to a few reasons. One being that flooding can create a natural deterrence to different types of disturbance, either prolonging the effect of drought and subsequently fire as humid forests are less prone to burn (Siegert *et al.*, 2001). Additionally, flooding may create less optimal logging conditions as swampy areas are sometimes left unlogged when surrounded with extensively logged areas (Wulffraat, 2009). Another being that periodic inundation from flooding may increase the soil fertility by replenishing the nutrients and may lead to higher productivity and AGB (Megonigal *et al.*, 1997).

The dbh of large dbh trees is also significantly different between areas that seasonally flood and areas that never or rarely flood. Seasonally flooded plots not only have significantly higher average dbhs, but also many more actual large dbh trees than areas that never or rarely flood. There are overall more seasonally flooded plots, about 2 times as many, but seasonally flooded areas have about 2.5 times the amount of large dbh trees than rarely flooded plots. The range and mean of large dbhs is significantly higher for seasonally flooded areas, which could also be due to similar factors as mentioned above relating to AGB. Similarly to the previous two categorizations, dbh seems to be directly related to AGB, as Baraloto *et al.* (2011) suggests, and as expected from the allometric equations used.

Seasonally flooded plots also have significantly higher total density and large dbh tree densities than rarely flooded plots. Hypothesis 2a that test if seasonally flooded areas will have lower stand density is rejected. The stand density of small dbh trees however is not significantly different between the two different flooding frequencies. This suggests that the main difference in stand densities of seasonally and rarely flooded areas comes from a difference in the densities of large dbh trees, but could be due to higher survival rates from fire when the humidity is higher, or lack of accessibility by loggers as mentioned above (Siegert et al., 2001; Wulffraat, 2009).

For flooding, both dbh and stand density seem to be directly related to AGB, unlike the previous disturbance categories where only dbh seemed to relate directly to AGB. This suggests that flooding and stand density may have more of a critical relationship than the other disturbance considerations. Also, that the hierarchical nature of the framework from Baraloto et al. (2011) fits better for environmental factors that indirectly influence AGB than for degradation due to external pressures such as fire and logging.

It is also notable that 64% of the plots were in seasonally flooded areas. This is expected as the study site is in a tropical region with high rainfall occurrence with little or no dry season at all (Brown, 1997). As historical information and remote sensing data suggests that all of the forest considered has been disturbed and degraded in some way, it could assumed that an influx of nutrients and water being transported in periodic flooding events does influence the stand characteristics and AGB to some extent (Megonigal et al., 1997).

4.1.4 Categorization based on observed soil types

Of the three observed soil type categories, there is no significant difference in AGB between plots with clay loam or silt loam soil, but peat soil does sustain significantly more AGB than the two loam soil types. This rejects hypothesis 2b that tests if AGB will increase with soil fertility, as then peat would have the lowest AGB followed by silt loam, then clay loam. This may be a symptom of only focusing on degraded forest, and that the peat soils were only found in seasonally flooded, moderately disturbed areas, which also had higher AGB than their counterparts. While drought and fire can be huge threats to peat swamps and forest if they are drained (Nishimura, 2003), this may further indicate that these areas may have not been as degraded by fire or logging as other plots in the region, which supports the categorization of moderately disturbed sites. Additionally, while peat may be less fertile than loamy soils, this also supports the idea that soil erosion can lead to soil degradation and loss of fertility (Assessing forest degradation, 2011; Lamb, 2001). As swampy peat is characterized by not losing water due to flooding (Louck, 2012), there would be little to no erosion in these peat areas that are seasonally flooded.

There is a significant difference in the dbh between silt loam and peat plots, but not between silt loam and clay loam, or clay loam and peat. This is not expected and does not fully follow the same trend at AGB between different soil types. The significantly higher dbhs in plots with peat soils may be due to these sites being less degraded initially with higher survival of existing trees, but these results do not support the theory of increased productivity and larger trees in more fertile soils (Paoli et al., 2008).

There are no significant differences in stand density between the soil types. Hypothesis 2b that tests if stand density decreases as soil fertility increases as found by Paoli et al. (2008) is rejected here. In relation to soil type, the stand characteristics measured do not appear to be very representative of the AGB, although there are few significant differences between the soil types.

Forest degradation due to natural and anthropogenic disturbances, flooding frequency and soil types all interact on a landscape level. Degraded land can be further degraded by the positive feedback loop between forest fires and logging, loss of forest cover can lead to increased runoff and flooding which can in turn lead to soil erosion and loss of soil fertility which further inhibits an areas ability to regenerate (Lamb, 2011; Pimentel & Kounang, 1998). The effects of these factors on stand characteristics is difficult to disentangle from one another, and there have been few studies comparing secondary forest regeneration after different types of disturbances or environmental factors that can be singled out (Lamb, 2001). This research has attempted to assess stand characteristics from the perspective of different disturbances or environmental factors even though they are known to overlap.

4.1.5 Oil Palm

Hypothesis 3 which tests if oil palms have significantly lower biomass than any of the forest plots is supported by this research. There is also no difference between AGB of oil palm that was previously heavily or moderately disturbed forest, which is expected as they are under the same company and management strategies.

This does support the idea that while the success of regenerating forests can be affected by disturbance and environmental factors, the success of oil palm does not seem to be related to the previous disturbances in the area. This suggests that for choosing where to expand plantations, oil palm may be able to grown in conditions that would not support a productive regenerating forest. However, in the field we did see that some palms that were planted in areas are inundated during flooding season do not always survive, they can become uprooted quite easily.

Furthermore, the AGB of oil palms measured are much lower than others of similar aged oil palms, although data of oil palm AGB vary greatly between studies. Syahrinudin (2005) collected oil palm biomass data from many studies and found numbers ranging from 192 to 202 t/ha for 14 & 19 year old palms respectively, to 68.9 t/ha of AGB for 25 year old palms, or 88.5 t/ha of 15 yr old palms reported by Ng *et al*, 1968 (Syahrinudin, 2005). The calculations from this research suggest an average oil palm biomass of 10.36 t/ha for palms planted between 1997-98, so 14-15 years old. While biomass figures vary greatly, the biomass that we have measured and calculated is much lower than the other numbers reported. There could be differences in the measuring technique, destructive measuring techniques are more accurate than using allometric equations, and differences can also be due to a difference in allometric equations, although the extreme range suggests that allometric equations alone would not be responsible for this difference. The palm equation from Frangi & Lugo (1985) used for this research was not specifically designed for oil palm trees, but for subtropical palms in Puerto Rico. The difference in AGB of the oil palms measured for this research and others may also be due to differences in management or the spatial planning of individual trees within the plantations.

Syahrinudin (2005) also calculated that the average carbon content of AGB for oil palms is 41.7% (41.3% for total palm system), instead of the assumed 50% carbon that is usually used to convert forest AGB to carbon stock. Based on these calculations, the oil palms measured here contain about 4.32 t/ha of carbon. This is vastly lower than the carbon storage amounts of oil palm plantations in Sumatra measured by Syahrinudin (2005). For 10 year old plantation, Syahrinudin (2005) found 37 t/ha of carbon, and 43.1 t/ha of carbon in 20 year old oil palm plantations. The carbon storage amount calculated in this research is even less than half of the carbon storage found for 3 year old plantations in Sumatra; 9.6 t/ha of carbon.

4.2 Methodological Limitations

There are some limitations to the methodologies exercised in this research from lack of information to sampling errors and the way they were converted into AGB.

There is a lack of historical information on the disturbances on a local level due to the difficulty of monitoring all disturbances and the inaccessibility of some information such as logging records. The categorizations for historical disturbance data were based on generalized historical reports, but as the plots were temporary and not measured over time, it is difficult to know if the disturbance levels across the categories were the same or not. This may be evident in the moderately disturbed category, as the AGB distribution was relatively uniform across this category rather than normally distributed as might be expected.

In the field some measurements such as dbh were estimated if they were physically unobtainable, mostly with very large trees, and this may have affected the range and distribution of the dbhs. They were however all estimated in the same way in relationship to trees around them. Also, the way that soil types were observed in the field may have limited the depth of the results produced by the soil categorization. Soil types were observed by sight and feel, but no samples were taken, and there was not a geologist present during this research. This may be why there is a lack of distinction between the soil category groups in relation to different stand characteristics. Similarly, flood frequency was based on the presence of signs of flooding such as erosion and pools of water and knowledge of local field guides. Some plots that were considered never or rarely flooding may have been seasonally flooded, but we were not aware of it.

The allometric equations used were specific to life forms, but not for wood density, and not always for the region as was the case for the palm equation from Frangi and Lugo (1985). Feldpausch et al. (2012) suggest that the appropriate choice of an allometric equation may be the most important source of error in estimating AGB, over sampling error or plot size. Additionally, many of the allometric equations used do not consider the height of the tree, which could affect the calculated AGB greatly in areas with a wide variety of tree species. The inclusion of height in the calculation of AGB may have also illuminated different relationships between some forest categories such as high forest closed canopy and degraded forest closed canopy. Furthermore, the error of the plots size could give an unrepresentative view on AGB when extrapolating a 0.1 ha plot to AGB in t/ha. Also, while GIS was used to select the plots, and an initial visual check was done to assess if the area was representative of the surroundings, some of the forest selected was relatively small patches that may have been influenced by other disturbance factors such as edge effects that were no considered in this research.

4.3 Relevance

This research aims to further understand the relationship between stand characteristics and degradation due to natural and anthropogenic disturbances or environmental factors. These relationships are important to study to further understand the degradation and regeneration processes of secondary forest in an area that is rapidly losing primary forest. A better understanding of these relationships could lead to more focused conservation efforts as well as helping plantation managers choose land for further conversion more wisely. If we are aware of the opportunity costs of land conversion including carbon storage plus tree size and stand density that could be used sustainably and selectively by local communities for a variety of degraded forest, choices for plantation expansion can be made that leave the most viable forests intact. For example, based on this research, it may be more beneficial to convert areas that have no flooding, high erosion, and relatively heavy disturbance histories to plantations for a lower opportunity cost of potential carbon sequestration by these regenerating forests.

Furthermore, continued research on AGB can aid in updating preexisting models for national and global AGB and carbon levels. This can also help in verifying remote sensing techniques and helping them become more accurate to detect land use changes that affect AGB and carbon storage. This is particularly important for areas where there are large amounts of land that are hard to reach to monitor, where there is a lot of illegal activity occurring, and where most of the forest has been degraded in some way (Berry et al., 2010). Accurate data on land change and AGB aid programs such as REDD+ that aim to monitor carbon fluctuations due to degradation and deforestation to create initiatives and incentives to decrease global greenhouse gas emissions that can influence climate change.

5 CONCLUSIONS

When assessing forest degradation based on different disturbances and environmental factors, it can be generalized that these factors have different relationships with forest stand characteristics such as AGB, dbh and stand density. In comparing forest that has a moderately disturbed history against forest with a heavily disturbed history, the level of disturbance seems to be more related to dbh and AGB than stand density suggesting that the size of trees are different, but the number of trees present are not. Looking at different categories of degraded forest as denoted by remote sensing techniques shows that remote sensing may not capture significant differences in AGB, but is more sensitive to significant differences in dbh and stand density between the forest categories. Assessing different flooding regimes that could lead to forest degradation or increase forest production show that seasonally flooded forest has significantly higher AGB, dbh and stand density than areas that rarely or never flood, which supports that drought can have severe negative impacts on forest health. The observed soil types studied in this research do not support other research that links forest productivity and growth to soil fertility, but this may be due to the degradation of the forest and the interaction of erosion and fertility with other disturbance factors. Peat soils seem to have significantly higher AGB levels than silt loam and clay loam, and significantly higher dbhs measured than silt loam, while stand density doesn't seem to differ between the different soil types. These relationships can be important for the understanding of under what circumstances degradation is taking place and monitoring the state of tropical forests in Indonesia.

Furthermore, the oil palm plots that were measured for this research have significantly lower AGB than the surrounding secondary forest, and also vastly lower AGB and carbon content than other oil palm data for stands of around the same age. This may not impede palm oil production and may not be a major concern for the plantations, but may become a concern when considering emission trade offs between forest conservation and land conversion.

The conversion of the AGB calculations to carbon stocks gives an idea of how much carbon is being stored in these forests and oil palm plantations. This data can help understand carbon storage amounts in similar forests in Indonesia, thus aiding in the national assessment of carbon emissions, storage and sequestration. This is extremely relevant for climate change models and for global and national assessments of greenhouse gases.

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