Carbon pools in tropical peat forest

Towards a reference value for forest biomass carbon in relatively undisturbed peat swamp forests in Southeast Asia

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Abstract

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This report presents estimates of carbon pools in relatively undisturbed peat swamp forests in Southeast Asia. We first identified available data sources and methodologies to use these data to estimate aboveground and belowground biomass. Available data published in both peer-reviewed and grey literature were used to quantify the carbon content of litter, coarse woody debris and peat soil. The report gives an overview of the most important data limitations, uncertainty of results and potential improvements of the current estimates.

Keywords: aboveground biomass,carbon stock, peat soil, peat swamp forest

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Executive summary

Tropical peatlands in Southeast Asia are an essential component of the global terrestrial carbon pool through both their aboveground biomass and underlying thick deposits of peat. It has been estimated that these tropical peat soils contain some 68.5 Gigatonnes of carbon, which is equivalent to 11-14% of the global peat carbon stocks. Originally, the vast majority of these peatlands was covered by forest, but large scale conversion of tropical peat forests to agricultural land has occurred within the last few decades. Timber extraction and the establishment of oil palm plantations have been identified as the major drivers of this deforestation. Some scientists have calculated that the conversion of tropical peatlands results in significant losses of peat carbon, caused by increased CO_2 emissions resulting mainly from drainage of the peat soil and consequent oxidation and peat fires. Recent studies have concluded that these CO_2 emissions are a significant contributor to global climate change. The conversion of peatlands is still ongoing, although efforts have been made by several institutes and agricultural cooperatives to define criteria for sustainable land use. An estimated 50% of the peat swamp forests in Southeast Asia have been cleared and drained for agriculture. The remaining half of the peat swamp forests are to some extent degraded through timber extraction and drainage, and are - depending on a variety of factors - either a net source or sink of carbon. In order to quantify the carbon loss that results from forest degradation it is relevant to compute the range in biomass carbon pools that naturally occurs in undisturbed peat swamp forests. The resulting values could consequently be compared to biomass data from degraded peat forests.

The objective of this study is to estimate the carbon pools of relatively undisturbed peat swamp forest. To achieve this goal we first identified relevant researchers or research groups in the field of biomass inventories in Southeast Asia and then determined appropriate methods to estimate the carbon pools based on the collected data. We also indicated the uncertainty in available data and methodologies. Based on our findings we can draw the following general conclusions regarding the availability of data:

- A limited number of research groups is involved in the estimation of carbon budgets of tropical peat lands, mainly focussing on aboveground living biomass.
- Data on biomass and greenhouse gas fluxes from peat lands is not widely published.
- Most data has been published in grey literature such as local reports and conference proceedings but because of political sensitivity data is not readily shared.
- Based on existing data it is possible to make estimates of the major forest carbon compartments.

We used historical and more recent forest inventory data and applied allometric equations to these data in order to assess the aboveground and belowground biomass. In addition, available data published in both peer-reviewed and grey literature were used to quantify the carbon content of litter, coarse woody debris and the peat soil. Based on our results the following can be concluded:

- Aboveground biomass (AGB) can be estimated based on available field inventory data using allometric equations. We found the AGB carbon store of relatively undisturbed peat swamp forests to be within a range of 132-199 t C/ha (see table below). Several published figures suggest a much broader range of 73-323 t C/ha. In comparison, the AGB in logged-over peat swamp forest ranged between 65-167 t C/ha.
- Allometrics can also be used to estimate root biomass based on stem diameters. Following this methodology we estimated that root biomass in relatively undisturbed peat swamp forest accounted for 29-45 t C/ha.
- Based on data sources from various tropical forest types, the coarse woody debris carbon pool was estimated to range from 16-56 t C/ha in unlogged peat swamp forest, with an average of 31 t C/ha.

- Litter biomass can be estimated based on peat swamp forest inventories and, more generally, based on litter-to-AGB ratios found in tropical moist forests. We estimated the litter pool in peat swamp forests to be around 5-12 t dry matter/ha (2-6 t C/ha).
- The peat soil is the most important reservoir of carbon in tropical peat lands. Recent estimates for Southeast Asia indicate that the average peat carbon store ranges from 252 to 3528 t C/ha in the different countries. The exact carbon store is spatially variable and depends on peat thickness, bulk density and carbon content of the peat. The quantification of this carbon reservoir is a priority issue in terms of the carbon budgeting in these ecosystems. Quantification of the carbon storage in vegetation will improve the total carbon estimate and decrease the statistical error, but more detailed quantification requires extensive inventories of the small biomass compartments that are less important in terms of carbon storage, like dead wood and fine litter.

Estimated biomass and carbon content of relatively undisturbed peat swamp forest. Data are from various sources.

	Biomass (t dry matter/ha)		**Carbon content (t C/ha)**	
Biomass compartment	Range	Average±SD	Range	Average±SD
Aboveground biomass	264.0-397.4	338.8±52.5	132.0-198.7	169.4±26.4
Belowground biomass	57.2-89.8	74.0±15.8	28.6-44.9	37.0±7.9
Coarse woody debris	32.2-113.8	62.9±9.8	16.1-56.9	31.4±4.9
Litter	4.5-11.9	7.9±1.2	2.3-5.9	3.9±0.6
Total forest	**363-613**	**486**	**182-306**	**243**

1 Introduction

Worldwide tropical peatlands cover an estimated 441.025 km^2 (44.1 million ha), which is approximately 11% of the global area of peatlands (Page et al., 2010). 56% of the tropical peatlands is located in Southeast Asia (25 million ha), with the vast majority in Indonesia (21 million ha) and Malaysia (2.6 million ha) (Page et al., 2010). Despite their relatively small area compared to boreal and temperate peats, tropical peatlands in Southeast Asia are among the largest terrestrial carbon stores (Jauhiainen et al., 2005; Rydin and Jeglum, 2006). Hence they play an essential role in the global carbon cycle (Hooijer et al., 2006; Parish, 2002; Chimner and Ewel, 2005). Southeast Asian peatlands store approximately 68.5 Gigatonnes (Gt) of carbon, which is equivalent to 77% of the global tropical peat carbon pool and 11-14% of the global peat carbon pool (Page et al., 2010).

The tropical peat soils of today result from thousands of years of organic matter accumulation of the peat swamp forests that grow on top of it. This net accumulation of organic material is made possible by the waterlogged conditions that prevent the aerobic decay of organic material. These conditions have developed in areas with high rainfall throughout the year and where water input exceeds the water loss through runoff and evapotranspiration. Peat swamp forests share several physiological adaptations to regular flooding such as stilt roots, buttresses, pneumatophores and a thick, superficial root mat. These structures play a major role in the hydrology of the peat swamp by decreasing the rate of surface water runoff. Thereby they guarantee a constant water supply to the peat dome, which is a prerequisite for peat formation (Joosten, 2008). The waterlogged peat soils are acidic (pH typically 2.9 -4.5), spongy, and low in plant available nutrients because there is no nutrient input from rivers into peat swamps (MacKinnon et al., 1996) and, contrary to dryland rainforests, because plant litter is not decomposed and recycled rapidly. The slow rate of decomposition of dead plant material including roots, coarse and fine woody debris and leaf litter is often attributed to the acidic, anoxic conditions, which inhibits microbial and fungal activity (Qualls and Haines, 1990; Gorham, 1991; Whitten et al., 2000; Zakaria, 1992; PahangFD, 2005).

Half of the peat swamp forests in Southeast Asia have been cleared and drained for agricultural use (Hooijer et al., 2010). The remaining half of the peat swamp forests are for a large part degraded through timber extraction and drainage (Joosten, 2009). Conversion of peat swamp forests to agricultural land results in significant losses of peat, due to drainage and subsequent oxidation and fires (Wösten et al., 2006). Peat fires and oxidation of peat are a significant contributor to the global green house gas emissions (e.g. Fargione et al., 2008; Inubushi et al., 2003; Page et al., 2002). About two thirds of these emissions originate from peat fires and about one third from peat oxidation caused by drainage (Couwenberg et al., 2010; Hooijer et al., 2010). Apart from the peat soil, aboveground biomass (AGB) of these forest ecosystems forms an essential part in carbon sequestration, not only as an existing store, but also to capture atmospheric carbon and transform it to peat. It has been estimated that wood globally holds some 425 Pg of carbon (1 Pg = 10^{15}g), a significant amount, compared to the current atmospheric stock of 730 Pg C[1] (Denman et al., 2007). Loss of tropical forest is a key contributor to greenhouse gas emissions to the atmosphere and responsible for about 20% of all human induced GHG emissions (IPCC, 2007). Tropical peat swamp forests are rapidly vanishing due to agricultural conversion (mainly to oil palm plantations), logging, drainage and fire (McMorrow and Talip,

[1] Assuming an average wood carbon density of 50%

2001). In Peninsular Malaysia for example, only a few remnants survive today along the east and west coasts and very little pristine peat swamp forest remains (Yule and Gomez, 2009).

During the last decade there has been a rapid development of new oil palm plantations on peatlands (Mantel, 2007; Reijnders and Huijbregts, 2008; Fargione et al., 2008), particularly on the islands of Borneo and Sumatra. The increasing global demand for biofuels puts further pressure on peat swamp forest areas (Santosa, 2008). Although efforts have been made by the Roundtable on Sustainable Palm Oil (RSPO) to define criteria for sustainable palm oil production (RSPO, 2005), the conversion of peat swamp forests to oil palm estates is still ongoing and plans for large-scale conversion of peat forest in Papua are underway (Santosa, 2008; Sheil et al., 2009).

To be able to determine the carbon-effects of conversion of the peat swamp forests into oil palm estates, it is crucial to quantify the carbon content and carbon dynamics of these forests and to combine that with data on the status of the peat swamp forests that remain today. This quantification is being complicated by different levels of forest disturbance, such as logging intensity and drainage, and the differences that occur naturally withing peat swamp forest vegetation types.

In this report we collate and synthesise existing data from tropical peat swamp forests in order to produce estimates on the carbon content of tree biomass, litter, coarse woody debris and soil. The following research questions are addressed:

1. Which research groups are involved in carbon/biomass assessments in tropical peat land ecosystems?
2. Which data is available within these groups and in what form is it available?
3. What can be calculated with the available data and how?
4. What are the limitations of available data and what data sources are still lacking in order to come up with sound estimates?

In addressing these questions we focus on the main carbon compartments of peat swamp forests: (1) the aboveground living biomass, (2) belowground living biomass, (3) litter, (4) dead wood or coarse woody debris and (5) peat soil. They will be treated in this order in chapters 2-6 according to a similar structure. Each chapter starts with a general introduction and subsequently enumerates the involved research groups and available data sources. The data sources are used to calculate the carbon stock in each of the biomass compartments. We conclude with an overview of limitations of the available data and consequent uncertainties in the carbon pool estimates for each compartment. In chapter 7 we discuss the overall trends and main uncertainties, and draw general conclusions on data availability and on our carbon stock estimates.

2 Aboveground biomass

2.1 Introduction

The aboveground biomass (AGB) comprises all the living aboveground vegetation, including stems, branches, twigs and leaves. It is the most studied part of all forest carbon pools and a fundamental variable for foresters, ecologists, biogeochemists, and policymakers. AGB in tropical forests may vary considerably in response to differences in climate and soil parameters. A study in Rondônia, Western Brazil for example found that AGB in primary forest was 290-495 t dry matter/ha and about 40-60% less in young secondary forests in the same area (Alves et al., 1997). Another study showed that dipterocarp hill forests in Sumatra had an AGB ranging from 271-478 t dry matter/ha (Laumonier et al., 2010), which corresponds to values found in the hill forests of Sulawesi (Hertel et al., 2009).

Contrary to most other tropical forests, peat swamp forest are generally characterized by the fact that the AGB carbon does not form the major part of the total ecosystem carbon pool, since most of the carbon is stored in the peat soil (Joosten, 2009). Nevertheless, aboveground vegetation may still form a significant part of the carbon pool, especially when the area is covered by primary peat swamp forests. Nowadays however, primary peat swamp forests are hardly found anymore throughout Southeast Asia (Sheil et al., 2009; Joosten, 2009). The AGB carbon storage in the peat swamp forests that remain today may greatly vary depending on disturbance history and natural variation. Large differences in aboveground biomass are found throughout tropical forests and most often relate to differences in the physical environment. Effects of logging on aboveground forest biomass have been studied throughout the tropics and results in general suggest that logging significantly reduces the AGB carbon store. For example, Okuda et al. (2004) estimated that AGB in selectively logged forest at Pasoh, Peninsular Malaysia, was on average 274 t/ha, and significantly lower compared to primary forest at the same site. Obviously, intensive logging will drastically reduce the AGB carbon store. Intensive logging has been carried out in extensive areas of tropical peat swamp forest because of their richness in commercial tree species, in particular Meranti (*Shorea albida*) and Ramin (*Gonystylus bancanus*). These practices have consequently led to significant reductions in AGB carbon in these forests. Nevertheless, logged-over forest biomass has insufficiently been studied in tropical peat swamp forests and it may, despite its logging history, still play an important role in the total biomass carbon store.

As outlined above, the AGB of peat swamp forests also differs between natural forest types. Depending on their floristic composition and vegetation structure, six different vegetation zones (or phasic communities, PC) have been distinguished (Anderson, 1961). These vegetation zones are related to different zones on the peat dome. Because of their distinct species communities and architecture, the different phasic communities may store quite different amounts of carbon in the aboveground biomass. In general, the biomass is highest in the PC1-PC3 and decreases towards the low pole forest of PC6. The occurrence of different forest types depends on the hydrology, chemistry and organic matter content of the peat, but these factors are in turn determined by vegetation, hence resulting in the interdependency of forest type and peat characteristics (Page et al., 1999). Melling et al. (2006) described that soil physical and structural characteristics differed remarkably between phasic communities in Logan Bunut National Park, Sarawak.

PC1 Mixed swamp forest
PC2 Alan forest
PC3 Alan bunga forest
PC4 Padang alan forest
PC5 Tristania- Parastemon-
Palaquium association
PC6 Padang keruntum

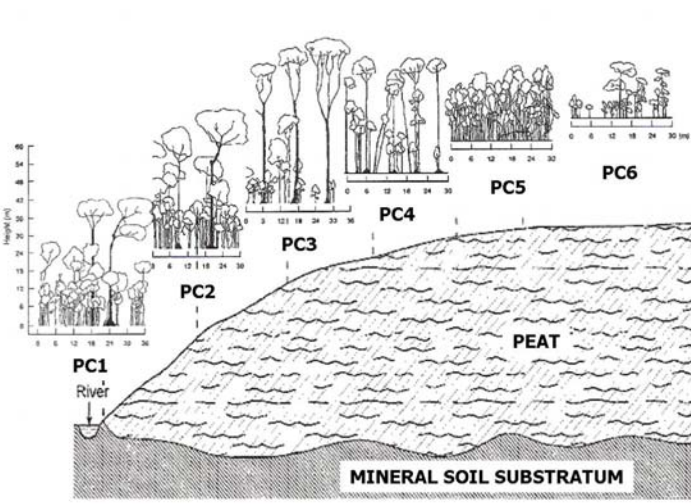

Figure 2.1
Peat swamp forest vegetation types or phasic communities (PC) relative to their position on the peat dome. From perimeter to core (modified after: Paramananthan, 2008)

Both these natural variations and degree of disturbance are important to take into account when studying the net effect of forest conversion on the AGB carbon content. Land use types other than forest also have their associated carbon content. For example oil palm (*Elaeis guinensis*), which is widely grown in peat lands in Southeast Asia, store on average 39 t C/ha over their 20-30 years life cycle (Dewi et al., 2009) and annual crops such as rice generally store <5 t C/ha.

Estimations of the AGB are often based on allometric relationships[2] that are in turn based on destructive sampling of some trees. This destructive sampling allows to measure and quantify the biomass volume of these trees and to assess the size relation between tree parameters and total tree biomass. The resulting relationship can be used to estimate the biomass of the rest of the forest, without destructive sampling. Such biomass inventory studies have been carried out in Southeast Asia, but mostly in dipterocarp forests[3] and not in peat swamp forests. At this stage there is no published allometric equation for peat swamp forests and attempts to quantify the AGB should therefore be based on the allometric relationships described in other forest types. Although the best available possibility, this approach will increase the uncertainty in biomass estimates for this ecosystem, and may, depending on the tree species composition, architecture and wood densities, over- or underestimate the actual biomass.

2.1.1 Available data

Several studies have been carried out to estimate the AGB in peat forests () and these are generally based on tree inventories. These studies show a remarkably broad range of AGB in relatively undisturbed peat forest 147-645 t/ha (~73-323 t C/ha).

2 Allometry is the study of the relationship between size and shape. In plant science it involves for example the estimation of total tree volume based on a few measurable parameters such as the stem diameter.

3 orests dominated by members of the tree family *Dipterocarpaceae*

Table 2.1
Published values of aboveground biomass (AGB) in (relatively) undisturbed and in logged-over or degraded (secondary) peat swamp forests

PSF type	Location	Province/State	Country	AGB (t/ha)	AGB (t C/ha)	Reference
Intact peat forest (shallow peat)	Mawas Conservation Project	Central Kalimantan	Indonesia	221.82	110.91	Petrova et al., 2008
Intact peat forest (deep peat)	Mawas Conservation Project	Central Kalimantan	Indonesia	146.96	73.48	Petrova et al., 2008
Primary peat forest		Sumatra	Indonesia	358	179	MoFor, 2008
Primary peat swamp forest		Jambi	Indonesia	432	216	MoFor, 2008
Primary peat forest		Kalimantan	Indonesia	392	196	Istomo et al., 2006
Primary peat forest		Central Kalimantan	Indonesia	222	111	MoFor 2008
Primary peat forest		Papua	Indonesia	422	211	MoFor 2008
tall interior forest	Sungai Sebangau catchment	Central Kalimantan	Indonesia	645.34	322.67	Waldes and Page, 2002
Shallow peat bog		Sarawak	Malaysia	246	123	Bruenig and Klinge, 1977
riverine peat swamp	Tanjung Putin NP	Central Kalimantan	Indonesia	400	200	Murdiyarso et al.. 2010
relatively undisturbed PC1	Lingga Water Catchment	Sarawak	Malaysia	271.26	135.63	own inventory data
relatively undisturbed PC1	Sungai Sebangau catchment	Central Kalimantan	Indonesia	311.94	155.97	Waldes and Page, 2002
relatively undisturbed peat forest		Narathiwat	Thailand	287-491	144-246	Kaneko, 1992
relatively undisturbed low pole forest	Sungai Sebangau catchment	Central Kalimantan	Indonesia	248.5	124.25	Waldes and Page, 2002
Mixed swamp forest	Sungai Sebangau catchment	Central Kalimantan	Indonesia	313.9	157	Sulistiyanto et al., 2007
Low pole forest	Sungai Sebangau catchment	Central Kalimantan	Indonesia	252.5	126	Sulistiyanto et al., 2007

Currently, many research institutes are involved in biomass assessments, possibly motivated by the increasing interest in the REDD finance mechanism[4], which requires reliable estimates of the amount of carbon sequestered in forest vegetation. Timber industries have been doing forest inventories already for a long time to assess the volume of commercial timber. However, these inventory data are usually unpublished and unfortunately hardly accessible. Among the first extensive inventories of peat swamp forest is the work of Wyatt-Smith (1995) and Anderson (1961). The inventories started before the commercial exploitation of peat swamp forests in the early 1960s. Since then, few institutes have been doing tree inventories in this forest type. An overview of available tree inventory data which can be used to estimate AGB is presented in Appendix 1.

2.2 Historical records in Sarawak and Brunei

The most extensive historical data for peat swamp forest in Sarawak and Brunei, known so far, was published in the PhD thesis of Anderson (1961). He selected a number of peat swamp areas based on the presence of a sequence of forest types and the accessibility of the area, derived from aerial photographs. In total he established 53 half acre (=0.2 ha) plots to measure all trees that had a stem circumference of at least 12 inch (~10 cm diameter) at breast height. See Appendix 3 for more detailed description of his methodology. This

4 Reduced Emissions from Deforestation and forest Degradation

yielded valuable data on the natural structure and community of peat swamp forests in Sarawak and Brunei and is the most detailed and extensive data source for (relatively) undisturbed peat swamp forest from that period. Therefore, we use it as a reference for a natural peat swamp forest system.

Figure 2.2
East Malaysia. The Anderson plots were located throughout Sarawak and Brunei

2.2.1 Wood densities

The carbon content of individual trees, and hence patches of forest depends for an important part on knowledge of the tissue density of a given tree. Wood density or wood specific gravity is the second most important parameter necessary to accurately predict the mass of a tree, after its diameter and height (Chave et al., 2005). Ignoring variations in wood density may result in poor overall predictions of AGB (Baker et al., 2004).

Wood density is generally defined as the oven-dry mass divided by fresh volume. The density of woody structures excluding open spaces in wood is *c.* 1.5 (Siau, 1984), thus wood density always falls within the range of 0-1.5 g cm^3. Wood density thus also describes the carbon storage per unit volume of stem. Importantly, wood density varies within individuals. As wood ages, the inward part of sapwood converts into heartwood through the polymerization of compounds (Schultz et al., 1995). Heartwood xylem lacks functional conduits and parenchyma and its density is often significantly higher than sapwood densities (Woodcock and Shier, 2002; Patiño et al., 2008). Wood density also varies with height within the plant (Swenson and Enquist, 2007), with growth stage or age (Thomas and Malczewski, 2007) and within the different functional parts of the plant. Roots for example tend to have lighter wood than stems (Pratt et al., 2007).

The carbon content of wood may vary considerably between species and between sites (Thomas and Malczewski, 2007). For example species with a high lignin content tend also to have a higher carbon content compared to low-lignin species (Elias and Potvin, 2003;Thomas and Malczewski, 2007), and a particular tree species can have denser wood in the one site compared to the other.

Compilations of species-specific wood density are made available (Reyes et al., 1992; Zanne et al., 2009; ICRAF Wood Density database[5]). These databases also include peat swamp forest tree species, hence can be used for biomass assessments in these forests.

[5] http://www.worldagroforestry.org/sea/Products/AFDbases/WD

2.2.2 Remote sensing data

Since it is impossible to observe and measure the state of all tropical peat swamp forests *in situ*, radar and satellite imagery (e.g. ALOS PALSAR, MODIS, Landsat, ESA Globcover) is used to produce accurate and up-to-date land use maps. Such maps are a crucial step towards extrapolation of *in situ* measured aboveground biomass data. Estimations of AGB based on satellite images depend on the resolution of such images. A first forest carbon map of Africa and Southeast Asia was published by Gibbs et al. (2007) (Figure 2.3). This map shows that a large portion of peat swamp areas fall within the class of 60-120 t C/ha. Improvements in the remote sensing techniques make it possible to produce more accurate high resolution maps than previously done. Recently a land use map for the island of Borneo has been published (Grim, 2009). For parts of tropical Southeast Asia high resolution aerial photographs are available in Google Earth©. These photographs form a useful tool for the validation of land use maps based on satellite data.

Land use maps of Borneo have been developed by SarVision, based on images from the Japanese Space Agency. In addition, initiatives such as the Global Observation of Forest and Land Cover Dynamics, GOFC-GOLD, Forest Carbon Tracking (GEO)[6], UN-REDD[7], TREES-3[8] and FAO FRA2010[9] aim to improve the quality and availability of land use and forest imagery on a global and regional scale.

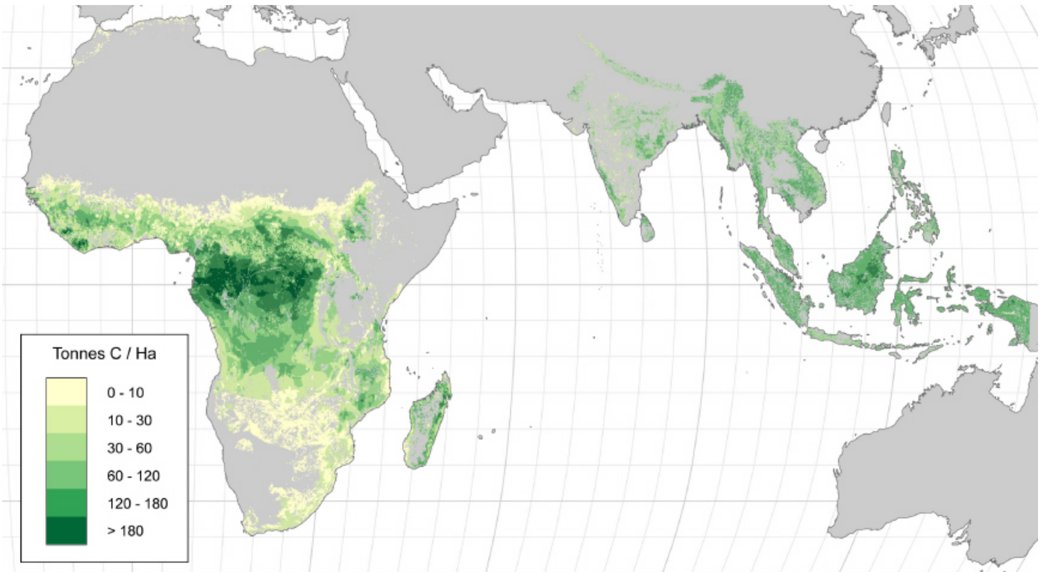

Figure 2.3
Forest biomass (AGB) carbon map for Africa and Southeast Asia produced by using regression-based models to extrapolate forest inventory measurements (source: Gibbs et al. 2007)

6 http://www.fao.org/gtos/gofc-gold/index.html
7 http://www.un-redd.org/ProductsandPublications/tabid/587/language/en-US/Default.aspx
8 http://ies.jrc.ec.europa.eu/index.php?page=70
9 ttp://www.fao.org/forestry/media/16300/1/0/

2.3 Potential use of data

The aforementioned forest inventory data provides diameter measurements of individual trees, and based on existing allometric equations these tree diameters, together with the species specific wood density can be used to predict the total AGB. In some forest inventories also tree height has been assessed, especially for smaller trees (<5m height). The diameter-height relations for species of forest stands in these inventories can be compared with the diameter-height relations for species of stands from forests for which allometric equations have been established. If the relation is comparable in both forest types, this would support the use of these allometric models for peat swamp forest stands.

2.3.1 Estimation of the carbon stock of AGB

2.3.1.1 Allometric models

Several allometric models are currently available to estimate aboveground biomass in humid and wet tropical forests (Appendix 4). These models are based on destructive sampling in non-peat swamp forest. They are not yet available for peat swamp forest and for that reason we applied a model which was calibrated based on 122 trees sampled in lowland mixed dipterocarp forests in East Kalimantan, which includes several of the dominant tree genera found in peat swamp forest such as *Shorea, Hopea* and *Palaquium* (Basuki et al., 2009):

$$\ln AGB = -0.744 + 2.188 \times \ln(DBH) + 0.832 \times \ln(WD)$$

in which WD is wood density and DBH is the stem diameter at breast height. This model assumes a fixed relation between diameter and height, which is useful because height measurements of individual trees are largely lacking in available forest inventory data. We applied this equation to the historical dataset of Anderson (1961) and to the forest inventory data from Lingga Water Catchment area in Sarawak in order to estimate the AGB of different peat swamp forest communities. Unfortunately no tree inventory data were available for PC6 so we excluded this vegetation type from the analysis. The wood densities were extracted from the Global Wood Density Database (Zanne et al., 2009). For taxa that were not included in this database we used the average wood density for the congenial species originating in South East Asia. The carbon content of biomass was assumed to be 50% of dry weight biomass (Basuki et al., 2009). Carbon content was then compared between five vegetation communities (phasic communities, PC, Table A3-1). An analysis of covariance (ANCOVA) was used to test whether the carbon stock differed significantly between phasic communities.

2.3.1.2 Results

Aboveground carbon stock differed significantly between phasic communities (ANOVA: $F_{4,36}$=9.14, p<0.01), reaching on average 169t C/ha in undisturbed peat swamp forest (Table 2.1). The results were not influenced by Plot (ANCOVA: $F_{1,35}$=0.031, p>0.05). The carbon stock in PC2 and PC3 was significantly higher compared to the other phasic communities. Both PC2 and PC3 are dominated by *Shorea albida*, which is known for its high abundance of relatively large trees in these specific communities (up to 469 individuals/ha recorded in Badas, Brunei). PC1 was not significantly different from PC4 and PC5, but these latter two communities did differ significantly from each other (Table 2.1). The AGB of mixed peat swamp forest (PC1) at Lingga Water Catchment area was on average 271 t/ha (~136 t C/ha) were in line with those calculated for the Anderson data. Our results fall within the range of range of 178-199t C/ha found in Amazonian wet forests in French Guyana (Chave et al., 2008), but are much lower compared to the AGB in lowland dipterocarp forest in Sibulu, East Kalimantan (~254 t C/ha).

Table 2.2
Average aboveground biomass (AGB) and carbon content of peat swamp forest communities in Sarawak and Brunei, based on historical inventories by Anderson (1961)

	AGB (t dry matter/ha, avg±SD)*		AGB (t C/ha, avg±SD)	
PC1	263.96	±8.10	131.98	± 4.05
PC2	373.76	±13.56	186.88	± 6.78
PC3	397.42	±11.56	198.71	± 5.78
PC4	348.78	±12.70	174.39	± 6.35
PC5	310.12	±7.20	155.06	± 3.60
AVG	**338.8**	**±52.86**	**169.40**	**± 26.43**

SD=standard deviation
*allometry based on Basuki et al., 2009

2.4 Data limitations

To extrapolate the biomass carbon values, data on the land use of peatlands is required, together with data on the standing biomass for each of the land use types. The assessment of forest biomass is hampered by the lack of available data and by the poor quality of some of the data. Limitations in AGB data availability and quality are outlined below.

Uncertainty in allometric relations
To make correct inferences about long-term changes in biomass stocks, it is essential to know the uncertainty associated with AGB estimates. After evaluating four types of error occurring in AGB estimates[10], Chave et al. (2004) concluded that the most important source of error is currently related to the choice of the allometric model. This indicates the importance of improving the predictive power of existing allometric models for biomass. Indeed we found high variation in AGB when applying different allometric equations for tropical moist and wet forest on peat swamp forest data. If we compare for example the model by Basuki et al. (2009) with other allometric models for tropical lowland moist and wet forests, the results may be highly different (Figure 2.4 and Figure 2.5). For example, the widely used allometric model by Brown (1997) would result in an average total AGB carbon stock of 211 t C/ha in the peat swamp forest plots used in this study. These findings indicate an urgent need for the development of a site-specific allometric model for peat swamp forests. In fact, GTZ has been cutting 50 peat swamp forest trees in Sumatra and developed an allometric model based on the data (Steinmann, GTZ. *pers.comm.*) This model has not been published.

None of the published allometric methods were developed from peatland data, so their applicability for this forest type remains to be proven, especially when we consider that tree architecture is likely to be influenced by the tree's physical environment. It seems that for many of the peat swamp forests species, regular flooding is essential to sustain growth and survival (Jans et al., unpublished). Peat swamp species have evolved specific organs to deal with regular flooding events, such as stilt roots and pneumatophores. It is not unlikely that the swampy environment in peat swamp forests requires different tree architecture and allometrics compared to other forest types.

[10] (1) error due to tree measurement; (2) error due to the choice of an allometric model relating AGB to other tree dimensions; (3) sampling uncertainty, related to the size of the study plot; (4) representativeness of a network of small plots across a vast forest landscape (see Chave et al., 2004)

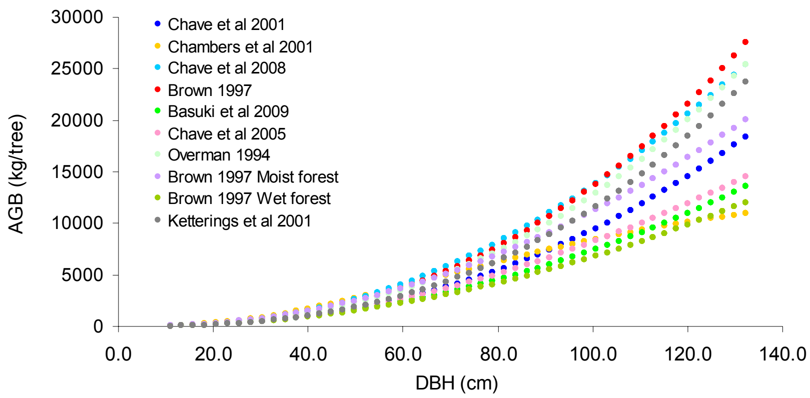

Figure 2.4

Estimation of aboveground biomass (AGB) per tree following different allometric equations for tropical moist and wet forest. DBH=diameter at 1.3 m height

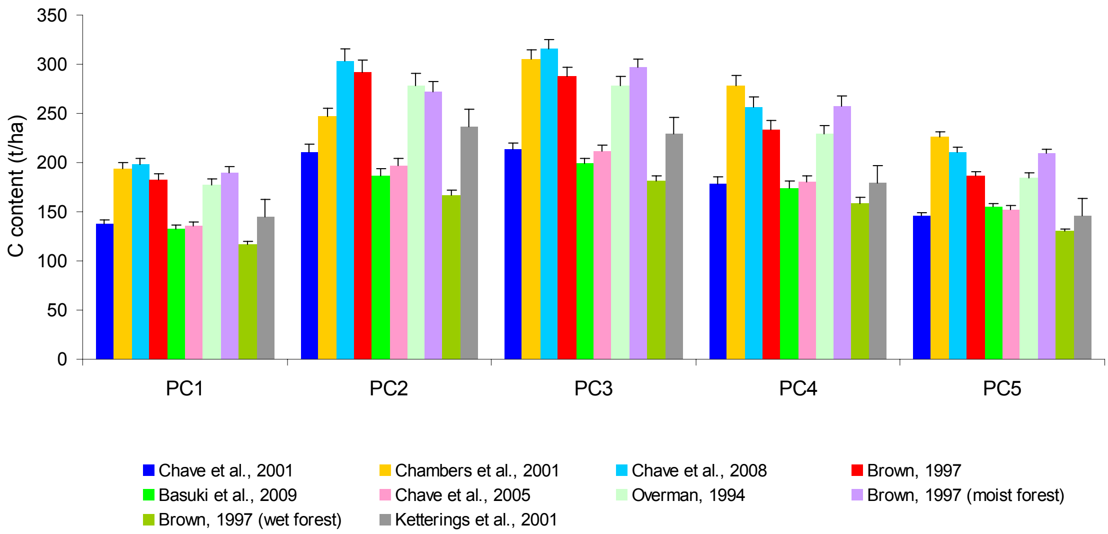

Figure 2.5

Carbon content per hectare based on 53 half acre plots across five different phasic communities, according to ten allometric equations for moist and wet tropical forest. Error bars indicate standard deviation between plots. Data on PC6 is not available.

Effects of logging

Published values indicate that aboveground biomass of relatively undisturbed peat swamp forests ranges from 111 to 645 t/ha, with a median value of 312 t/ha (Table 2.1) and our calculations based on historical data fall within the same range (Figure 2.5). However, as the majority of the remaining peat swamp forests have been exploited for timber, it is likely that their current carbon stock lies within a much lower range. A study in French Guyana revealed that conventional selective logging led to emissions equivalent to more than a third of aboveground carbon stocks in plots without timber stand improvement treatments such as liberation of future crop trees and liana cutting (85 t C/ha). Plots that did receive treatments lost more than one-half of aboveground carbon stocks (142 t C/ha) (Blanc et al., 2009). A study in dipterocarp forest in Malinau (East Kalimantan) showed that forest management (logging intensity, minimum cutting diameters etc.) significantly influenced the standing volume of AGB, and is therefore an important factor determining carbon sequestration potential. In Amazonian moist forests, secondary vegetation biomass was 40 60% of the primary forest biomass after 18 years of abandonment (Alves et al., 1997). The high density of commercial tree species in peat swamp forest, mainly in phasic communities 1-3, suggests that logging of peat swamp forests has resulted in big losses of AGB. The high density of commercial trees can be deduced also from aerial photographs of peat swamp forest showing limited remaining canopy cover (see Appendix 5). According to values published in various sources, the aboveground biomass of logged-over and secondary peat swamp forest ranges from 130 to 334 t/ha (~65-167 t C/ha) (Table 2.3).

Table 2.3
Published values of aboveground biomass (AGB) in logged-over or degraded (secondary) peat swamp forests

PSF type	Location	Province/ State	Country	AGB (t/ha)	AGB (t C/ha)	Reference
logged-over PC1	Kota Samaharan	Sarawak	Malaysia	244.28	122.14	Ipor et al. 2006
Secondary peat forest		Sumatra	Indonesia	284	142	MoFor 2008
Secondary peat forest		Jambi	Indonesia	306	153	Istomo et al., 2006
Secondary peat forest		Kalimantan	Indonesia	310	155	MoFor, 2008
Secondary peat forest		Central Kalimantan	Indonesia	130	65	Istomo et al., 2006
Secondary peat forest		Papua	Indonesia	334	167	MoFor, 2008

Wood density of the species, specifically for peat
So far, wood densities of forest trees have been obtained from several field studies, particularly on non-peat areas. Wood density databases documented mentioned earlier do not indicate the soil type or climate parameters. As it is not known whether wood density is influenced by soil type, using these databases may result in over- or under estimations. Wood densities, specifically for peat areas are lacking.

Hollow trees
Hollow trees tend to be abundant in logged-over peat swamp forests. So far, no data on the effect of hollow stems on the biomass calculations are reported. Not accounting for their hollowness may result in an overestimation of the total biomass stock, especially in logged-over peat swamp forests, where hollow trees are left over by the loggers. Brown et al., 1995 estimated hollowness of trees in Amazonian forest and found that less than 20% of the inspected trees in their study were hollow. Of those, about 20% of the basal area was hollow. They stated that hollowness was relatively unimportant, affecting less than 4% of the biovolume in their study area. The importance of hollowness is also related to the position of hollows. For instance, if half the diameter of a tree is hollow and that hollow is in the center, the biomass loss for that tree is about 25%. Because adult *Shorea albida* regularly has hollow stems, this effect may be profound in peat swamp forests, and in particular in the vegetation types where this species is dominant.

3 Belowground biomass

3.1 Introduction

Belowground biomass (BGB) comprises the living coarse and fine roots of trees. In peat swamp forests roots may be the most important contributors to peat formation (Joosten, 2008). Studies to root biomass in South-East Asia are scarce due to the difficulty in directly measuring root biomass in the forest (Cairns et al., 1997;Jackson et al., 1996; Vogt and Persson, 1991). Nevertheless tree root systems must be considered because they are an important part of total forest biomass, representing 2 25% of the total biomass in various tropical rain forests (Jackson et al., 1997, Lugo, 1992, Sanford and Cuevas, 1996, Santantonio et al., 1977). In pre-montane forests on Sulawesi, the total biomass was estimated to be 303 t/ha (or 128 tC/ha), of which coarse and fine root biomass (down to 300 cm in the soil profile) made up 11.2 and 5.6 t/ha respectively (Hertel et al., 2009). The density of fine roots decreased exponentially with soil depth and closely correlated to the concentrations of base cations, soil pH and in particular of total P and N.

For many ecosystems other than peat swamp forest, estimates of root biomass are already available. Root biomass is often estimated based on the root-to-shoot ratio which is determined based on the excavation of trees. For tropical forests root-to-shoot ratios[11] of 0.19 (Jackson et al., 1996) and 0.24 (Cairns et al., 1997) have been published. Default values of root-to-shoot ratios have been published in the Good Practice Guidance for LULUCF and in the REDD sourcebook (GOFC-GOLD, 2009). These estimates do not include measurements from peat swamp forests. The REDD sourcebook uses a default value of 0.24 as average root-to-shoot ratio in humid tropical forests with >125 t biomass/ha (see Table 3.1). These ratios correspond to those found in some of Sarawak's secondary forests on mineral soil (Kenzo et al., 2009, Figure 3.1).

It has been suggested that In peat swamp forests the roots are the major contributor to peat formation (Chimner and Ewel, 2005). Trees growing in swampy conditions need extensive root systems for their stability on the lose peat soil. Some tree species such as *Shorea albida* have been observed to create massive root mats that are strangled into the root systems of other trees.

Table 3.1
Root-to-shoot ratios used for BGB estimations in humid tropical forest (source: GOFC-GOLD, 2009)

	AGB (t/ha)	Root-to-shoot ratio	Range
Tropical rainforest or humid forest	<125	0.2	0.09-0.25
	>125	0.24	0.22-0.33

[11] Here we consider root-to-shoot ratio to be equal to BGB/AGB

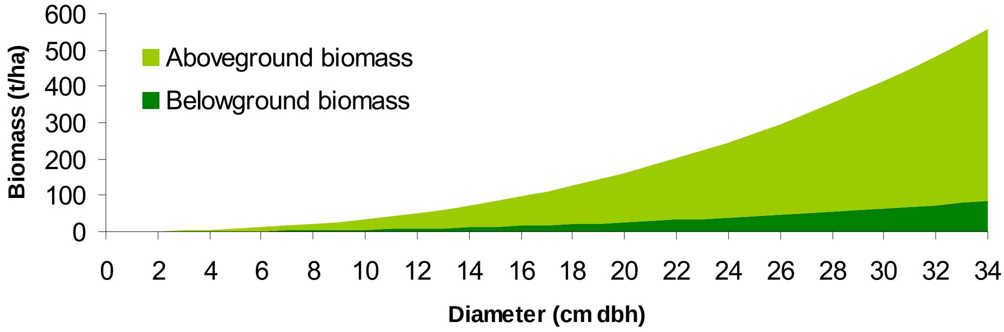

Figure 3.1
Above- and belowground biomass in post fire secondary forest and roadside secondary forest in Sarawak (based on data by Kenzo et al. 2009).

3.2 Available data

Belowground biomass assessments are generally poorly available due the intensive monitoring work required for it. Root biomass is however a vital part of a tree's total biomass. As far as we know, only GTZ performed the root biomass measurements in peat swamp forests. There is no published allometric equation for belowground biomass in peat swamp forests. So far, no root biomass data has been published for peat swamp forests. In lowland dipterocarp forest, ICRAF has been modelling the belowground root biomass. Nevertheless, the data used for this is not shared. Some data for secondary forest in Sarawak was published in 2005 by Kenzo et al., (2009), but this was not on peat soil.

3.3 Potential use of data

Similar to the assessment of AGB, total BGB can be linked to stem diameter at breast height. This means that the same data used for estimations of AGB could be used to approximate BGB, assuming a similar relation between DBH and BGB as found in other forest types (see Appendix 4, Table A4-2). When BGB measurements from peat swamp forests would become available, a new allometric relationship, specifically for peat swamp forests can be applied to existing forest inventory data, which would increase the reliability of current estimates.

3.3.1 Estimation of carbon stocks in BGB

3.3.1.1 to determine root biomass have been established for primary moist tropical Allometric models

Allometric relationships forest (Niiyama et al.m 2005; Sierra et al., 2007; Niiyama et al., 2010) and secondary moist tropical forest (Sierra et al., 2007; Kenzo et al., 2009). The available allometric relationships are given in Appendix 4, Table A4-2. To estimate the belowground biomass in unlogged peat swamp forests, we applied the equation by Niiyama et al. to the dataset of Anderson (1961) and to the relatively undisturbed peat swamp forest at Lingga Water Catchment area in Sarawak:

$$BGB = 0.02186 * DBH^{2.487}$$

in which DBH = tem diameter at 1.3m height.

3.3.1.2 Results

Using this equation yields an average belowground carbon content of 36.98 t C/ha for the unlogged peat swamp forest (Table 3.2). Similar to the aboveground biomass the BGB differed significantly between phasic communities (ANOVA: $F_{4,36}$=13.64, p<0.01). Results from the mixed swamp forest at Lingga showed a BGB of 26.67 (standard deviation=0.05).

Table 3.2
Average belowground biomass (BGB) and carbon content in BGB of peat swamp forest communities in Sarawak, based on historical inventories by Anderson (1961)

	BGB (t dry matter/ha, avg±SD)*		BGB (t C/ha, avg±SD)	
PC1	57.18	± 2.00	28.59	± 1.00
PC2	89.88	± 3.82	44.94	± 1.91
PC3	89.72	± 2.78	44.86	± 1.39
PC4	73.68	± 2.78	36.84	± 1.39
PC5	59.34	± 1.40	29.67	± 0.70
AVG	**73.96**	**± 15.78**	**36.98**	**± 7.89**

SD=standard deviation
*allometry based on Niiyama et al,2005

3.4 Data limitations

At present no measured data is published for BGB in peat swamp forests. Estimates presented in this report should be considered as approximations. Limitations on the quality and availability of data is outlined below.

Extent of root systems and carbon density in roots
Data on the extent of root systems of peat swamp forest trees and the carbon density of coarse and fine roots is lacking. The current BGB is inferred from measurements of stem diameters. The allometric relations used for that originate from destructive sampling in forest types other than peat swamp forest. Measurements of excavated root systems of peat swamp forest trees would solve this data lack. In practice, careful excavation and separating dead biomass from living roots is extremely difficult in peat areas and damaged caused to roots during excavation should be corrected for.

Allometrics for peat swamp forests
To estimate root biomass we have been using an allometric equation for primary rainforest in Pasoh, Peninsular Malaysia, although root growth might be significantly different in peat swamp forests.

One of the other equations available for belowground biomass in tropical Southeast Asia has been constructed by Kenzo et al., (2009), who excavated 77 trees in tropical secondary forest at Niah Forest Reserve and the Sungai Liku area located in the Lambir Hills National Park in Sarawak, Malaysia. Nevertheless, this model is based on secondary forest tree species, which have different structural traits such as lower wood density, tree height and rooting depth compared with the primary forest trees. About 50% of the trees at both study sites were *Macaranga* and *Ficus* species. The others consisted of *Glochidion* spp., *Callicarpa* spp., *Dillenia suffruticosa* and *Endospermum diadenum*. In general, secondary-forest trees have lower wood density with lower variation among species from approximately 0.2 - 0.5 g cm-3 compared to late-successional tropical rain-forest trees, which range from 0.2 - 0.8 g cm-3 in the tropical rain forests of South-East Asia (Suzuki, 1999; Whitmore, 1998). In addition, the nutrient status of the soil may also affect the root biomass differences between tropical forests (Cairns et al., 1997, Sanford and Cuevas, 1996). Peat swamp forests are very nutrient poor and virtually all available nutrients are in the topsoil which may lead to alternative rooting behaviour (i.e. foraging for nutrients) compared to similar tree species occurring in non-peat areas.

4 Coarse woody debris

4.1 Introduction

Coarse woody debris (CWD) involves large pieces of standing and fallen dead wood. Depending on the forest type, stage of succession, land use history and management practices, CWD can be a significant contributor to the total AGB compartment. For example, in an old growth tropical rain forest in Costa Rica, Clark et al. (2002) found that fallen CWD accounted for 46.3 t/ha (22.3 t C/ha) while standing CWD averaged 6.5 t/ha (3.1 t C/ha). The annual inputs of CWD were 4.9 t/ha (2.4 t C/ha), with an average turnover time for fallen CWD of nine years. In total standing and fallen CWD equalled 33% of the aboveground live woody biomass in this forest. The carbon content of this CWD varied from 46.4% in fully decomposed material to 48.3% in sound material. Interestingly, Clark et al.(2002) reported that CWD stocks and inputs were not correlated to stand structure (incl. number of trees, stand basal area and aboveground biomass). In a lowland rainforest in Rondônia, Brazil the stock of fallen CWD was some 30 t/ha, which made up 10.5% of the live AGB (Brown et al., 1995). A study in dipterocarp forests in Borneo revealed a total average mass of 12.4 t/ha standing dead biomass and 27.2 t fallen dead trees (Gale, 2000). The volume of dead trees ranged from 97 to 154 m3/ha. Values of 61 t/ha have been recorded in Borneo (Bruenig, 1996) and 39 t/ha for trees >10 cm DBH in a mixed dipterocarp forest in Sumatra (Yoneda et al., 1990). Several other studies have been carried out to quantify the carbon pool of dead biomass in tropical forests and the results indicate that the carbon content of CWD in unlogged tropical forests may range from 16.5 to 58.4 t C/ha, equalling 9.5-33.5% of the live AGB (Table 4.1).

Table 4.1
Estimated carbon stock in coarse woody debris, including standing and downed dead woody biomass, in various undisturbed forest sites

Forest type	**Country**	**% of AGB**	**CWD (t dm/ha)**	**CDW (t C/ha)***	**Reference**
Tropical wet forest	Costa Rica	33	111.80	55.90	Clark et al., 2002
Tropical wet forest	Venezuela	N/A	69	34.50	Delaney et al., 1998
Tropical moist forest	Venezuela	N/A	84.66	42.33	Delaney et al., 1998
Moracae/Myristicaceae forest	Ecuador	N/A	52.76**	26.38	Gale, 2000
Dipterocarp hill forest	Brunei	N/A	43.7**	21.85	Gale, 2000
Dipterocarp hill forest	Malaysia	N/A	33.07**	16.54	Gale, 2000
Dipterocarp hill forest	Indonesia	9.5	39	19	Yoneda et al., 1990
Tropical moist forest	Brazil	9.62	30	15	Chambers et al. 2004
Tropical moist forest	Brazil	10.5	35.58	15	Brown et al., 1995
Tropical moist forest	Brazil	9.7	32.4	16.2	Pyle et al., 2008
Tropical moist forest	Brazil	26.8	80	40	Pyle et al., 2008
Tropical moist forest	Brazil	33.57	96	48.0	Rice et al., 2004
Tropical moist forest	Brazil	9.78	55.2	27.6	Keller et al., 2004
Tropical moist forest	Brazil	20.71	116.8	58.4	Palace et al., 2008
Tropical moist forest	Brazil	17.38	98	49	Palace et al., 2008
Average		**18.06**	**69.48**	**31.45**	

* ssuming carbon content is 50% of oven-dried mass (e.g. Rice et al., 2004; Chambers et al., 2004)
** assuming biomass equals 0.343 of volume based on Yoneda et al., (1990)

Decomposition of this accumulated dead material plays a crucial role in the recycling of nutrients within the ecosystem (Box 1).

BOX 1. Breakdown of CWD

CWD forms a crucial contributor to soil organic carbon through its slow decay. For undisturbed peat swamp forests this means that CWD contributes to long term peat formation, although the relative importance of aboveground CWD to peat formation remains unknown and depends on the respiration rates. The respiration rate of coarse litter is significantly correlated with wood density and moisture content of the material. Higher moisture content increases the respiration rate whereas higher wood density decreases respiration rates, which is most likely due to the inverse relationship between wood moisture and wood density (Chambers et al., 2001). Nevertheless, under flooded conditions, fungi colonisation and termite attack (hence wood decay) will likely be hampered by anoxic conditions, suggesting that the breakdown of coarse litter in peat swamp forest will be slow under flooded conditions. Yiu-Liong (1990) provided data on decomposition of leaf litter, small wood and large wood in three different phasic communities in Sarawak's peat swamp forests: PC1, PC4 and PC6. He found that the decomposition rates differed significantly between the three phasic communities, with the slowest decomposition occurring in PC6 and the most rapid in PC1. The study revealed that CWD that was buried was decomposed significantly slower than the same material at the soil surface (Figure 4.1). In agreement with these results, the decomposition of tree roots and wood has been found to be inhibited under anaerobic conditions (Chimner and Ewel, 2005). This suggests that in aerobic peat soil the decomposition rate of such woody fragments is higher, resulting in larger CO_2 emissions compared to anaerobic peat and hence a relatively smaller importance of CWD as a carbon pool. Decomposition rates are very much species dependant. For example fast-growing pioneers tend to produce wood that decomposes rapidly. Therefore, as the majority of remaining peat swamp forests has been logged-over for commercial species, the species composition is likely to have shifted towards more fast-growing pioneer species with low wood densities. These species may rapidly sequester carbon dioxide but they contain lower amounts of carbon compared to old growth forest species.

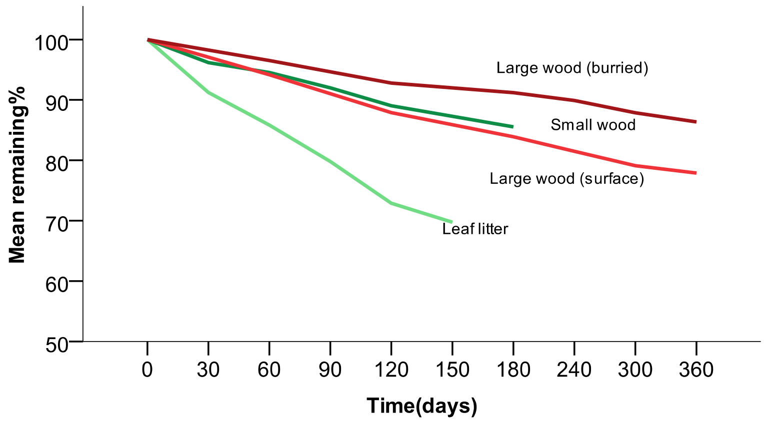

Figure 4.1

Weight loss of leaf litter and woody fragments in peat swamp forest (mean for PC1, PC4 and PC6) (data by: Yiu-Liong 1990)

4.2 Available data

Dead wood inventory data is necessary to accurately assess the CWD pool in peat swamp forest. Such an inventory consists of measurement of the dimensions of dead wood parts, their density, and their carbon content derived from oven-dried samples. To our information this has not been done for peat swamp forests and no research groups are currently exploring the issue. A pilot study by Alterra has measured the density of dead tree stumps in logged-over peat forest in Sarawak (avg. 131 stumps/ha) but these data are too limited for further analysis and only refer to disturbed forest. Among the available data from relatively undisturbed peat swamp forests are decomposition rates of CWD in Sarawak (Yiu-Liong 1990), but these cannot be used to estimate the total CWD carbon pool.

4.3 Potential use of data

4.3.1 Estimation of carbon stocks in CWD

4.3.1.1 Analysis of review data from non-peat swamp forest

The range of CWD biomass in peat swamp forest can be estimated roughly using the ratio between CWD and AGB found in non-peat tropical forests and apply this ratio to the AGB calculated for peat swamp forest (as presented in Chapter 2). In this report the biomass carbon pool of CWD is based on the studies in tropical moist and wet forests shown in Table 4.1. On average these studies revealed that the CWD biomass pool may comprise 9.5-33.6% of the live AGB pool.

4.3.1.2 Results

Using the values for AGB presented in Chapter 2, the total carbon pool of coarse woody debris lies between 16.09-56.75t C/ha in unlogged peat swamp forest (average = 31.44 t C/ha) (Table 4.2). In response to the difference in AGB between phasic communities, the CWD biomass is also different between phasic communities and is highest in PC3 (73.76 t/ha or 36.88 t C/ha) and lowest in PC5 (57.56 t/ha or 28.78 t C/ha). In the mixed swamp forest at Lingga Water Catchment area, the CWD biomass ranged from 12.89-45.57 with an average value of 25.17 (SD=0.04).

Table 4.2

Average, minimal and maximal Coarse Woody Debris (CWD) mass and carbon content of peat swamp forest communities in Sarawak and Brunei, based on historical inventories by Anderson (1961)

	CWD (t dry matter/ha)*				CWD (t C/ha)			
	min	max	avg±SD		Min	max	avg±SD	
PC1	25.08	88.43	48.99	±1.50	12.54	44.31	24.50	±0.75
PC2	35.51	125.21	69.37	±2.52	17.75	62.74	34.69	±1.26
PC3	37.75	133.13	73.76	±2.15	18.88	66.71	36.88	±1.07
PC4	33.13	116.84	64.73	±2.36	16.57	58.54	32.37	±1.18
PC5	29.46	103.89	57.56	±1.34	14.73	52.06	28.78	±0.67
AVG	**32.19**	**113.50**	**62.88**	**±9.81**	**16.09**	**56.87**	**31.44**	**±4.91**

SD = tandard deviation

* calculated as proportion of AGB presented in Chapter 2

4.4 Data limitations

The values presented here are estimates that indicate the potential range of the CWD carbon stock in peat swamp forests. Limitations of the available data and methods are outlined below.

Lacking CWD inventory data
Our estimates are based on a number of studies carried out in non-peat swamp forest. Hence the resulting average value entails high uncertainty. Values presented in the aforementioned studies are however indicative for the potential range of the CWD carbon pool. Inventory data of dead wood in peat swamp forests are lacking, as are the densities and carbon content of CWD. Improvement of the estimates presented in the previous section is therefore not yet possible based on the currently available data from peat swamp forests.

Hollow trees
The proportion of dead hollow trees in a study in Borneo appeared to be related to site and tree diameter. Here, on average 29.7% of the dead trees were hollow and larger diameter trees were more likely to be hollow (Gale, 2000). Dead hollow stems tend to be abundant in logged-over peat swamp forests and form therefore an important portion of the total CWD. It would be interesting to quantify the effect of hollow trees on total CWD, although this seems to be irrelevant for the total ecosystem carbon stock considering the relative importance of this biomass compartment.

Effects of logging
Figures presented here are based on values found in unlogged forest. Effects of logging on the CWD carbon pool have been studied in Brazil and the results showed higher volumes of CWD compared to non-logged forests (avg. 84.95 t C/ha or 30% of AGB), but these results were not significant (Palace et al., 2008). The intensity of logging and harvest techniques used (i.e. damage caused to residual trees) determine the effects of logging on the CWD biomass pool. Considering the high intensities of logging applied throughout peat swamp forests it is likely that the CWD pool will be higher in logged-over peat swamp forest compared to unlogged peat swamp forest.

5 Litter

5.1 Introduction

The litter biomass pool comprises fallen leaves, twigs, flowers and inflorescence, fruits and seeds. Estimates of the litter carbon pool are variable, ranging from 2.4 t C/ha (Delaney et al., 1997) to as much as 15 t C/ha (Chiti et al., 2010). At Rodônia, Brazil, the litter carbon pool was equivalent to 3.5% of the carbon sequestered in live AGB (Brown et al., 1995). This is on the higher end of ranges reported for moist-wet tropical forests by Nascimento and Laurance (2002) and Delaney et al., (1997) (Table 5.1). The latter study showed that the litter pool was smallest in dry and in wet forest and peaked in moist forest.

Similar to CWD, the litter biomass pool is the result of continuous input through litter fall and loss through decomposition. Decomposition of fine litter is an important process by which carbon fixed during photosynthesis is returned to the atmosphere (Schlesinger 1977; Singh and Gupta, 1977). The rate of decay of litter typically depends on climate, litter quality (e.g. chemical composition) and the decomposer communities present (e.g. bacteria, fungi and soil fauna). In general litter decomposition is rapid across tropical forests, with >95% mass loss within a year, and highly correlated with mean annual precipitation (Powers et al., 2009). In most tropical forests litter built up is therefore relatively small and, consequently, litter is of limited importance in the total AGB carbon store. 80-90% of annual biomass produced is decomposed quickly and not accumulated in soil organic matter (Rieley et al., 2008). In peat swamp forests however, the rate of decomposition of litter is slow, ranging between 0.068-0.177% per day and may differ greatly between species (Yule and Gomez, 2009) (see Box 2). Therefore, litter biomass may be relatively more important in peat swamp forests compared to other forest types in the tropics, although quantitative data to confirm this is lacking so far.

Table 5.1
Estimated carbon stock in fine litter in various undisturbed forest sites

Forest type	Country	% of AGB	Litter (t dm/ha)	Litter (t C/ha)*	Reference
Tropical moist forest	Venezuela	1.34	4.8	2.4	Delaney et al., 1997
Tropical moist forest	Brazil	3.5	10	5	Brown et al., 1995
Tropical moist-wet forest	Brazil	2.13	7.49	3.75	Nascimento and Laurance 2002
Average		**2.32**	**7.43**	**3.72**	

*assuming carbon content is 50% of oven-dried mass (e.g. Rice et al., 2004; Chambers et al., 2004)

Box 2. Breakdown of leaf litter

A recent study in the North Selangor peat swamp forest showed that although the endemic peat swamp species were resistant to decomposition, leaves of the non-peat swamp species *Macaranga tanarius* did break down despite the acidic, anaerobic conditions of the peat swamp (Figure 5.1; Yule and Gomez, 2009).

This rapid break down of *M. tanarius* suggests that the slow rate of decomposition, leading to the formation of peat, is not due to the extreme conditions of a peat swamp forest which inhibit microbes, but rather due to the physical and chemical properties of the leaves which are resistant to microbial decomposition. Leaves from peat swamp forests are noticeably tougher, thicker and more leathery than *M. tanarius* leaves and have different chemical properties related to toxic secondary compounds. It has been suggested that peat swamp plants -that are not capable of rapid growth due to low nutrient availability- protect their leaves from herbivory by means of toxins in the leaves (latex, resins, oils, phenols and tannins), a tough cuticle, high levels of lignin and crude fiber (PahangFD, 2005; Lim, 2008) and these features also inhibit microbial colonization and decomposition of dead leaves (Yule and Gomez, 2009). Most of the weight loss observed in peat swamp forest litter occurred within the first few weeks of leaf fall into the swamp, which corresponded to the increased levels of dissolved organic carbon (DOC) in the peat water. Most of the DOC appears to be leached in these first few weeks and it therefore seems likely that the cycling of DOC occurs before the leaves become part of the peat deposits (Yule and Gomez, 2009). This could also explain the presence of a thick, superficial root mat layer (also a response to waterlogging) that is a key feature of tropical peat forests, because the processes of nutrient cycling would occur in the upper leaf litter layer, rather than the deeper, waterlogged peat. Indeed, the activity of bacterial enzymes associated with carbon, phosphorus and nitrogen cycling has been found to be highest at the surface and declined markedly with increasing depth of peat (Jackson et al., 2008). The lowering of the concentration of DOC after these first few weeks suggests that the leached DOC might be used as a substrate for bacterial growth (as is found across much of the boreal zone: France, 1999) and probably the growth of aquatic fungi as well, hence lowering the concentration of DOC in the water.

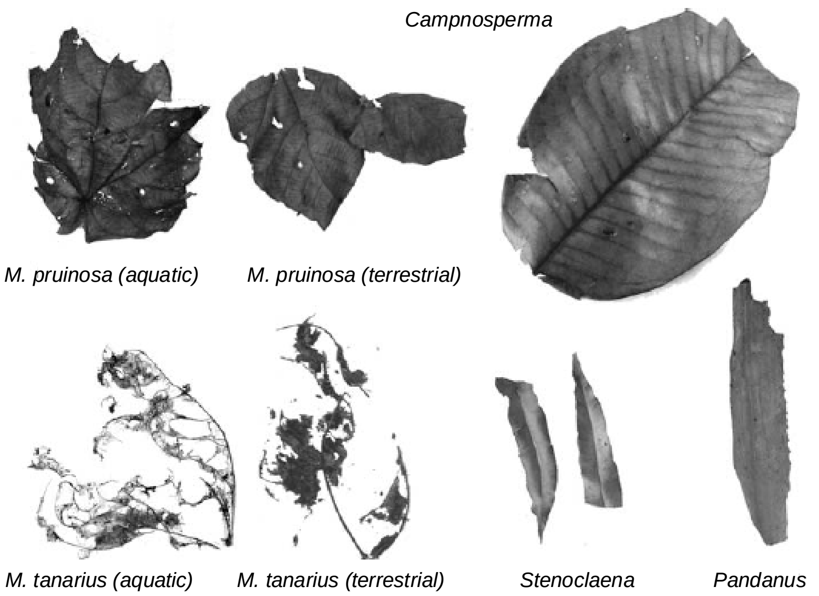

Figure 5.1
Leaves of peat swamp forest species and the non-peat swamp species Macaranga tanarius after one year of exposure in North Selangor Peat Swamp Forest (Source: Yule and Gomez, 2009)

5.2 Available data

Leaf litter production is known for several forest types throughout the world, but in peat swamp forests only few litter studies have been carried out. As part of the Ramin Project, a joint effort between Malaysia and The Netherlands, a number of litter traps were placed in a mixed peat swamp forest (PC1) at the Maludam National Park in Sarawak, Malaysia (JWG 2005). From January 2004 to December 2005 litter fall was monitored monthly by collection of the litter in the litter traps. The mass of collected samples was measured according to its origin: leaves, fruits, twigs, flowers, inflorescence, seeds and remaining parts ('trash'). Figure 5.2 shows the results of this litter trap study expressed as tonnes of carbon per hectare.

Further inventories of the litter pool in this forest type have not been published, although some data on the decomposition rates of fine and coarse litter from different phasic communities in peat swamp forests are available (Yiu-Liong, 1990; Brady, 1997).

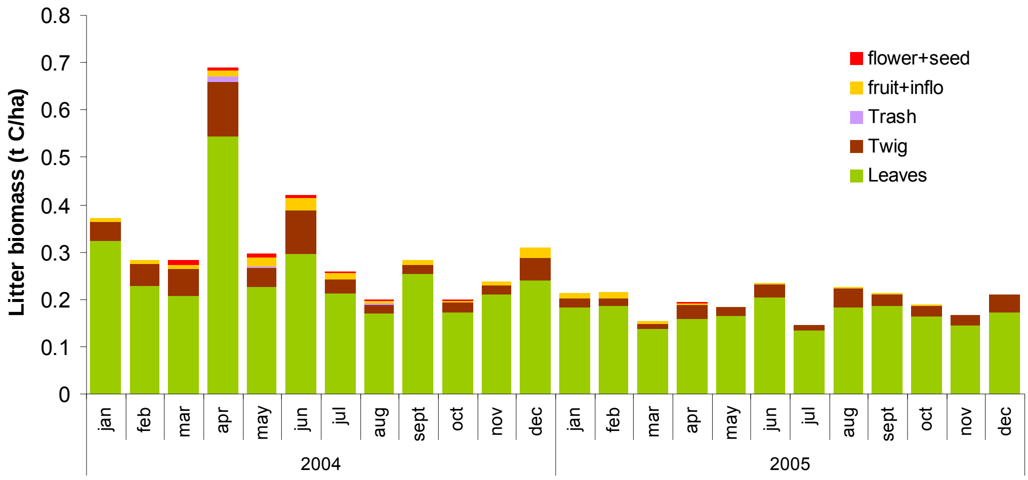

Figure 5.2
Average biomass carbon of monthly produced litter at Maludam NP, sampled during 2004-2005 (JWG, 2005)

5.3 Potential use of data

5.3.1 Estimation of carbon stocks in litter

5.3.1.1 Litter-to-AGB ratios and analysis of litter trap data

Similar to the CWD carbon pool we estimate the total litter carbon pool by assuming a fixed Litter-to-AGB ratio. Here we use a ratio of 0.029-0.035 based on studies by Delaney et al.
(1997) and Brown et al. (1995) in several moist tropical forest types.

Additionally, based on extrapolation of littertrap data from Maludam National Park we estimate the total amount of litter produced per census period. This yields the biomass dry weight of litter parts. The carbon content of the litter parts may differ between leaves, branches, fruits etcetera. However, since these figures are unknown for tropical peat swamp forests we assume that, similar to the other biomass compartments, carbon makes up 50% of the total litter dry weight, although this value might vary between species and sites (e.g. Bockstette, 2010). The range of annual net carbon accumulation in litter (L_{net}) is estimated by using the minimum and maximum daily litter decomposition rates (DR_{daily}) reported in Yule and Gomez (2009) and subtracting the decomposed fraction from the total produced litter biomass (L_{tot}):

$$L_{net} = L_{tot} - \left(\left(DR_{daily} \times 365\right) \times L_{tot}\right)$$

5.3.1.2 Results

Application of the fixed litter-to-AGB approach based on the AGB values presented in chapter 2, results in a total average litter carbon pool of 2.27-5.93 t C/ha in relatively undisturbed peat swamp forest. Table 5.2 indicates the range of litter carbon within different phasic communities using this same method. The values are within the same range compared to data from mixed swamp forest and low pole forest in Central Kalimantan, where the total litter carbon pool was 4.6 and 3.7 t C/ha/yr respectively (Sulistiyanto et al., 2007). In the mixed swamp forest at Lingga Water Catchment area the total litter carbon pool ranged from 1.82 to 4.75 t C/ha with an average value of 3.15 (SD=0.01).

Results of litter trap data show that the total litter production was 7.62 t/ha/yr (~3.81 t C/ha/yr) in 2004 and 4.68 t/ha/yr (~2.34 t C/ha/yr) in 2005. Those values are comparable to the 7.17t/ha/yr (leaf litter: 5.57 t/ha/yr, non-leaf litter: 1.6 t/ha/yr) found by Yiu-Liong (1990) in the same, but relatively undisturbed, phasic community (PC1)[12]. The annual net accumulation of litter at Maludam National Park is estimated to range between 1.66-5.74 t dry matter/ha (~0.83-2.87 t C/ha). Similar values of annual net litter accumulation have been reported by Maass et al. (2002) for tropical deciduous forests in Mexico.

Table 5.2

Average, minimal and maximal litter mass and carbon content of peat swamp forest communities in Sarawak and Brunei, based on historical inventories by Anderson (1961)

	Litter (t dry matter/ha)*				Litter (t C/ha)			
	min	max	avg±SD		min	max	avg±SD	
PC1	3.54	9.24	6.14	±0.18	1.77	4.62	3.07	±0.09
PC2	5.02	13.08	8.68	±0.32	2.51	6.54	4.34	±0.16
PC3	5.32	13.9	9.24	±0.26	2.66	6.95	4.62	±0.13
PC4	4.68	12.2	8.1	±0.3	2.34	6.1	4.05	±0.15
PC5	4.16	10.86	7.2	±0.16	2.08	5.43	3.6	±0.08
AVG	**4.54**	**11.86**	**7.86**	**1.22**	**2.27**	**5.93**	**3.93**	**0.61**

SD=standard deviation
* calculated as proportion of AGB presented in Chapter 2

12 In contrast, the forest at Maludam can be classified as disturbed due to historical logging and ongoing illegal timber harvesting.

5.4 Data limitations

As with CWD, the range of the litter carbon pool presented in this study should be interpreted as a rough estimate, because limited empirical data is available. The limitations of the method used in this chapter are briefly outlined below.

Lacking Litter inventory data
No figures have been published on the litter biomass pool of peat swamp forest. Therefore we used a similar approach as for the assessment of CWD: taking the average of the litter-to-AGB ratios found in non-peat moist and wet tropical forests. The resulting average value entails high uncertainty and can only be improved by using empirical data from peat swamp forests.

Long term data for litterfall and litter decomposition in peat swamp forest
We estimated net annual litter accumulation based on litter production and decay rates that were known from two studies in peat forest. Available litter trap data is short term data (<2 year) which may be useful to detect monthly variation patterns, but is too limited to detect inter-annual patterns. Extrapolation of these short term results increases the uncertainty around the mean estimates of net litter accumulation.

Carbon density of litter
As the density of litter pools strongly depends on the decay phase and litter loses part of its carbon in the first weeks after litterfall as DOC, it can be assumed that litter carbon content is much lower than the 50% of biomass dry weight which is regularly assumed for AGB pools.

6 Peat soil

6.1 Introduction

In peatlands the belowground carbon storage may greatly exceed the aboveground carbon storage, depending on peat depth and bulk density. In total tropical peatlands cover an area of approximately 44 million ha (11% of global peatland area) and they have been estimated to store 81.7-91.9 Gt of carbon, which is equal to 15-19% of the global peat carbon pool. The majority of these tropical peatlands are found in Southeast Asia, primarily occurring in Sumatra, Borneo and Papua, where they cover about 25 million ha and store approximately 68.5 Gt of carbon (Page et al., 2010). Depending on location, the depth of the peat ranges from less than a meter up to 25 m (Whitten et al., 2000; Hooijer et al., 2006). Owing to their great average depth, tropical peat deposits may represent 15% to 30% of the world's total peat carbon pool (Maltby and Immirzi 1993; Page et al., 2000; Siegert et al., 2002).

Tropical peat soils, especially the extensive coastal deposits, are geologically recent, most having formed over the past 5,000 years, with an accumulation rate of between 2 and 5 mm per year. This is about 2 to 10 times the rate for boreal and subarctic peatlands (0.1 – 0.8 mm per year) (Gorham, 1991; Aaby, 1976). When the organic matter in these peat deposits undergo decomposition (either aerobic or anaerobic), vast quantities of greenhouse gasses such as especially CO_2, and to a lesser extent CH_4, and nitrous oxide (N_2O) can potentially be released into the atmosphere. Peat quality, temperature, and hydrological conditions are the major factors controlling C-release. Tropical peatlands are constantly subject to relatively high temperatures and may therefore show a potentially higher carbon release in decomposition compared to temperate peatlands (Chimner, 2004). Hydrological conditions are among the most important factors determining the soil carbon emission rates in ombrotrophic tropical peat. Large-scale water table lowering during the dry season will deepen the oxic surface peat zone, and increase substrate availability for CO_2-releasing decomposition processes (Jauhiainen et al., 2005). Couwenberg et al. (2010) and Hooijer et al. (2010) estimate that 0.8-0.9 t CO_2, per hectare per year is released for every centimetre of lowering of the water table.

6.2 Available data

The most extensive overview on the global acreage of peat soil and related carbon store was recently published in Global Change Biology (Page et al., 2010). Several other estimates exist on the extent of peat lands in Southeast Asia, which are within the same range as indicated in this publication (Joosten, 2009; Rieley et al., 2008; Paramananthan, 2008). Nevertheless, all studies show that carbon density per square meter of peat may widely vary owing to the uncertainty in the thickness of tropical peatlands. For this reason, extra-polations are often made using the lower end of the estimated range of peat thickness per area, hence resulting in conservative estimates of the peat carbon store.

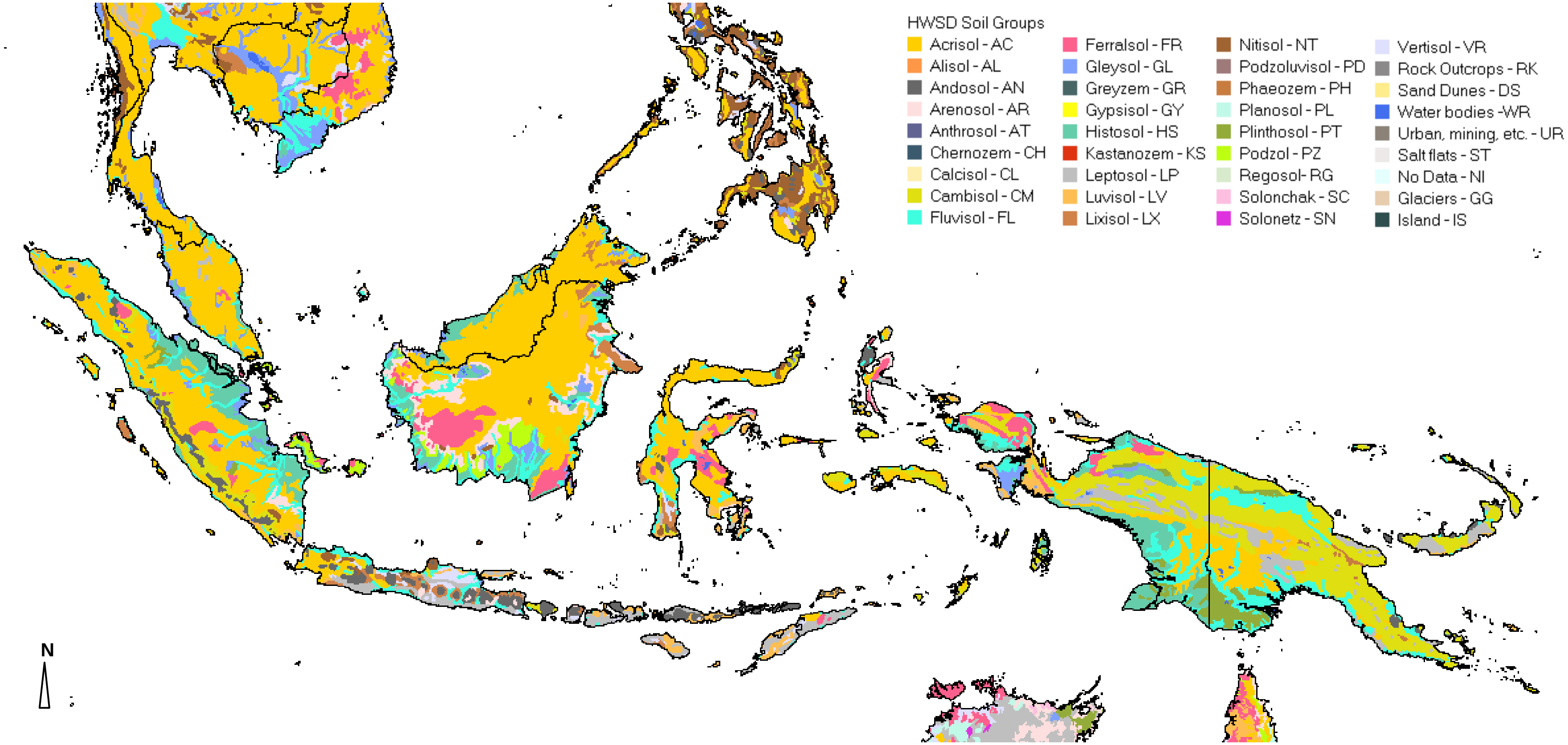

Figure 6.1

Soil map of Southeast Asia showing the HWSD Soil Groups (Harmonized World Soil Database, http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/). Peat soils are categorised as Histosols, and mainly occurring in the coastal plains of Sumatra, Borneo and Papua

6.3 Potential use of data

Peat depth, bulk density and carbon density data are normally based on point sampling in the field. Peat area may also be estimated based on vegetation cover and surface elevation maps. Estimates of the total peat carbon store in tropical peatlands (e.g. Hooijer et al., 2006) use these point based measurements. They have received many critics because of the perceived inaccuracy. To improve the current estimates requires extensive additional auguring of peat depth and profile morphology.

6.3.1 Estimation of carbon stocks in peat

6.3.1.1 Analysis of available data

The amount of carbon in peat swamp forests depends for a large part on the peat depth and bulk density, as most of the carbon is accumulated in the belowground peat deposits:

$$C_{peat} = A \times D \times BD \times C$$

where A is the total area of peat land, D is the average peat depth, BD is bulk density and C is the carbon content. Estimates by Melling et al. (2008a) show for example a peat carbon content of 3771 t C/ha on deep peats in Sarawak. If we assume an average carbon content of 60 kg C/m^3 (Page et al., 2002), a peat layer of 3 m thick would contain 1800 t carbon ha^{-1} and a 6 m thick peat layer 3600 t C ha^{-1}. Although an extensive, detailed peat depth inventory is lacking in Southeast Asia, in several areas the peat profile has been studied. Page et al. , 2010 published an extensive review on the extent of peat lands, depth and carbon content for the tropics. This study provides an average peat bulk density of 0.09 g/cm^3 and an average carbon concentration of 56%. The best estimate of average peat thickness was 5.5 m and 7 m for Indonesia and Malaysia respectively.

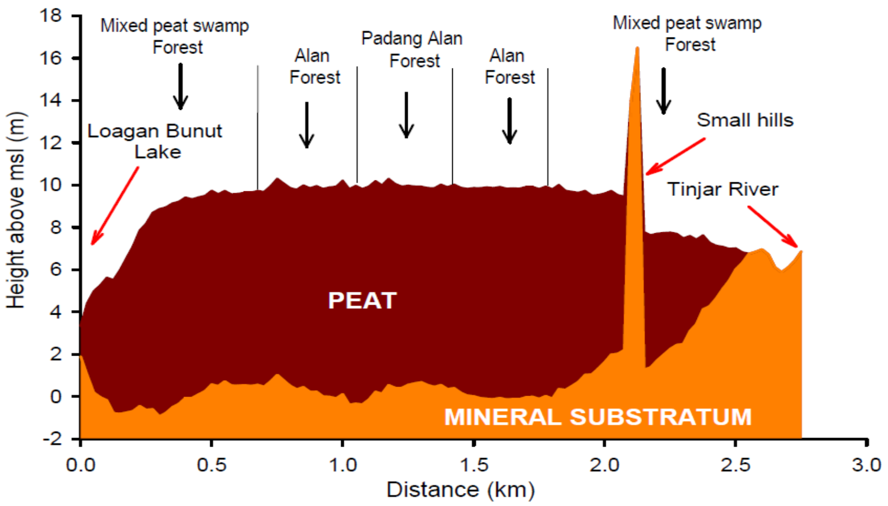

Figure 6.2
Cross-section of a peat dome at Logan Bunut National Park, Sarawak (source: Melling et al., 2008b)

Figure 6.2 shows a cross-section through the peat dome at Logan Bunut National Park in Sarawak, where the average peat depth was around 9 meter. According to the above equation, C_{peat} in this example from Logan Bunut would become 7600 t C/ha, 5610 t C/ha and 4875 t C/ha for Mixed swamp forest, alan forest and padang alan forest respectively. However, this is a rough estimation since peat depth and profile morphology could differ significantly even within small areas.

6.3.1.2 Results

The best estimates of peat area, thickness, volume and carbon content in Southeast Asian countries which have been published in Page et al., 2010 (Page et al., 2010) are given in Table 6.1. The majority of peatland in Southeast Asia is located in Indonesia, followed by Malaysia and Papua New Guinea. The total carbon pool of tropical Southeast Asia is estimated at 69 Gt carbon and the average carbon content per hectare ranged from 252 to 3528 tonnes, depending mainly on the thickness of peat deposits.

Table 6.1
Best estimates of peat area and mean thickness, volume and carbon stocks in tropical Southeast Asia (source: Page et al., 2010)

	Area (km^2)	**thickness (m)**	**volume ($m^3 * 10^6$)**	**C-content (Gt C)**	**C-content (t C/ha)**
Brunei	909	7	6363	0.321	3528
Indonesia	206,950	5.5	1138225	57.367	2772
Malaysia	25,889	7	181223	9.134	3528
Myanmar (Burma)	1,228	1.5	1842	0.093	756
Papua New Guinea	10,986	2.5	27465	1.384	1260
Philippines	645	5.3	3418.5	0.172	2671
Thailand	638	1	638	0.032	504
Vietnam	533	0.5	266.5	0.013	252
Total Southeast Asia	**247,778**	**-**	**1,359,441**	**69**	**-**
Avg C-content/ha					**1,909**

6.4 Data limitations

Although estimations of the peat carbon pool in the tropics still show a wide range, they have been seriously improved within the last decades as more regional data became available. Nevertheless, some improvements could be made to arrive at more precise values that apply for specific areas. These improvements may become relevant especially when peat lands will be involved in the REDD financing mechanism.

Spatial variation of peat depth
Peat thickness can be highly spatially variable. Extrapolation of peat depth measurements at certain locations to values for larger areas may result in large over- or underestimations of the total volume of peat present. Improvement of this situation does require an increase in the currently limited number of peat depth measurements. Since the accessibility of tropical peatlands is limited this is both a difficult and expensive task to fulfil. A significant fraction of peatlands are over 4 metres thick and there are extreme cases of > 20 metres thick peat (Hooijer et al., 2010). However, accurate maps of peat depth are not yet available. This would require extensive monitoring and establishment of peat transects.

Peat profile morphology and bulk density
Bulk density of the peat is difficult to measure because the peat profile is often highly variable with depth, containing large fractions of water and large volumes of non-decomposed tree roots. Because peat structure is not at all homogeneous it is difficult to determine an average bulk density for the different horizons of a peat profile.

Effects of hydrology on peat profile morphology and bulk density

It is known that peat areas form comprehensive hydrological units. Effects of hydrological changes in some part of the peat dome may extent far into the rest of the dome. For example, the establishment of a network of drainage canals to facilitate agricultural use of peat land will influence the hydrology and related soil properties. As hydraulic conductivity may be extremely high in tropical peat swamp forests (0.38-9.36 cm/s), these effects of drainage could seriously affect the subsurface runoff and lower the water table in a large part of the dome. Obviously, after drainage the peat bulk density increases as a result of soil compaction.

7 Discussion and conclusion

7.1 Overview of carbon pools

Most of the carbon in peat lands is stored in the peat soil. Quantification of this peat carbon pool requires detailed information on the area, peat thickness, bulk density and peat profile morphology. The vegetation may also contribute significantly to the total ecosystem carbon store, depending on land use type and management. This is important in the light of large scale land use changes occurring across the globe. For example, most of the carbon losses from aboveground biomass of peat forests occurs during land conversion to agriculture and it depends on the replacing vegetation whether these losses are compensated. In Chapters 2-6 the carbon stock of different biomass compartments in peat swamp forests has been discussed. The resulting figures are briefly summarized in Table 7.1.

Table 7.1
Estimated biomass and carbon content of relatively undisturbed peat swamp forest. Data are from various sources

	Biomass (t dry matter/ha)		Carbon content (t C/ha)	
Biomass compartment	Range	Average±SD	Range	Average±SD
Aboveground biomass	264.0-397.4	338.8±52.5	132.0-198.7	169.4±26.4
Belowground biomass	57.2-89.8	74.0±15.8	28.6-44.9	37.0±7.9
Coarse woody debris	32.2-113.8	62.9±9.8	6.1-56.9	31.4±4.9
Litter	4.5-11.9	7.9±1.2	2.3-5.9	3.9±0.6
Total forest	**363-613**	**486**	**182-306**	**243**

Net ecosystem carbon balance

Forests are dynamic ecosystems that play a crucial role in the global carbon cycle. Terrestrial carbon dynamics are characterized by long periods of small rates of carbon uptake, interrupted by short periods of rapid and large carbon releases during natural disturbances or harvests (IPCC, 2007). It depends on the stage of the individual forest patch and its hydrology whether it acts as a carbon source or sink. Primary peat swamp forests are wetlands that are characterized by a water table at or near the soil surface. In a primary peat swamp forest, atmospheric CO_2 is being fixed through photosynthesis (gross primary production, GPP). Some of the fixed carbon is released back to the atmosphere in the parallel process of plant respiration (autotrophic respiration, R_a), but the surplus is stored in plant biomass (net primary production, NPP). Part of this NPP is released by respiration of consumers and decomposers (heterotrophic respiration, R_h). The resultant of this, the annual net carbon sequestration in live biomass and soil, is called the net ecosystem production (NEP):

$$NEP = GPP - R_e$$

where R_e=ecosystem respiration (=R_a+R_h). Besides these processes, organic carbon may also enter the ecosystem from elsewhere (import, I) and leave the system (export, E), for example as dissolved organic carbon via rivers. Additionally, part of the carbon stored in plant biomass could be released by non-biological oxidation such as fire or ultraviolet (UV) oxidation (Ox_{nb}). The resultant of this is the net ecosystem carbon balance (ΔC_{org}):

$$\Delta C_{org} = GPP - R_e + I - E - Ox_{nb}$$

The stock of carbon in living biomass may be fairly constant over time, but in primary peat swamp forest the decomposition of dead organic material is generally limited due to anaerobic and acid conditions which result in organic matter accumulation and growth of the peat layer, hence increasing the peat carbon stock. Consequently, in a primary peat forest ecosystem the long term ΔC_{org} is slightly positive. It has been described that it is the highly irregular soil surface (which is a result from the typical forest vegetation structure and dynamics) that guarantees the necessary continuous water supply to the peat soil (Joosten, 2008). For that reason, forest disturbances such as logging can disrupt this water storage and increase the rate of evaporation of surface water. Under extreme logging operations, these processes could curb peat formation and result in peat oxidation.

7.1.1 Peat oxidation

Drainage of peatlands results in peat oxidation and the consequent release of CO_2 into the atmosphere. This process could disturb the long term carbon balance and turn the system into a net emitter of carbon. Peat structure, temperature, and hydrological conditions are largely the dominant C-release controlling factors. In temperate and boreal regions ombrotrophic peat consists primarily of *Sphagnum* mosses, whereas in the tropics peat is formed primarily from wood debris. Tropical peatlands are constantly subject to relatively high temperatures and may therefore have a higher potential carbon release in decomposition compared to temperate and boreal peats (Chimner, 2004). As well as in cooler regions, hydrology may be expected to play a major role influencing the carbon cycle in ombrotrophic tropical peat (Vasander and Kettunen, 2006). Under natural conditions peat swamp forests are regularly flooded, thus creating differing oxic conditions for debris decomposition and plant roots in a microtopographically uneven forest floor. Studies to the net ecosystem carbon balance of ecosystem are published for several ecosystems, including the peat swamp forests in the Sebangau catchment in Kalimantan. Such studies use Eddy Covariance techniques to measure the incoming and outgoing carbon fluxes. As opposed to regularly used soil CO_2 chamber measurements, the EC-flux measurements determine both the respiration and sequestration of carbon in the ecosystem. In a primary dipterocarp rainforest in Pasoh the net ecosystem exchange (NEE, Lovett et al., 2006)[13] was -124 g C m^{-2} yr^{-1} in the period 2000-2003, meaning that this forest was an effective net sink of carbon (Kosugi et al., 2008). An ecosystem with high soil respiration rates could form a net source of carbon to the atmosphere when the vegetation sequesters less carbon than emitted by the soil, but it will be a net sink of carbon when the sequestration in biomass equals or exceeds the respiration. Therefore, soil respiration is only one part of the net carbon balance. However, it has become a rather important one in peat lands because of the large scale peat oxidation occurring caused by massive drainage of peat swamps for development. Peat soil respiration consists of both root respiration (R_a) and the microbial respiration from peat decomposition (R_h).

7.2 Uncertainties and data limitations

The estimations of peat forest carbon pools presented in Chapters 2-6 are subject to a number of uncertainties. Table 7.2 provides a brief overview of the most prominent data limitations and uncertainties and the key assumptions used to calculate carbon pools based on available data.

[13] NEE is equal to NEP plus sources and sinks for CO_2 that do not involve conversion to or from organic C, such as weathering reactions and precipitation or dissolution of carbonates (Lovett et al., 2006).

Table 7.2
Overview of key assumptions made in this study and consequent uncertainties of estimated carbon pools in peat swamp forests

Key issue	**Alternative used**	**Remaining problem**
Allometrics for biomass estimation are lacking for peat swamp ecosystems.	Use of allometric scaling developed for non-peat forest types, consisting of different species and perhaps different wood densities and/or architectural traits.	The use of non-peat allometrics likely increases the standard error around the estimation.
Baseline data are lacking for peat swamp ecosystems. The main missing components are: belowground living biomass (course and fine roots, mycorrhizas) and dead wood and coarse litter.	Use of available historical data of relatively undisturbed peat swamp forests as a reference value for biomass.	Variability in biomass within peat swamp forests is high. Hence, detailed biomass estimates should refer to clearly defined sites.
The peat soil carbon pool remains poorly quantified at the local level.	Assumption of peat depth, bulk density and carbon content based on the national average.	Due to the lack of peat depth measurements such assumptions could seriously over- or underestimate the real extent of the peat carbon pool.
Carbon content of CWD and litter is poorly documented.	Applying 50% rule for carbon content of dry weight biomass.	Exact carbon content remains uncertain
Lack of biomass estimates in peat swamp forests	Use of local forest inventory data	Small sample size in combination with assumptions for allometrics and wood density results in relatively high uncertainty

7.3 Conclusions

Although peat swamp forests are among the most rapidly disappearing forest types in the world, the importance of these forests for carbon sequestration and other ecosystem functions are widely recognized. Nevertheless, data availability on biomass and carbon content in the remaining peat swamp forests is scarce. First estimates of biomass can be made based on historical forest inventories but these will not represent the aboveground biomass in remaining peat swamp forests since the majority of peat swamp forests has been selectively logged over the last decades. Because peat swamp forests originally support high densities of commercial species new inventories are crucial to estimate the biomass losses that have occurred through timber extraction. On the other hand, in peat swamp forests on deep peat (>2m) most of the carbon is stored in the soil and changes in aboveground biomass may have less relative effect on the carbon stock of these systems, especially when forest is replaced by fast-growing plantations. In this case soil carbon losses occurring as a result of drainage-induced oxidation and peat fires forms the major source of carbon loss to the atmosphere.

The general conclusions concerning data availability and our estimates of carbon pools are summarized below.

Data availability:
- A limited number of research groups is involved in the estimation of carbon budgets of tropical peat lands, mainly focussing on aboveground living biomass.
- Data on biomass and greenhouse gas fluxes from peat lands is not widely published.
- Some data has been published in grey literature such as local reports and conference proceedings but because of political sensitivity data is not readily shared.
- Based on existing data it is possible to make estimates of the major forest carbon compartments excluding the peat soil.

Carbon pool estimates:
- Aboveground biomass (AGB) for peat swamp forests can be estimated based on available field inventory data using allometric equations. We found the AGB carbon store of relatively undisturbed peat swamp forests to be within a range of 132-199 t C/ha. However, several published figures suggest a much

broader range: 73-323 t C/ha in relatively undisturbed peat forest and 65-167 t C/ha in logged-over and (partially) degraded peat swamp forest. Effects of logging may be highly variable depending on logging intensities, rotation cycles and damage to the residual stand. Logging effects on carbon stocks are as yet unclear for this peat swamp forests.

- Allometrics can also be used to estimate root biomass based on stem diameters. Following this methodology we estimated that root biomass in relatively undisturbed peat swamp forest accounted for 29-45 t C/ha.
- Based on data sources from various tropical forest types, the coarse woody debris carbon pool was estimated to range from 16-56 t C/ha in unlogged peat swamp forest, with an average of 31 t C/ha.
- Litter biomass can be estimated based on peat swamp forest inventories and, more generally, based on litter-to-AGB ratios found in tropical moist forests. We estimated the litter pool in peat swamp forests to be around 5-12 t dry matter/ha (2-6 t C/ha).
- The peat soil is the most important reservoir of carbon in tropical peat lands. Recent estimates for Southeast Asia indicate that the average peat carbon store ranges from 252 to 3528 t C/ha in the different countries. The exact carbon store is spatially variable and depends mainly on peat thickness and bulk density. The quantification of this carbon reservoir is a priority issue in terms of the carbon budgeting in these ecosystems. Quantification of the carbon storage in vegetation will improve the total carbon estimate and decrease the statistical error, but more detailed quantification requires extensive inventories of the small biomass compartments that are less important in terms of carbon storage.

8 Recommendations

Carbon accounting is gaining an ever increasing role in global environmental policies, not only as a result of GHG reporting obligations under the Kyoto Protocol but also because new policies to cease high rates of deforestation and forest degradation are on the rise (e.g. REDD+, PES). Successful implementation of these policies requires substantial scientific input especially on the regional level. For many regions these data are as yet poorly available and further field measurements are needed. Because both carbon pools and carbon emissions may vary considerably on a spatial scale, the research focus should be on quantification of carbon pools and emissions related land use and land use change and linking these data to clearly defined spatial data. The most important improvement of current biomass data for peat swamp forests involves the allometric models used to estimate biomass. New allometric models need to be developed specifically for peat swamp forests.

This report presents values of biomass carbon stocks in relatively undisturbed peat swamp forests, which could be used as reference values. Nevertheless, as outlined earlier, most of the remaining peat swamp forests are to some extent degraded and it is especially these degraded areas that are being converted to agriculture (Sheil et al., 2009). Regardless of the degradation status of these areas, the quantification of biomass and peat carbon pools should be part of the environmental impact assessment.

There is scientific consensus on the high rates of greenhouse gas emissions related to the conversion of relatively undisturbed peat swamp forests to agriculture. Additionally, there is strong evidence that drainage of peat areas leads to permanent losses of carbon from the ecosystem, mainly through CO_2 emissions from peat oxidation and peat fires and leakage of dissolved organic matter (see also Verwer, 2008). The process of peat drying is irreversible, hence the loss of peat carbon through these processes will be permanent. Considering the emissions related to cultivation of tropical peatlands it is preferable to prevent further drainage and degradation of peat areas.

Emissions resulting from the conversion of degraded tropical peat forests are highly variable, depending on the level of disturbance. Degraded peat swamp forests are for a large part classified as 'conversion land' in national land use policies. Nevertheless, these areas can still play a crucial role as essential reservoirs of carbon. In terms of reducing carbon losses from land use change, the rehabilitation of degraded tropical peat lands is recommended as a preferred land use policy for future development. This point is supported by recent research which suggests that the peat swamp forest vegetation provides both the organic material and the hydrological conditions required for peat formation (Joosten, 2008). As a consequence, conservation of the peat swamp forest vegetation will be crucial in preserving the peat carbon store.

Literature

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Appendix 1 Collected data for different biomass compartments in peat swamp forests

Biomass compartment	Country/ Region	Data type	Inventory year	Location	Source	Available
Aboveground biomass	Malaysia	Plot data (species, tree density, diameter class)	1954-1958	Rejang Delta; Baram; Maludam; Lawas; Bintulu	Anderson, 1961, Appendix	Yes
	Brunei	Plot data (species, tree density, diameter class)	1954	Badas	Anderson, 1961, Appendix	Yes
	Malaysia	Basal area, tree density, height/diameter ratio	1981-1988	Maludam; Baram; Marudi; Btg.Tinjar; Sg.Sawai	Tie Yiu-Liong, 1990. p84	Yes
	Malaysia	Yield Plot data (species, tree density, diameter, height)	1971-2002	Maludam; Naman;	Forest Department Sarawak; Sarawak Forestry Corporation	Partly
	Malaysia	Research Plot data (species, tree density, diameter, height)	1971-2002	Maludam;	Forest Department Sarawak	Partly
	Malaysia	Ramin field experiments	2004	Lingga PF Naman FR	SFC/Alterra	Yes
	Malaysia	Inventory data	1973-1990	North Selangor PSF	Hahn-Schilling, 1994	Yes
	Malaysia	Summary of inventory data	1954-1961	Perak; Selangor; Johore	Wyatt-Smith, 1995	Yes
	Malaysia	1 ha plot data (species, tree density, diameter, basal area, leaf area index, aboveground biomass)	2006	Kota Samarahan, Kuching, Sarawak	Ipor et al., 2006	Yes
	Thailand	Total AGB values	Unknown	Narathiwat	Kaneko, 1992	Partly
	Indonesia	Total AGB values	Unknown	Kalimantan	Istomo et al., 2006	Partly
	Indonesia	Plot data and transect data	2007	Mawas conservation project, Central Kalimantan	Petrova et al.,, 2008	Partly
	Indonesia	Plot data (total AGB)	2001	Sungai Sebangau, Central Kalimantan	Waldes and Page, 2001	Partly
	Indonesia	Plot data and transect data (total AGB)	Unknown	Tanjung Putin NP, Central Kalimantan	Murdiyarso et al., 2010	Partly
	Indonesia	Plot data (total AGB)	Unknown		Ministry of Forestry Indonesia 2008	No
	Malaysia	Greenhouse experiment data of *Gonystylus bancanus* (diameter, height, growth rates)	2003-2004	Kuching	SFC/Alterra	Yes
	Southeast Asia	Global Wood Density Database	N/A	N/A	Chave et al., 2009	Yes
	Southeast Asia	ICRAF Wood Density Database	N/A	N/A	ICRAF website	Yes

Belowground biomass	Indonesia	Course and fine roots	2009	Sumatra	GTZ	No
Coarse woody debris	Malaysia	Plot data (density of tree stumps per species)	2009	Ever Herald Plantation, Sarawak	unpublished	Yes
	Malaysia	Decomposition rates in PC1, 4, 6 (large woody fragments at and below soil surface, small woody fragments)	1990	Sarawak	Tie Yiu-Liong 1990. pp. 182-183	Yes
Litter	Malaysia	Litter trap data (mass of leaves, twigs, fruits/seeds, flowers/inflorescense and trash)	2004	Maludam National Park, Sarawak	Sarawak Forstry Corporation; Alterra, Wageningen UR	Yes
	Indonesia	Litter trap data (total fine litter)	2007	Central Kalimantan	Sulistiyanto et al., 2007	Partly
	Malaysia	Decomposition rates in PC1, 4, 6 (leaf litter)	1990	Sarawak	Tie Yiu-Liong 1990. pp. 182-183	Yes
	Indonesia	Leaf litter fall and total litter fall	1997	Padang Sugihan, Sumatra	M.A. Brady, 1997	Yes
	Malaysia	Leaf litter fall and total litter fall	1979	Tasek Bera, P. Malaysia	Furtado et al., 1979	Yes
Peat soil	Malaysia	Area of organic soils	1979	Kuching and Samaharan, Sri Aman, Sibu, Sarikei, Miri and Bintulu, Limbang	Tie and Kueh 1979	Yes
	Southeast Asia	Area of organic soils (total peat area in 1998 and 2008, forested peat area in 1998 and 2008)	2009	N/A	Joosten 2009	Yes
	Malaysia	Peat profiles	2007-2009	Logan Bunut	Melling et al., 2008b	Yes
	Malaysia	Peat profiles	Unknown	Rejang Delta	Anderson, 1961	Yes
	Malaysia	Peat profiles	Unknown		Wyatt-Smith, 1995	Yes

Appendix 2 Institutes directly involved in biomass measurements in peat swamp forests

Biomass compartment	Involved institutes	Country
Aboveground biomass	Sarawak Forestry Corporation (SFC)	Malaysia
	Forest Department Sarawak (FDS)	Malaysia
	Centre for International Forest Research (CIFOR)	Indonesia
	International Centre for Agro-forestry Research (ICRAF)	Indonesia
	Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ)	Germany
	Alterra, Wageningen UR	The Netherlands
Belowground biomass	Sarawak Forestry Corporation (SFC)	Malaysia
	Forest Department Sarawak (FDS)	Malaysia
	Forestry and Forest Products Research Institute	Japan
	Centre for International Forest Research (CIFOR)	Indonesia
	International Centre for Agro-forestry Research (ICRAF)	Indonesia
	Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ)	Germany
Coarse woody debris	N/A	N/A
Litter	School of Science, Monash University, Selangor	Malaysia
	Sarawak Forestry Corporation (SFC)	Malaysia
	Alterra, Wageningen UR	The Netherlands
Peat soil	Soil Department Sarawak	Malaysia
	Tropical Peat Research Laboratory Unit	Malaysia

Appendix 3 Inventory method used by Anderson in the late 1950's

Anderson (1961) selected a number of peat swamp areas based on the presence of a sequence of forest types and the accessibility of the area, derived from aerial photographs. In the selected swamps a transect was cut from the perimeter to the centre and 53 half acre plots were enumerated at regular intervals, usually half a mile. Species were identified and 42 plots were classified to phasic community (Table A3-1). In all plots the diameter class at breast height (DBH, 4 ft. 6 ins. (=1.37 m)) was measured for all tree species >12 inch girth (9.7 cm DBH), using 3-inch classes. Trees with buttresses or stilt roots were measured at twelve inches (30 cm) above the obstruction. The height of individual trees was assessed in profile diagrams for all the forest types, following (Richards, 1952).

Table A3-1
The number of half acre plots in each of the identified phasic communities. PC=phasic community; N=number of plots; SD=Stem density

PC	Scientific name	English Name	***N*** **(# plots)**	***Avg. SD*** **(# stems/ha)**
1	*Gonystylus Dactylocladus Neoscortechinia* association	Mixed Swamp Forest	7	670.01
2	*Shorea albida Gonystylus Stemonurus* association	Alan Forest	12	649.89
3	*Shorea albida* consociation	Alan Bunga Forest	8	506.57
4	*Shorea albida Litsea Parastemon* association	Padang Alan Forest	12	711.25
5	*Tristania Parastemon Palaquium* association	-	2	1280.01
6	*Combretocarpus Dactylocladus* association	Padang Paya Forest	1	NA
Total			42	

Appendix 4 Overview of allometric models for estimating biomass

Table A4-1

Published allometric equations to estimate aboveground biomass (AGB) for moist and wet tropical forest. D=stem diameter at 1.3m height, WD=wood density

Equation	Area	source
$\ln AGB = -0.744*2.188*\ln(D)+0.832*\ln(WD)$	Lowland mixed dipterocarp forest, East Kalimantan, Indonesia	Basuki et al., 2009
$AGB = \exp[-2.00+2.42*\ln(D)]$	Lowland wet rainforest, French Guiana	Chave et al., 2001
$AGB = \exp[-0.37+0.333*\ln(D)]$	Old growth Amazonian rainforest, Brazil	Chambers et al., 2001
$AGB = \rho*\exp[-1.239+1.980*\ln(D)+0.207*(\ln(D)^2)-0.0281*(\ln(D)^3)]$	Wet tropical forest, various countries	Chave et al., 2005
$AGB = \rho*\exp[-1.499+2.148*\ln(D)+0.207*(\ln(D)^2)-0.0281*(\ln(D)^3)]$	Moist tropical forest, various countries	Chave et al., 2008
$\ln AGB = -2.13+2.53*\ln(D)$	Generic tropical forest, various countries	Brown, 1997
$AGB = 42.7-12.8*D+1.24*D^2$	Moist tropical forest, various countries	Brown, 1997
$AGB = 21.3-6.95*D+0.74D^2$	Wet tropical forest, various countries	Brown,1997
$\ln AGB = -1.97+1.24*(\ln(D)^2)$	Superhumid tropical forest, Araracuara, Colombia	Overman, 1994
$AGB=0.11*WD*D^{2+0.62}$	Mixed secondary forests, Sepunggur, Sumatra, Indonesia	Ketterings et al., 2001
$AGB=0.0829*D^{2.43}$	Secondary roadside forest, Sarawak	Kenzo et al., 2009

Table A4-2

Published allometric equations to estimate belowground biomass (BGB) for moist and wet tropical forest. D=stem diameter at 1.3m height

Equation	Area	Source
BGB = exp[-4.394 + 2.693 ln (D)]	Primary and secondary tropical forest, Colombia	Sierra et al., 2007
$BGB = 0.02186*D^{2.487}$	Primary lowland dipterocarp forest, Pasoh, Malaysia	Niiyama et al., 2005
$BGB = 0.0214*D^{2.33}$	Post fire secondary forest and roadside secondary forest, Sarawak, Malaysia	Kenzo et al., 2009
$BGB_{coarse\ roots} = 0.023*D^{2.59}$	Primary lowland dipterocarp forest, Pasoh, Malaysia	Niiyama et al., 2010

Appendix 5 High resolution aerial photographs of remaining peat swamp forests

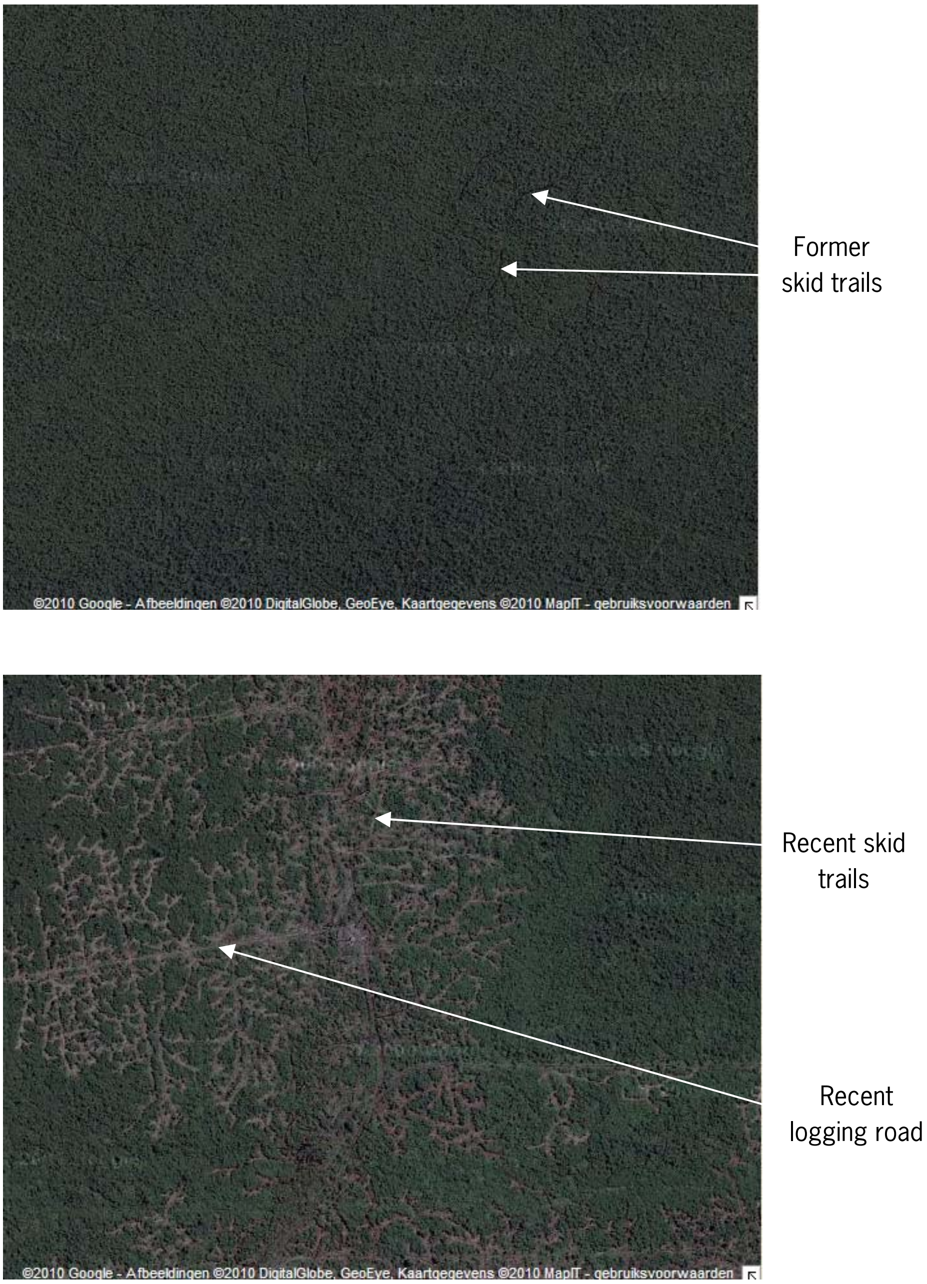
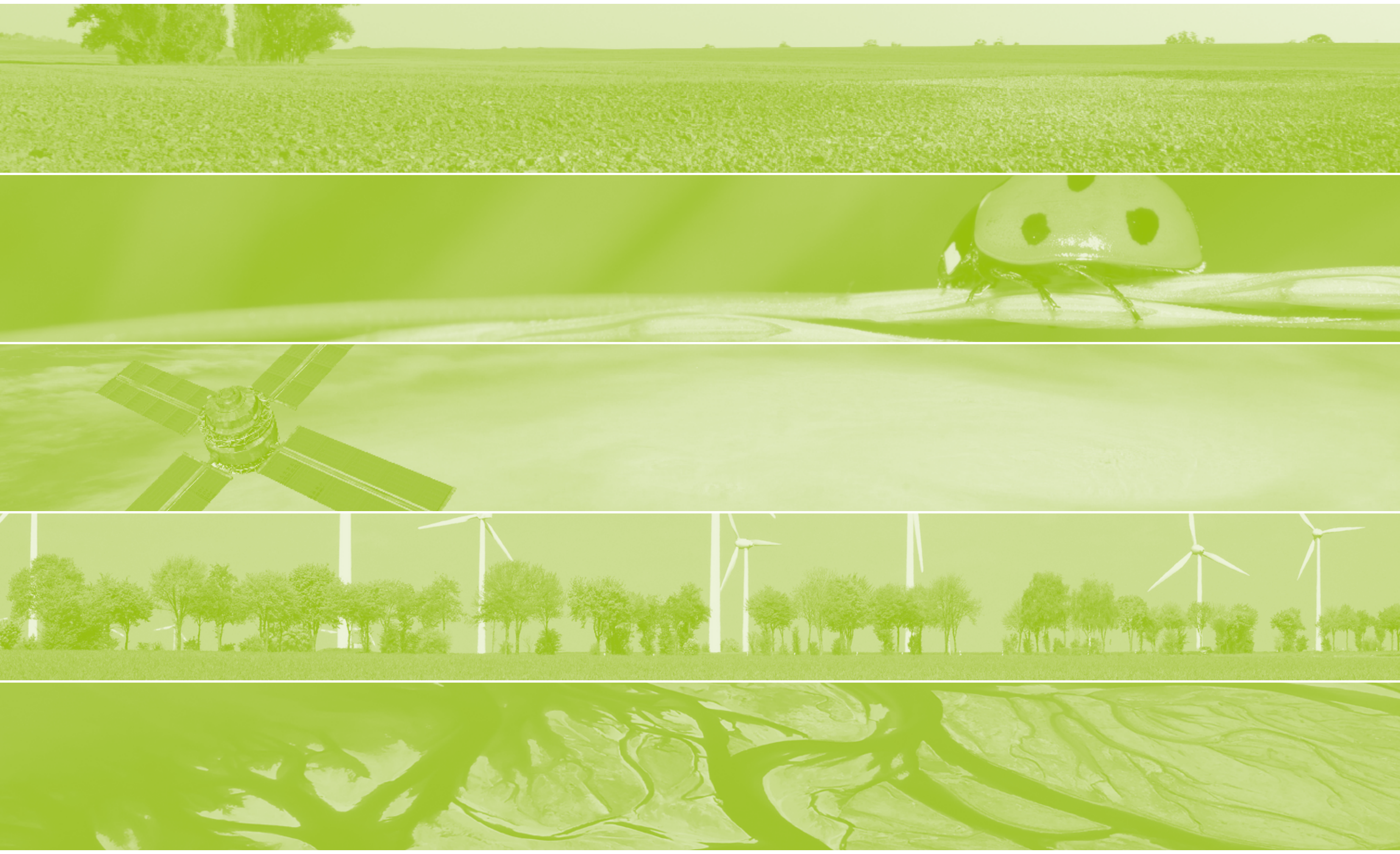


Figure A5-1
High resolution photographs of recovering peat swamp forest and recently logged peat swamp forest in the Maludam peninsula, Sarawak, Malaysia. (source: Google Earth © 2010). Such photographs may potentially be used to estimate aboveground biomass



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