WORKING PAPER 221

Protocols for the measurement, monitoring, and reporting of structure, biomass, carbon stocks and greenhouse gas emissions in tropical peat swamp forests

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Contents

List of figures and tables

Figures

Tables

Acknowledgments

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Quick reference guide for sampling carbon stocks

This reference provides an outline of approaches to measure ecosystem carbon stocks of peat swamp forest. This design and the sampling approach have been used throughout Kalimantan and Papua (Indonesia) as well as in Kosrae (Federated States of Micronesia) and the Peruvian Amazon (Figure 1).

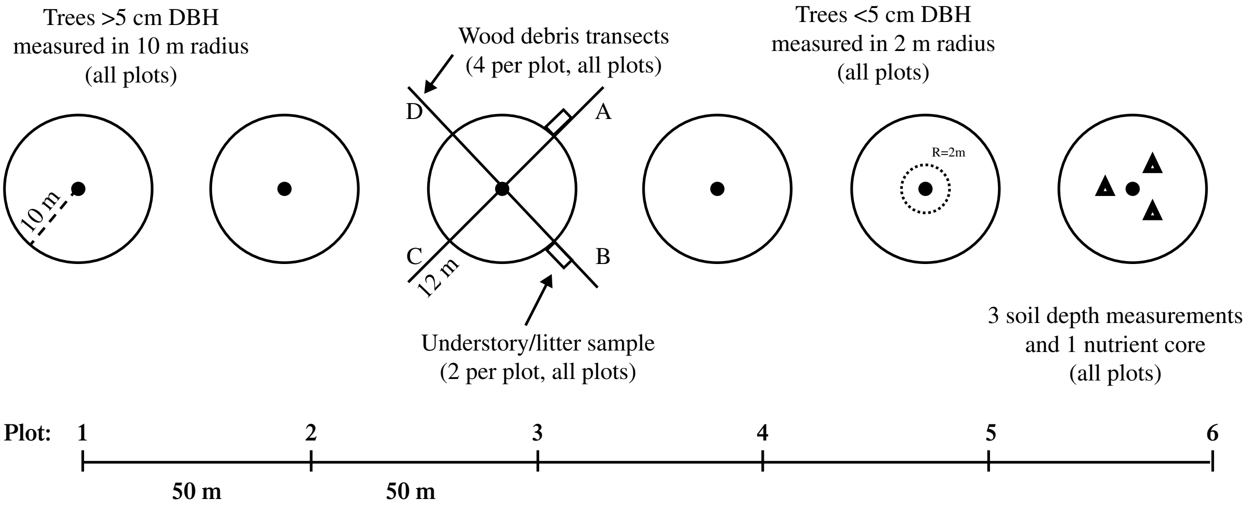


Figure 1. The plot layout for C stock assessments of tropical peat forests utilized throughout Indonesia with the Sustainable Wetland Adaptation and Mitigation Program (SWAMP) and the Kalimantan Wetlands and Climate Change Study (KWACS).

The first step following site selection is the establishment of a main transect that is 150 to 250 m in length and from which all sampling plots are established (Figure 1). Metadata to be recorded include Geographic Positioning System (GPS) locations of all plot centers and the compass direction of the transect.

Trees

Standing live and dead trees are measured in six plots each with a 10 m radius with centers located at equal distances apart along the main transect (Figure 1). This plot radius could be increased or decreased depending on tree density and the structure of the forests of a given region. The goal is for the plot size to most efficiently and accurately sample tree carbon pools. In general, a plot radius that captures an average of 10–20 trees per plot should be sufficient to adequately describe the tree mass of peat forests.

- Within each subplot measure the diameter of all trunks/main stems (live and dead) that are >5 cm at 1.3 m aboveground (diameter at breast height; DBH) or above the buttress.

Two-meter-radius nested subplots located in the center of each 10 m plot are used to sample small trees with a DBH of <5 cm. Care should be taken to leave large undisturbed (non-compacted) areas for soil sampling. Similar to above, the size of this plot can be optimized for the unique character of the forest areas to be sampled.

Downed wood

Downed wood mass is determined via the planar intercept technique. Four 12 m transects extending from each plot center and oriented to 45° angles off the main transect line are measured (Figure 1).

Downed wood diameter classes and recommended sample lengths are:
- *>7.5 cm diameter measured from 2 m to 14 m; measure diameter and record as "solid" or "rotten"*
- *2.5–7.5 cm diameter measured from 2 m to 7 m*
- *<2.5 cm diameter is typically combined with litter (below).*

Forest litter layer (undecomposed plant parts above the peat layer)

Litter is harvested in two 50 cm × 50 cm sample microplots that are placed at the 10 m point along downed wood transects A and B (Figure 1). The following is usually collected in the microplots:
- *Forest floor litter includes leaves, fruits, reproductive parts, bark fragments*
- *Fine wood (<2.5 cm)*
- *All herbaceous and woody understory with height <1.3 m (usually collected in a separate bag).*

Soil carbon pools

Soil carbon is measured through collection of samples extracted using a soil auger. One core is taken at (or close to) each subplot center. Soil/peat samples are collected at the midpoints of each plot at depth intervals of 0–15 cm, 15–30 cm, 30–50 cm, 50–100 cm and 100–300 cm, and at 200 cm intervals for peat exceeding 300 cm in depth. If possible, cores should be taken until true mineral substrates are reached.

Peat depth can be ascertained by using the sampling auger to measure the distance from the soil surface to underlying mineral soils.

1 Introduction

1.1 What is a peat swamp forest?

Peat swamp forests are oligotrophic terrestrial wetland ecosystems that have high soil acidity (pH less than 4.0) and are low in nutrients (Dwiyono and Rachman 2006). Peat forests are those with organic soil horizons (peat). The supply of water and nutrients to the ecosystem may come solely from rainfall (ombrogenous) or flooding and groundwater (minerogenous). High rainfall rates, low drainage and high temperatures with little seasonal variation influence peat formation in the tropics (Rieley et al. 1996). Peat swamp forests are usually inundated at least during the rainy season, which promotes anaerobic conditions affecting rates and pathways of decomposition and accumulation (Rieley et al. 1996).

The organic soil horizons (peats) are largely comprised of partially undecomposed plant materials that are carbon rich (sometimes >60% carbon). However, definitions of peat soils vary among authors and the ecosystem in which they work. Organic matter concentration and thickness are two main principles used to define peat soils. Definitions of peatlands and peat soils differ by the minimum thickness of organic matter and the concentration threshold of organic matter (IPCC 2014). The United States Department of Agriculture (USDA) Soil Taxonomy Classification categorizes peat soils as Histosols that contain more than 30% organic matter in a 40 cm organic layer within the upper 50 cm of the soil surface (Soil Survey Staff 2014). Maltby and Immirzi (1993) define peat soil thresholds of 50% organic matter and 30 cm peat depth. In tropical ecosystems, peat soils have been defined as those with a concentration >65% of organic matter and at least 50 cm thickness (Rieley and Page 2005). Joosten and Clarke (2002) reduced those thresholds to 30% of organic matter and 30 cm thickness. Andriesse (1988) defines peats as organic soils with more than 50% organic matter in the upper 80 cm of the soil. Regardless of definition, it is important to know the peat depth and carbon concentration of peat layers in order to determine soil carbon pools.

1.1.1 Extent and distribution

The majority of the world's peat forests are in temperate and boreal regions; tropical peatlands comprise about 10% of all global peatlands. Peat forests are located throughout the world's tropical regions. More than 50% (25 Mha) are likely located in Southeast Asia and have been estimated to account for more than three-fourths of the tropical peat carbon pool (Page et al. 2011b). Indonesia has more peat forest than any other country – about 14.9 million ha (Ritung et al. 2011).

The process of organic matter (peat) accumulation in tropical forests was likely initiated in the Late Pleistocene (~20,000 year BP; Jaenicke et al. 2010; Kurnianto et al. 2015). Peat accumulation reflects the conditions in which the rate of organic matter productivity exceeds that of decomposition. Slower rates of decomposition are related to the anaerobic or anoxic conditions of saturated soils (Chimner and Ewel 2005).

Tropical peat swamp forests provide a wide range of valuable environmental services and important ecological functions (Page and Rieley 1998). They are unique habitats for a wide variety of wildlife and fish species, including endangered and peat swamp specialist species. In addition, tropical peat swamp forests have been used for centuries for timber and non-timber forest products (fish, fruits, seeds, palms, honey, fungi and medicinal plants). Tropical peat swamp forests are important for flood control, regulation of water quality and water supply to local communities. Tropical peat swamp forests are also of value with respect to ecotourism and aesthetics. For example, Tanjung Puting National Park in Central Kalimantan is a famous ecotourism destination for orangutan (*Pongo pygmaeus*) conservation.

The ecosystem service that is the focus of this paper is carbon storage. Tropical peat swamp forests store an immense amount of carbon that should be considered a high priority in climate change mitigation strategies (Murdiyarso et al. 2013). But the quantity can great vary from on forest to the next. For example, ecosystem carbon stocks shallow peats near Tanjung Puting were as low as 558 Mg ha^{-1} while they were as high as 5591 Mg ha^{-1} in forests with peats exceeding 8 m in West Kalimantan (Novita 2016; Basuki 2017).

Currently, tropical peat swamp forests in insular Southeast Asia are being subjected to extensive forest conversion, most commonly to oil palm plantations (Hergoualc'h and Verchot 2011). Rates of deforestation and forest loss are among the highest of any tropical forest region or forest types in the world. For example, deforestation rates of 2.2% per year during 2000–2010 were reported by Miettinen et al. (2011). The remarkable fire season during the El Nino events of 2015 were certainly related to the widespread land cover change and forest degradation in peatlands.

2 Purpose and scope

The purpose of this publication is to provide the reader with the approaches needed to accurately measure, monitor and report species composition and structure, aboveground biomass and carbon stocks of tropical peat swamp forest ecosystems. We outline the rationale, design, field measurements, analysis and reporting for carbon assessments. While the focus is the accurate measurement of the carbon dynamics of tropical peat swamp forests, the approaches would generally be applicable to other wetland ecosystems. This is a companion paper to the CIFOR Working Papers on the protocols for the measurement and reporting of carbon stocks in mangrove forests (Kauffman and Donato 2012; Kauffman et al. 2014a). We developed methods for sampling mangroves at the same time as we developed methods for the quantification of carbon stocks of peat forests. Many approaches to sampling peat swamp forest wetlands are similar to those for mangrove wetlands, and much of the information presented here originally appeared in those documents.

The approaches described in this manual are relevant for those involved with monitoring restoration, adaptation or mitigation projects (e.g. participation in regulatory or voluntary carbon markets). There are a number of suitable methods and approaches for measuring forest carbon stocks. The most efficient and accurate approach would vary from one peat forest to the next. The focus here is consistency with international standards as per guidelines of the Intergovernmental Panel on Climate Change (IPCC) and relevant sourcebooks. For aboveground tree and root estimates, we focus on methods of field measurements that use allometric equations based on diameter and sometimes height for biomass estimates. Additionally, it should be noted that the technical aspect of quantifying forest carbon is one of several elements of carbon accounting schemes. Other important elements include social, political and economic factors. For example, this includes addressing permanence, leakage, governance, etc., which is beyond the scope of this paper. Definitions and information on those topics can be found in the IPCC guidelines (IPCC 2006, 2014) and associated sourcebooks (e.g. GOFC-GOLD 2015). Some of these guidelines cover information relating to carbon financing and carbon markets. Notable examples include IPCC (2003, 2006), Pearson et al. (2005, 2007) and GOFC-GOLD (2015). Recommended sources for information on forest sampling and the establishment of permanent plots and related sampling methods include Walker et al. (2012).

This document aims to provide a general conceptual background as well as specific instructions for the collection and analysis of carbon stocks and emissions in peat forest. Specific recommendations for overall sampling design, plot layout and measurements are based on the authors' experiences in measuring forest structure and carbon pools of peat forests. Other approaches using differing plot shapes, plot sizes, sample sizes, allometric equations and statistical analyses may be perfectly adequate. Project personnel may choose to adapt specific methods according to their local knowledge, training, resource constraints, other data collection needs or the evolving nature of IPCC and related sourcebook guidelines.

3 Conceptual basis

3.1 What needs to be measured for carbon stock assessments

Carbon stocks are the combined storage of carbon in terrestrial and wetland ecosystems (IPCC 2014; Fourqurean et al. 2014; GOFC-GOLD 2015). In simplified terms, forest carbon accounting tracks changes in carbon stocks caused by land-use and land-cover change: deforestation, degradation, conversion, restoration, etc. To quantify carbon stocks of peat forests, the ecosystems are conceptually subdivided into components that can be accurately measured using specific techniques for each pool (Figure 2). Some pools are more critical than others for obtaining accurate estimates of forest biomass and ecosystem carbon stocks. Carbon stocks can also be subdivided on the basis of susceptibility to loss by land-use or land-cover change. Generally, carbon pools most vulnerable to these changes are aboveground biomass and belowground pools in the top meter of the soil profile. However, in wetland organic soils, the entire belowground pool can be susceptible to loss via tidal and storm surges as well as decomposition following land-cover change. Further, Kauffman et al. (2014, 2016) report losses of soil carbon in mangroves at depths exceeding 200 cm. Basuki (2017) finds that peat soils >3 m in depth are affected by deforestation and land cover change. In order to accurately quantify total carbon losses and emissions from land use, peat soils should be sampled to mineral soils or at least to a depth of 3 m.

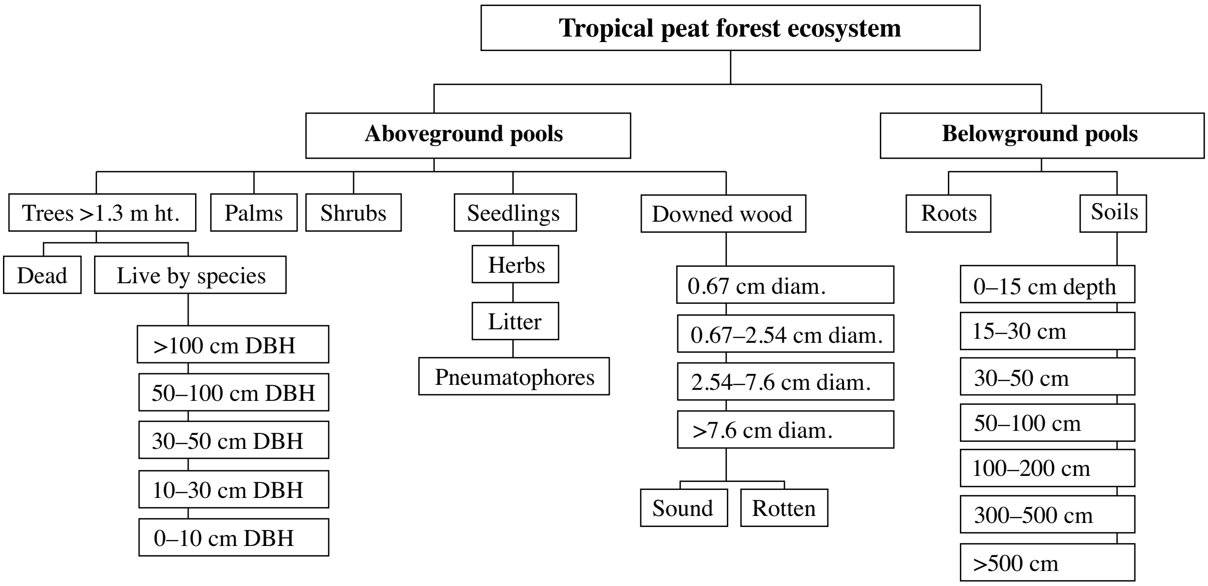


Figure 2. The breakdown of forest ecosystems into meaningful components that facilitate accurate measurement of total ecosystem carbon stocks.

3.2 Data types

Carbon inventories require two data types: activity data and emission factors data (GOFC-GOLD 2015). *Activity data* refers to delineation of the landscape into different cover classes such as forest, agricultural lands, grassland, or settlements, and the degree of transfer between them. Activity data usually rely heavily on remote sensing analyses to classify land-use types and to track changes between land uses over time. *Emission factors* refers to the changes in various C pools of a forest. Changes may occur due to land cover change (e.g. conversion of primary forest to agricultural uses), or due to changes within a land cover type (e.g. forest degradation due to selective logging). Accurate quantification of emission factors requires ground-based measurements of ecosystem carbon stocks. Such methods are the dominant focus of this report.

3.3 Tiers of assessment

For participation in REDD+ programs and other climate change mitigation strategies, the IPCC has established a tier system reflecting the degrees of certainty or accuracy of the C stock assessment (Table 1). Tier 1 uses IPCC default values of carbon stocks for different forest biomes and simplified assumptions. Tier 1 estimates may have a large error range of ± 50% for aboveground pools and ± 90% for soil carbon pools. For ecosystems such as peat forests that may have peat depths ranging from 0.5 to>12 m, the differences in soil carbon pools may vary by two orders of magnitude. For wetlands of the world, default values can be found in IPCC (2014). Tier 2 requires some country-specific carbon data for key factors. Tier 3 requires highly specific inventory-type data of carbon stocks partitioned into different pools, and repeated measurements of key carbon stocks through time, which may also be supported by modeling. The methods described in this report are relevant to approaches geared to achieving a Tier 2 or 3 level of assessment of C stocks.

Table 1. Tiers that may be used to assess carbon (C) emission factors. Adapted from GOFC-GOLD (2015).

Tier	Requirements
1	IPCC default factors
2	Country-specific data for key factors
3	Detailed inventory of key carbon stocks, and repeated measurements of stocks through time or modeling

The IPCC recommends that countries should aspire to reach Tier 3 where possible for the measurement of key carbon stocks/sources/sinks. Tiers 2 and 3 produce more credible estimates and may support higher rates of carbon payment. On the other hand, Tier 3 is more costly to implement and requires more professional capacity than other tiers.

Forest inventories or forest carbon assessments are conducted to determine forest carbon stocks. These inventories can then be repeated to quantify increases or decreases in carbon stocks through time. Two approaches to this estimation are the stock-change approach and the gain–loss approach (IPCC 2006; GOFC-GOLD 2015).

The stock-change approach estimates the difference in carbon stocks at two points in time or by comparison of an intact forest (reference site) with a degraded site. The assumption is that before disturbance, the degraded and intact sites were equal. The difference in carbon stocks between the two time periods or between the two sites is the carbon emission or gain. The stock-change approach is used when carbon stocks in relevant pools have been measured over time, such as in forest inventories (or with space substituted for time if comparing intact and degraded sites). Thus, Tier 3 assessments often rely on forest inventories and use stock-change methods. For example, carbon emissions from conversion of peat forest to oil palm plantations were estimated to be 3000 Mg C ha^{-1} in Central Kalimantan, Indonesia (Novita 2016) and 2132 Mg C ha^{-1} in West Kalimantan (Basuki 2017).

The gain–loss approach estimates the net balance of additions to and removals from a carbon stock. The gain–loss approach is used for assessments in vegetation C pools when annual data of carbon inputs and outputs such as biomass growth rates, decomposition and reliable data on wood harvests are available. The gain–loss approach is the method recommended by the IPCC together with the subsidence method to calculate annual net changes in organic soil C stocks. In reality, the mix of the two approaches to obtain the most accurate estimates of carbon stocks and emissions may be part of any assessment.

3.4 Developing a measurement plan

The steps to prepare a robust measurement plan should follow a rational series of steps to obtain justifiable estimates of carbon stocks/emissions (see Figure 6 in Pearson et al. 2005). Each of these steps must be carried out in a transparent, consistent and well-justified manner (Figure 3).

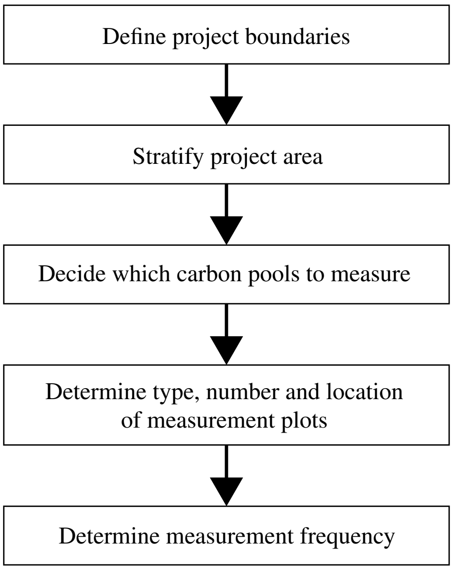


Figure 3. Suggested steps in the preparation of a carbon stock/emissions measurement plan.

Source: Pearson et al. 2005).

3.4.1 Step 1: Define the project area boundaries

The definition of area boundaries will depend on the scope and objectives of the project or study. Project areas for voluntary markets may be a single peat swamp forest. In contrast, regulatory markets may entail regional or even national-scale assessments. For broad-scale assessments, an approach that adequately samples a representative number and range of peat swamp types can provide an accurate carbon stock estimate. An efficient way to accomplish this is to stratify the project area into distinct forest types or communities.

3.4.2 Step 2: Stratification of the project area

Plot locations can be arranged randomly or systematically. Both approaches are acceptable and tend to yield similar precision. However, if some parts of the project area or strata have higher carbon content than others, systematic selection (stratification) usually results in greater precision than random selection. Systematic sampling is also widely recognized as credible (IPCC 2006; Pearson et al. 2007).

Stratification refers to the division of any heterogeneous landscape into distinct subsections (or strata) based on some common grouping factor (GOFC-GOLD 2015). The goal is to derive accurate carbon stock estimates in the most efficient manner possible. Stratification approaches used to quantify C stocks in the landscape may be based on: (a) vegetation or the natural cover, (b) abiotic factors that affect the productivity and species composition, such as geomorphology, hydrological features, climate, elevation and landform; and (c) anthropogenic factors, especially land use and land cover (Hairiah et al. 2011).

In landscapes with extensive land use, it will be important to stratify on the basis of degree of disturbance or land use history. For example, the National Standardization Agency of Indonesia (Badan Standardisasi Nasional 2011) categorized peat swamp landscapes into: (1) primary swamp forest, (2) logged or second-growth forest, (3) swamp forest regrowth dominated by low vegetation – shrubs grasses and ferns) and (4) non-vegetated areas. In a West Kalimantan carbon dynamics study, the peat landscape was partitioned into intact forest, logged and drained forest, degraded grasslands/shrublands and oil palm plantations (Basuki 2017).

Useful tools for defining strata include satellite imagery; maps of vegetation, soils or topography; and experience (Kauffman and Donato 2012).

3.4.3 Step 3: Determination of the carbon pools to be measured

In order to assess carbon stocks, accurate measurements of all relevant pools must be made (Figure 2). Peat swamp forest ecosystems can be broken down into meaningful compartments such as those suggested by IPCC guidelines (IPCC 2006). Forests can be divided into five general carbon pools: 1) aboveground biomass of live vegetation; 2) belowground biomass of live vegetation (roots); 3) dead wood; 4) forest floor (litter); and 5) soil. A carbon pool should be measured: (1) if it is large (≥5% of the total ecosystem carbon stock); (2) if it is likely to be affected by land use (a significant source of carbon emissions); (3) if the future land-use effects are uncertain; and (4) if the pool size is uncertain. (Kauffman and Donato 2012).

Trees are always included in the carbon pool measurement since they are heavily affected by land use, are relatively easy to measure and good allometric equations to determine biomass exist. Dead wood is often an important pool, especially following disturbances such as land-use change or tropical storms (Kauffman et al. 2009). Peat swamp forests may have deep, organic-rich soils (peat) resulting in large belowground carbon pools. The large size of these pools and their poorly understood vulnerability to land-use change make their measurement very important. Each of these components require different approaches and sampling intensities in the field to obtain an accurate estimation of the carbon stocks (Figures 4 and 5).

3.4.4 Step 4: Determine the type, number and location of measurement plots

Type. Whether plots are temporary or permanent depends on the purpose of the sampling. Permanent plots are usually established for the purpose of repeated measurements (e.g. to measure long-term changes of carbon stocks that may be required for participation in an appropriate mitigation activity). In permanent plots, the location is recorded with a GPS and boundaries may be clearly marked. Trees within plots are sometimes mapped and/or tagged (usually with numbered aluminum tags). Downed wood and other vegetation components may also be marked or tagged. Pearson et al. (2005, 2007) provide valuable reviews on approaches to monitoring calculations using tagged trees. In temporary plots, the objectives are usually for a single measurement of forest composition, structure and/or carbon pools. However, marking locations of these plots with a GPS may prove to be valuable for future studies. Permanently marked plots have greater long-term value and credibility when determining carbon stock changes through time. Examples of potential permanent plot designs suitable for peat forests can be found in Figures 6, 7 and 8.

Plot shape and size. There are many plot sizes and shapes that can adequately describe forest composition, biomass and ecosystem carbon pools. These may be either circular or rectangular. No single plot size and shape is optimal for all forest sites. Nested plot designs where large trees are measured within the largest plots, and smaller trees (i.e. those <5 cm DBH) are only measured in smaller plots provide optimal estimates at more efficient scales of measurement (Figure 4).

The shape and size of sample plots will involve a trade-off between accuracy, precision, time and cost. The objective in plot design is to achieve optimal shape, size and sampling intensity to accurately describe the ecosystem properties without needless redundancy.

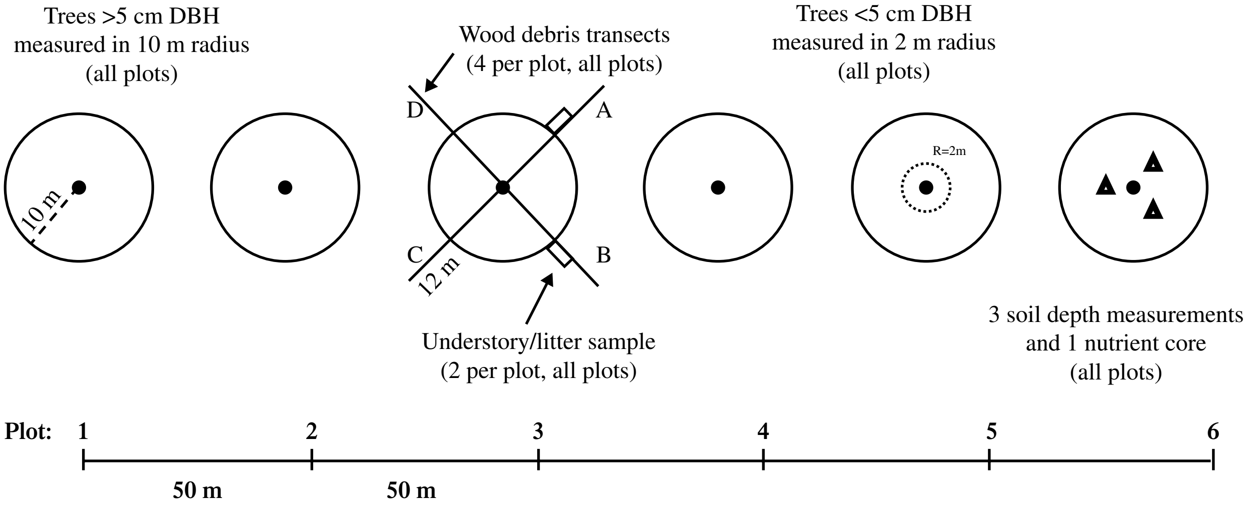


Figure 4. Plot layout for C stock assessment in tropical peat forest.

Note: This design has been used throughout Indonesia and in Peru and Kosrae, Federated States of Micronesia, to quantify ecosystem carbon stocks of peat forests (Warren et al. 2012; Novita 2016; Basuki 2017).

A single estimate of carbon stocks for a given forest stand or area should be measured in at least 4–6 plots. The sampling layout in Figure 4 has six plots arranged linearly; the observational/analytical unit is the mean of the plots. Many national inventories have a sampling design with 4–6 plots within each observational unit. Plot number is dependent upon the heterogeneity of the carbon stocks as well as the size of the plot that is sampled. The use of several replicated plots within a forest stand provides not only a more accurate assessment of ecosystem carbon stocks, but can also elucidate within-stand variation. Another important design consideration is how multiple sample units might be clustered together. Many well-established forest inventory programs, such as the United States' Forest Inventory and Analysis (FIA) program (USDA 2015), use clustered sample units, commonly referred to as 'subplots' (Figure 5B). Because they are spread across a larger proportion of the sampled site than a single plot of the same area, clustered plot designs capture more microsite variation in vegetation, soils, etc., thereby reducing among-plot variation and increasing overall precision.

In tropical forested wetlands such as peat forests and mangroves, movement by field personnel performing the survey is difficult due to the presence of pneumatophores, mud, deep channels, standing water, and extremely dense thickets of stilt roots, main stems and sometimes spiny vegetation. It is important to consider this reality in sample design and layout. The difficulties (and dangers) in movements encountered by field technicians, the desire to minimize trampling damage during measurements and movements, and the need to encompass the variation along the inherent gradients of peat forests and mangroves, led the SWAMP and KWACS teams as well as Donato et al. (2011) and Murdiyarso et al. (2015) to use a linear plot layout (Figures 4 and 6c) in their carbon stocks studies.

Linear designs (Figure 5C) are more efficient to establish and result in less trampling damage than do clustered plots such as those in Figure 6A and 6B. For these reasons, the SWAMP and KWACS teams have utilized linear transects that varied from 150 to 250 m in length (Figure 4). This means that six plots were established 30 to 50 m apart in each sampled peat forest. Distances between plots have varied due to forest characteristics and patch size.

Plots should be carefully referenced with a GPS and can be marked with flagging or a reference stake. If plots are established for long-term monitoring, then steel or polyvinyl chloride (PVC) stakes may be used to mark plot centers. Compass bearing and distance from a large reference tree could also be included, in case stakes are unexpectedly removed or destroyed.

The initial plot location is usually determined either randomly or systematically in a manner that is non-biased to the greatest practical extent. Some sites should be excluded if they are dangerous to sample or prohibitively difficult to access.

Location. It is important to avoid bias in where plots are established. This is best accomplished by determining plot locations prior to going to the field. The probability of plot location bias is lessened when a design consisting of multiple plots such as in Figure 5 is used.

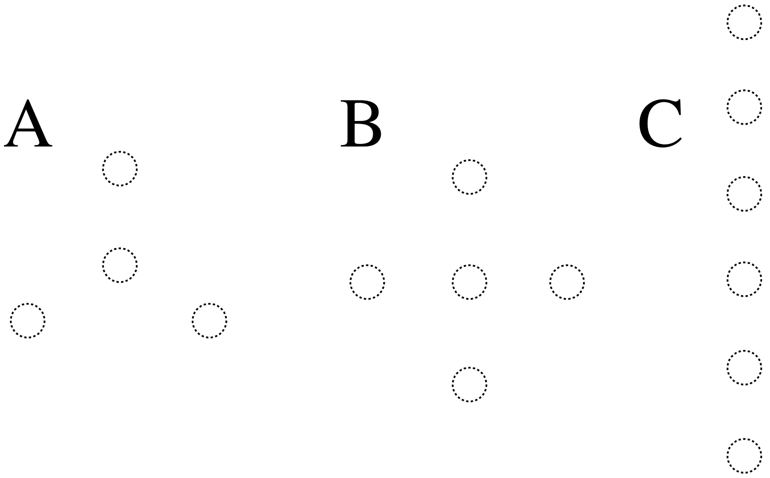


Figure 5. Examples of clustered sampling designs.

Note: The carbon stock is be derived from a series of plots. (A) and (B) are from the United States' Forest Inventory and Analysis (FIA), Forest Health Monitoring (FHM) and Current Vegetation Survey (CVS) programs (e.g. USDA 2015) and are used for efficiently assessing larger ground areas and increasing overall precision. (C) is the layout for many published SWAMP and KWACS funded studies (e.g., Kauffman and Cole 2010; Donato et al. 2011, Novita 2016) and is used for assessing directional gradients, reducing species contagion and increasing precision.

Number of sites or stands to be sampled. Any sampling effort should be carried out with statistical rigor if the project is to be credible and successful. The number of sites to be sampled should be determined by the desired precision level. This determination is best made based on local knowledge and experience, as well as simple statistical tests.

Typically, the desired precision level is to target within 10% of the true value of the mean at a 95% confidence level. To estimate the number of plots required, some prior knowledge of the variation in carbon pools within the project area is needed (e.g. from a previous inventory if available, or from a preliminary sample of 6–10 plots).

At the simplest level, the number of plots required should be calculated as follows:

$$n = \left(\frac{t \times s}{E} \right)^2$$

where n = the number of sample plots, t = the sample statistic from the t-distribution for the 95% confidence interval (t is usually set at 2, as sample size is unknown at this stage); s = standard deviation expected or known from previous or initial data; E = allowable error or the desired half-width of the confidence interval, calculated by multiplying the mean carbon stock by the desired precision (i.e. mean × 0.1 for 10% precision).

If the project area is stratified into different cover types (i.e. intact forest, logged forest, oil palm, etc.), the sample size determination must be conducted for each type within the classification. Finally, the total project sample size should be increased by about 10% to allow for plots that, in the future, cannot be relocated or are lost due to unforeseen circumstances.

3.4.5 Step 5: Determine measurement frequency

Establishing the time interval between sampling depends on the rate of expected change in the peat swamp forest being sampled as well as the requirements of the verification agency. The causes of carbon stock change that influence the frequency of sampling include unforeseen natural disturbances such as forest fires, natural rates of carbon sequestration, changes in land cover due to land-use activities, and alterations due to climate change. Frequency of sampling may also be determined by established requirements for participation in carbon markets. Frequency of monitoring also involves consideration of the costs and benefits of sampling. Frequent sampling (i.e. annually) may yield the best estimates but is costly and is likely more frequent than is needed to monitor changes. Given the dynamics of forest processes, forests are generally measured at intervals of about 5 years (Pearson et al. 2005, 2007). For carbon pools that respond more slowly, such as mineral soils, even longer periods can be used – perhaps 10 or 20 years between sampling events. A disadvantage of long intervals is the risk of natural or anthropogenic disturbance, the effects of which may be missed with widely spaced monitoring intervals (Pearson et al. 2007).

4 Field procedures

Metadata include the general Information to be collected at each plot. General plot information of value may include:

- plot identification – name and/or number of the sampled plot or stand
- location of plot/sampled stand and other identifying information (e.g. management district, etc.)
- plant community/site type: e.g. intact forest, logged forest, grassland, oil palm or other (if other, describe)
- ecological condition – evidence of any recent or past disturbances such as:
  - timber harvest
  - hydrological status – drained or undrained
  - recent wildfire
  - other disturbances – natural (e.g. disease, insects, etc.) or anthropogenic (e.g. roads, trails, non-timber harvest or use, etc.)
  - plantations/restoration sites – age of planted trees
- date of sampling
- GPS coordinates and precision (± X m);
- directions to the plot location
- crew members present.

The following general plot information may also be useful to record:

- topography
- geomorphic setting: river banks, peat dome, interior or basin, etc.
- soil surface description: wet, dry, litter presence, etc.

In addition to descriptive data, it is valuable to establish permanent photo points in plots.

4.1 Specific measurements (biomass and carbon pools)

4.1.1 Trees

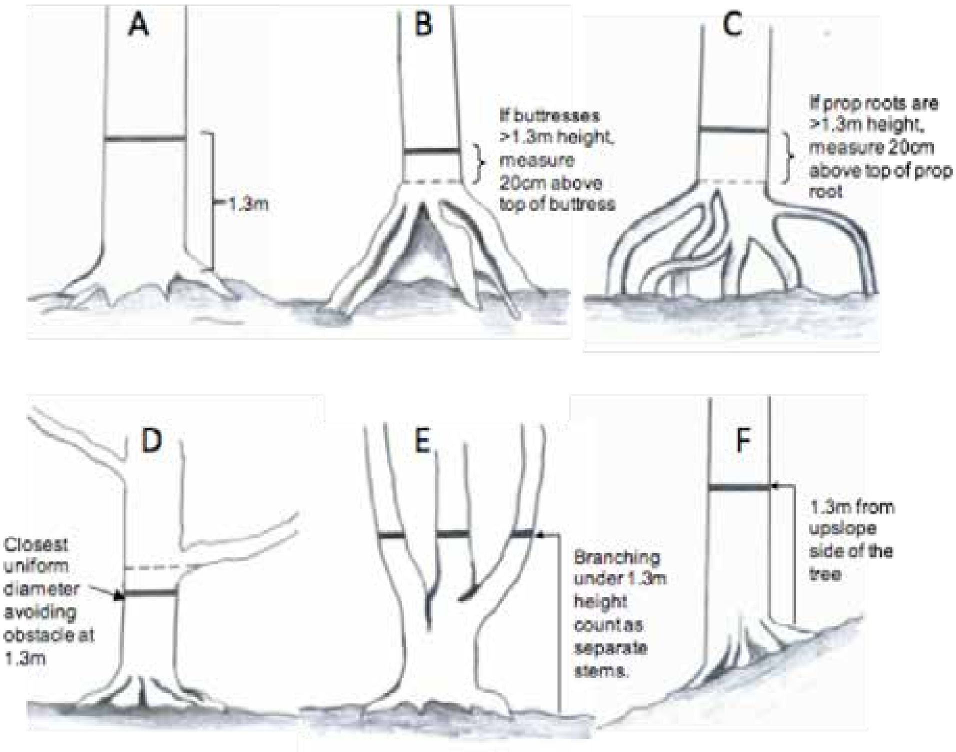
Trees are almost always measured in inventories. The most important variable to measure is the main stem (trunk) diameter. Identification of the tree species (for wood density) greatly improves accuracy of the mass determination. Tree heights are also sometimes measured. However, accurate height measurements in the field are difficult in dense tall tropical forests including peat forests.

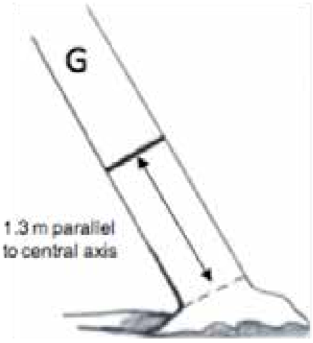
Tree mass and carbon pools are determined using allometric equations where the main stem diameter (and perhaps wood density and height) are the independent variables used to determine mass. For uniform trunks, the diameter is measured at 1.3 m above the soil surface. This height is termed the “diameter at breast height” (DBH; Figure 6). Crew members measuring trees are suggested to determine where the point of measurement (DBH) is on their own body. Measuring tapes calibrated to convert circumference to diameter (DBH tapes) are preferred to be used to measure tree DBH. Specialized tree calipers can also be used (Figure 10).

Many trees encountered in peat swamp forests have modified root systems and buttressed trunks where measurement of the diameter at 1.3 m may not yield an accurate estimate of mass. Several guidelines deal with the measurement of such trees (Figure 7). Typically, diameter measurements are made at 20 cm above the buttressed or irregular part of the trunk.

Figure 6. Measuring tree diameter using a DBH tape.

Note: The tape is calibrated to convert circumference to diameter. The diameter measurement is read where the "0" line meets the other side of the tape. In this case, DBH is 36.1 cm.





Guidelines to measuring diameters of irregular trees

- A) Straight tree measured at 1.3 m aboveground.
- B) Buttresses: If buttress height is >1.3 m above the ground, the diameter is measured 20 cm above the top of the buttress.
- C) Prop roots: If height of prop roots exceeds 1.3 m, diameter is measured 20 cm above the highest prop root.
- D) Abnormal boles: If there is a bole abnormality such as swelling or branching, measure above or below the abnormality.
- E) Branching: When there is branching of the boles below 1.3 m, measure the DBH of each bole.
- F) Measurements on slopes: Measure at 1.3 m. aboveground on the upslope side of the tree.
- G) Leaning trees: Measure 1.3 m above the point where the bole emerges from the soil.

Figure 7. Measurement of trees with modified root systems.

Note: Figure is modified with permission from Manuri (2009).

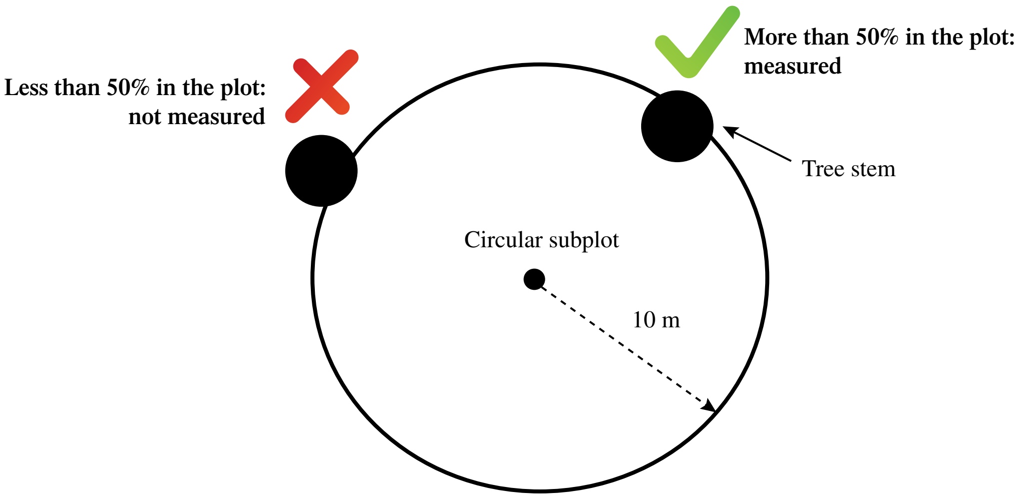


Figure 8. Determination of when to include a tree on the plot boundary in the measurements.

Note: If a tree's main stem (trunk) intersects the plot boundary by more than 50% in the plot, it is measured (green check). If less than 50% of the tree base is in the plot, it is not measured (red X).

Boundary trees. Some trees will invariably be located on the plot boundary (Figure 8). If a tree's base is more than 50% outside of the plot, it is not measured. If the tree base is more than 50% inside the plot, it is included in measurements. This is one of the advantages of a circular plot. As a circle has a lower edge-to-area ratio, there are fewer conflicts about whether to include individual trees or not.

Tree Identification. If possible, trees that are measured should be identified to the species or genus level. Trees can also be identified using local common names, and taxonomy can then be determined by taxonomists. Voucher specimens should also be taken in the field to verify the accuracy of the field identification. Proper tree identification will increase the accuracy of C storage estimations, since species- or genus-specific allometric equations or wood density values can be used to refine estimates (Manuri et al. 2014). Analyses of forest community composition can also be performed if trees are accurately identified.

4.1.2 *Dead trees*

Standing trees are separated into live and dead trees. Dead trees (defined as trunks or main stems that are no longer living, and actively decaying) can be separated on the basis of decay status as follows (Figure 9). This separation facilitates more accurate measurements of biomass:

- Status 1: Small branches and twigs are retained; resembles a live tree except for absence of leaves.
- Status 2: No twigs/small branches; may have lost a portion of large branches.
- Status 3: Few or no branches, has standing trunk or main stem only; the main stem may be broken.

For Status 3 dead trees, record the diameter of the tree and total tree height (using a laser tool, rangefinder, clinometer or estimate). Similarly, for stumps (harvested tree bases), the base diameter and height is measured.

4.1.3 Small trees (saplings)

Understory trees (such as those <5 cm DBH but more than 1.3 m in height), known as saplings, can found in very high densities in tropical peat forests. As such, they are most efficiently measured in smaller nested plots (Figure 4). Often, smaller-diameter trees, especially those in very dense stands, can be measured quickly and precisely with a caliper rather than DBH tapes (Figure 10).

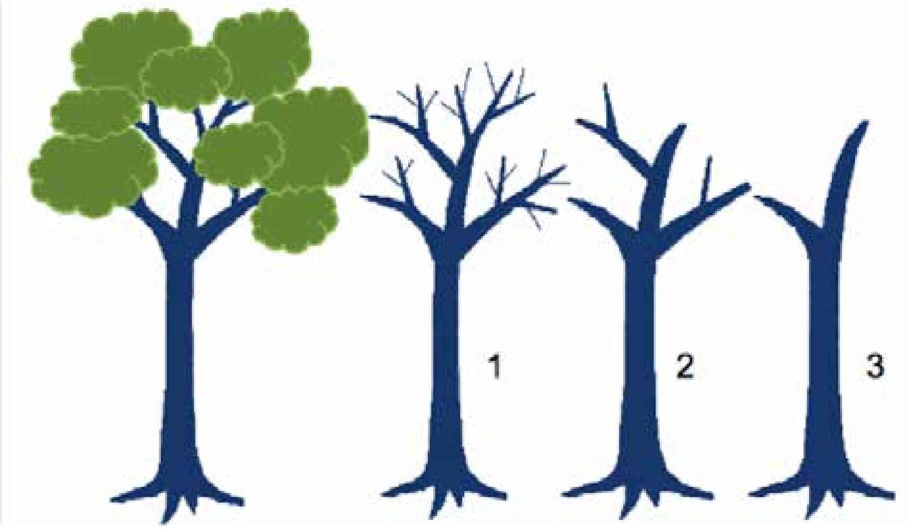


Figure 9. Examples of dead tree decay status for tropical forest trees.

Note: 1) Status 1 trees are recently dead and maintain many smaller branches and twigs. 2) Status 2 trees have lost small branches and twigs, and a portion of large branches. 3) Decay Status 3 applies to standing 'snags,' where most branches have been lost and only the main stem remains. The main stem is often broken. Reprinted with permission from: Manuri (2009) .

Figure 10. Measuring tree diameter at breast height using a tree caliper.

4.1.4 Non-tree vegetation

Non-tree vegetation includes palms, lianas and herbaceous vegetation. Biomass of these components may be determined either through nondestructive sampling, or in the case of herbaceous vegetation, destructive harvests. Herbaceous vegetation includes ferns, grasses, sedges, rushes and broad-leaved herbs.

4.1.5 Oil palm

Oil palm (*Elaeis guineensis Jacq*) plantations are now a very common cover type in tropical peat forest landscapes of Southeast Asia. Oil palm is most abundant in Indonesia and Malaysia (Figure 11; FAOSTAT 2015). Methods for the measurement of carbon stocks in oil palm plantations are included in this manual because they are among the principal drivers behind peatland deforestation and now occupy thousands of square kilometers of land once occupied by peat forest (Koh and Wilcove 2008). In Indonesia, it is estimated that 80% of oil palm plantations occur on mineral soil and 20% on peat soils (Wahyunto et al. 2013). Page et al. (2011a, 2011b) report that oil palm plantations covered 10% of the peatland area in Indonesia (excluding Papua) in 2010.

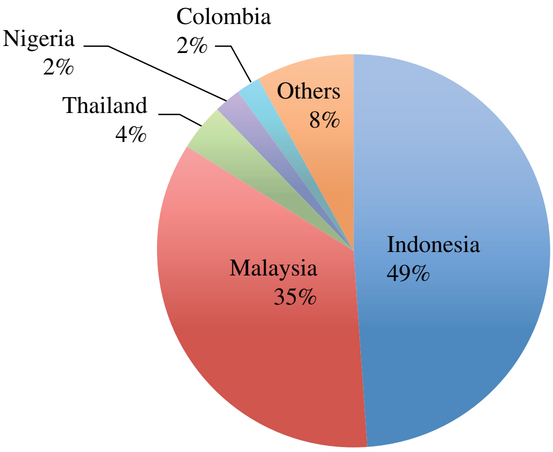


Figure 11. Most of the world's oil palm production occurs in SE Asia and many plantations are located on peat soils.

Note: The figure is based on 2013 statistics (FAOSTAT 2015).

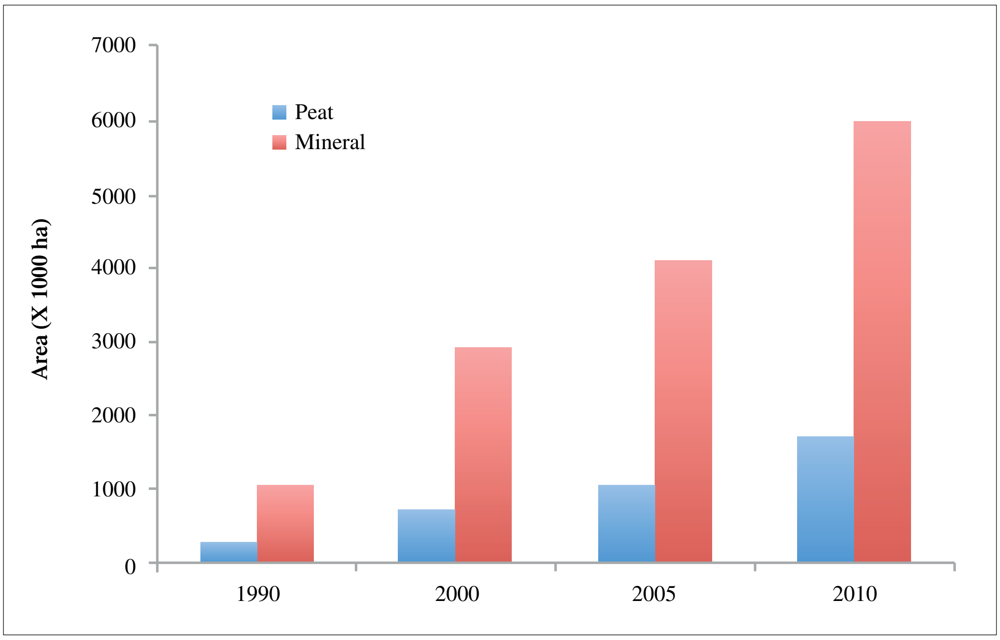


Figure 12. Oil palm expansion on mineral and peatland soils in Indonesia during 1990–2010 (modified from Agus et al. 2013).

The mass of palms including oil palm is usually predicted through measurements of height and trunk diameter. For example, Dewi et al. (2010) provide a method to determine oil palm mass based on measurements of stem height and/or age:

The equation of mass based on trunk height is:

$$W = 0.0976H + 0.0706 \ (r^2 = 0.73)$$

The equation of mass based on palm age is:

$$W = 5.0141a + 15.947 \ (r^2 = 0.88)$$

Here, H is stem height (cm), a is age of the oil palm, and W is the aboveground biomass (Mg ha^{-1}; Dewi et al. 2010). Height can be manually measured with a tape, a clinometer, or be estimated. There are even phone apps that facilitate tree height measurement.

Yulianti et al. (2010) also provided an allometric equation to determine oil palm biomass based on measurements of main stem diameter and height. The equation to determine biomass is:

$$W = 2.29e^{-5} * D^{1.55} * H^{1.29} \ \ (r^2 = 0.99)$$

where: W = the aboveground biomass, D is stem diameter including rachis and H is total height.

This equation was derived from palms of ages ranging from 1 to 18 years on peat soil with a sample size of 34.

Khasanah et al. (2011) developed an allometric equation to estimate biomass of oil palms based on the height of oil palms growing in peat soils:

$$AGB = 0.0939 * H + 0.0951$$

where AGB is the aboveground biomass (Mg), and H is the palm height (m).

The C stock in oil palm plantations is calculated by multiplying the dry matter weight (AGB) by a C content of 0.418 (Lamade and Setiyo 2012).

4.1.6 Lianas

Lianas or vines can be a significant component of some peat forest ecosystems and their measurement may be important. Lianas may vary in size from small plants only a few millimeters in diameter to large individuals 30 cm or more in diameter whose height reaches the highest parts of the canopy. Most studies have used liana diameter to determine biomass. Upon calculation, liana biomass can be converted to carbon mass using a locally derived carbon concentration if available. Like most components, it would be best to acquire exact measurements for liana carbon concentration from the project area. The carbon concentration of lianas in tropical forest uplands has been reported to be about 46% (e.g. Jaramillo et al. 2003). Thus, a default value for carbon concentrations of lianas could be 0.46.

A number of equations to determine liana biomass exist that have been developed from upland forests (Schnitzer et al. 2006), but structure and allometric equations are not likely to vary to a great extent for lianas in peat forest. Liana biomass can be estimated using the following general allometric equation:

$$B = D^{2.657} * e^{-0.968} * \ln(D)$$

where B = biomass (kg), D = diameter (cm) of the liana measured 130 cm from the root–soil surface interface; $R^2 = 0.69$, N = 424 (Schnitzer et al. 2006).

Another general equation for lianas in tropical uplands of China was presented by Lu et al. (2009):

$$B = 0.1498 + 1.7895 * \ln(D) * \ln(D)$$

where B = biomass (kg), D = diameter (cm) of the liana 130 cm from the root–soil interface; $R^2 = 0.87$, N = 25 (Lu et al. 2009).

Finally, Gehring et al. (2004) provides an allometric equation for lianas based on 561 samples with diameters ranging from 1 to 136 mm:

$$\ln(\text{Total biomass}) = -7.114 + 2.276 * \ln(\text{Diameter})$$

4.1.7 The forest floor litter and understory vegetation

The understory is defined as all standing vegetation that is <130 cm in height. This includes the biomass of low shrubs, tree seedlings, herbs, ferns and nonvascular plants. Forest floor litter is defined as the surface detritus and recognizable organic matter that lies above soil/peat horizons, excluding larger fragments of wood. Forest floor litter consists of fallen leaves, seeds, fruit, bark fragments and small pieces of wood. The litter layer and understory vegetation represent a small, but important fraction of the ecosystem C stock of peat swamp forests. In addition, the proportion of total aboveground C stored in understory and litter pools can be significant in deforested and abandoned sites and especially in land cover types such as abandoned farm lands where grasses, ferns and shrubs are dominant.

The rate of litter accumulation on the forest floor is indicative of other ecosystem processes, such as the relationship between productivity and decomposition. Litterfall rates are usually determined through measurements of litterfall accumulating in traps or designated areas and measured on a monthly basis; this is only conducted if litterfall rates or dynamics are an objective. In contrast, litter and understory vegetation biomass is usually measured via harvesting and weighing all materials found in microplots. The sample area of microplots used to sample litter varies among studies, but usually ranges from 25 cm × 25 cm to 50 cm × 50 cm. Microplots of this size are easily made using a folding ruler, made of PVC or small-diameter steel bars. The exact inside dimensions of the microplot should be measured and recorded to convert litter/understory biomass to standardized units such as kg m^{-2} or Mg ha^{-1}.

In the SWAMP and KWACS studies, microplots were located along two transects 10 m away from each of the six plot centers (i.e. a sample size of 12 for each sampled site; see Figure 4). This systematic approach eliminates bias in sample location. All litter and understory materials are collected, separated, and placed in labeled and sealed plastic or paper bags. Paper bags should be avoided if surface litter is wet. If plastic bags are used, samples should not be left enclosed too long, to avoid mold growth. Small twigs should be broken into pieces to avoid puncturing the bag and losing a portion of the sample. Pruning shears or a knife can be used to cut around the microplot to ensure that only the litter occurring within the microplot is collected. Samples are then transported back to a laboratory where they are dried to a constant weight to obtain mass on a dry weight basis. Alternatively, it may be easier to obtain a ‘wet’ sample weight in the field. Then a small representative subsample can be taken to the laboratory and dried to determine moisture content for determination of mass on a dry weight basis.

Figure 13. Sampling litter in a Central Kalimantan tropical peat swamp forest.

Note: All litter and seedlings within the plot are harvested. Often it is easier to obtain the wet sample weight in the field. Then a small representative subsample (also weighed in the field) is transported to the laboratory and dried to determine moisture content. This is required to calculate the mass on a dry weight basis.

4.1.8 Dead and downed wood

There are several guides that describe methods for the determination of downed wood volume and mass (Brown 1971; Harmon and Sexton 1996; Waddell 2002). Dead and downed wood can be a significant component of aboveground carbon pools, particularly following logging or fire (Figure 14). Dead wood also has a number of important ecological functions in forest ecosystems. To accurately assess ecosystem carbon pools and influences of natural and human disturbances, dead and downed wood is an important variable to measure.

Downed wood is usually sampled using either plot-based methods or the line-intersect method (Brown and Roussopoulos 1974; Waddell 2002). Plot-based approaches include measurement of the diameter and length of all pieces within larger macroplots. Here, the length and diameter (at both ends) can be used to calculate volume. Multiplying volume by the dead wood's specific gravity yields mass. This is practical for the largest pieces of downed wood but not for small wood particles.

A commonly used approach to determine the mass of all sizes of downed wood is the nondestructive line-intersect technique (van Wagner 1968; Harmon et al. 1996). The line (or planar) intersect technique involves counting intersections of woody pieces along a vertical sampling plane (transect). In each plot, a series of transects are established to measure downed wood mass (Figure 4). The plot design in Figure 4 consists of establishing four transects in each of six macroplots to determine wood mass (N=24 transects/sampled forest). These approaches have been widely used to determine wood mass in intact and slashed tropical forests in many parts of the world (e.g. Kauffman et al. 2009). All wood pieces that intersect the transect plane are measured.

Any downed, dead woody material (fallen/detached logs, twigs, branches, prop roots or stems of trees and shrubs) that has fallen is measured using this technique. Wood pieces of different size classes can be separated into different classes and measured along the transect (Figure 15). Downed wood has often been separated into four size classes based on the timelag constant (Brown 1971): 1-hr, 10-hr, 100-hr

Figure 14. Large quantities of downed wood are often present following logging or fire in peat forests.

Note: This is a forest site that was slashed and burned before conversion to oil palm plantation in central Kalimantan, Indonesia (photo by B. Kauffman).

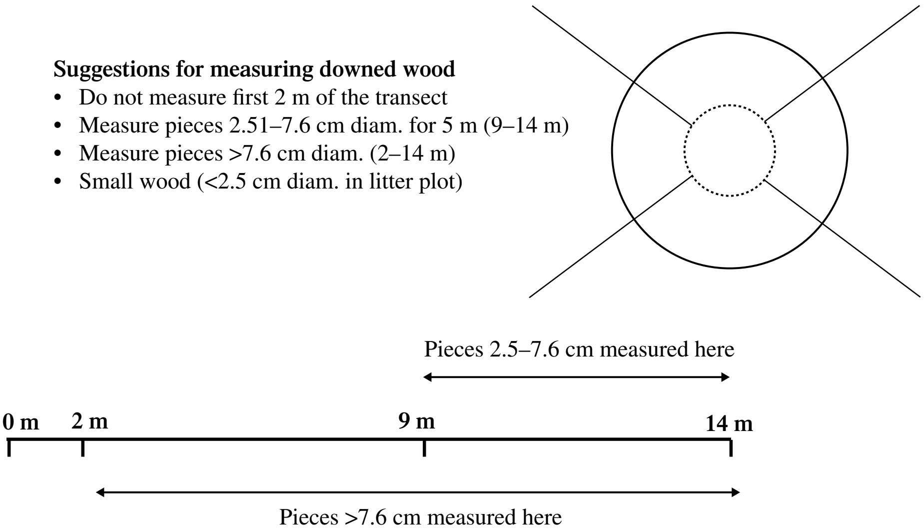
Table 2. Commonly used size classes of dead and downed wood based on the diameter of the piece of wood. Partitioning the wood into size classes improves the efficiency of measurement.

Description	Timelag	Diameter
Fine	1 hr	0–0.6 cm
Small	10 hr	0.61–2.5 cm
Medium	100 hr	2.51–7.6 cm
Large	1000 hr	>7.6 cm

and 1000-hr size classes; or alternatively, fine, small, medium and large wood particles (Table 2). These size classes are regularly used in forest inventories (Brown 1971). An aluminum downed-wood gauge or caliper can be used to determine the size class (diameter) of each piece encountered (Figure 16).

The transect length for the largest wood pieces may vary from 10 to 20 m depending on wood abundance (Figures 15 and 16). Because smaller pieces can be very abundant, they are usually sampled along nested subsections of each transect. In the example in Figure 15, fine pieces (1-hr timelag) are only tallied along 2 m of transect. Small pieces (10-hr timelag) are only tallied along 5 m of transect. Medium pieces (100-hr timelag) are tallied for 10 m along the transects. In contrast to the smaller wood pieces, the diameter of each large wood piece (1000-hr timelag) encountered along the entire transect is recorded (Figure 15). Length of the sampling plane can vary for each size class depending on the quantity of the wood pieces in the ecosystem.

Fine, small and medium pieces are usually tallied as the number of pieces that cross the transect. They are tallied separately for each size class. No diameter measurement is needed, as an average diameter

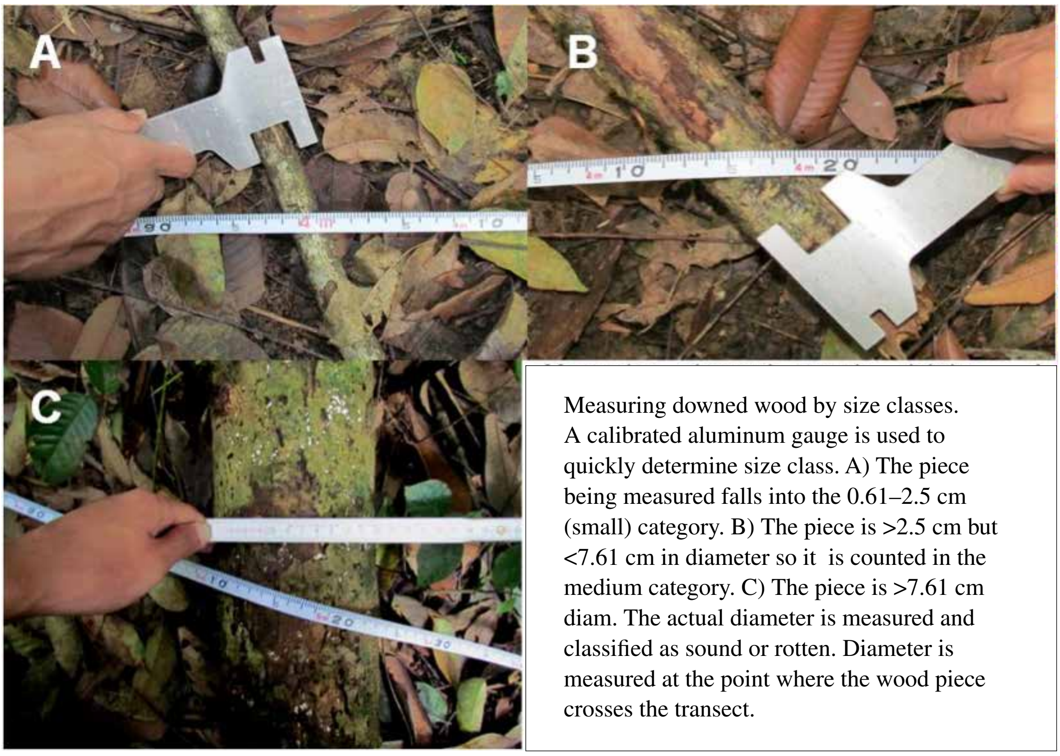


Suggestions for measuring downed wood

- Do not measure first 2 m of the transect
- Measure pieces 2.51–7.6 cm diam. for 5 m (9–14 m)
- Measure pieces >7.6 cm diam. (2–14 m)
- Small wood (<2.5 cm diam. in litter plot)

Figure 15. Example of a transect for sampling downed wood in peat forest using the line-intersect technique (also referred to as the planar-intercept technique).

Note: For ease of establishment, the transects begin in the center but the first 2 m are not sampled. The diameter of each large wood piece (>7.6 cm diam) encountered along the transect is measured over the range of 2–14 m. Smaller diameter pieces (2.5–7.6 cm diam) are counted along 5 m of the transect over the range of 9–14 m. This minimizes oversampling in the center. Smaller pieces of wood (<2.5 cm diam) can be ignored in the planar intersect and be combined and sampled with the litter fraction.



Measuring downed wood by size classes. A calibrated aluminum gauge is used to quickly determine size class. A) The piece being measured falls into the 0.61–2.5 cm (small) category. B) The piece is >2.5 cm but <7.61 cm in diameter so it is counted in the medium category. C) The piece is >7.61 cm diam. The actual diameter is measured and classified as sound or rotten. Diameter is measured at the point where the wood piece crosses the transect.

Figure 16. Measuring downed wood using a calibrated aluminum gauge to determine size classes.

Note: Larger pieces (C) are measured with a tape measure. Note in photo C that the diameter is measured where the transect crosses the center of the downed wood.

(or quadratic mean diameter) is usually used for calculation of the mass of these smaller size classes. Large pieces require more data to be collected. The diameter of each piece crossing the transect is measured at the point where the transect line crosses the midpoint of the wood piece (Figures 16 and 17). Also, the decay status is recorded as either sound (machete bounces off or only sinks in slightly when struck) or rotten (machete sinks in deeply and wood is crumbly with significant loss).

Important rules in measuring downed wood include:
- Dead trees that are standing are not measured using the line-intersect technique.
- Dead branches and stems still attached to standing trees or shrubs do not count.
- The transect tape must intersect the central axis of the wood piece for it to be counted. This means that if the tape only intersects a corner at the end of a log, it does not count.
- Any piece can be recorded multiple times if the tape intersects it more than once (e.g. a curved piece, or at both the branch and the stem of a fallen tree).
- In a practical sense, only the large wood fraction (>7.6 cm) is a significant C pool (Kauffman and Cole 2010; Kauffman et al. 2011). It may be simpler to include the smaller wood pieces (<7.6 cm diameter) in the litter sample, and only measure the large wood pieces (>7.6 cm diameter) in the transects.

4.1.9 Soils/peats

Soils of the peat swamp forest are an extremely important carbon pool as they often comprise well over 90% of all carbon stored in these ecosystems. To accurately measure the soil carbon pool, three parameters must be quantified: 1) depth of the peats; 2) soil bulk density; and 3) organic carbon concentration. Careful consideration is essential regarding the number of samples, the location of sampling within the plot and the depths of sample collection.

Soil sampling

In deep peats, even obtaining a measurement of depth can be challenging and time consuming. Considerations of accuracy and sample effort must be balanced to obtain accurate, as well as cost-effective estimates. In the SWAMP, KWACS and related projects, 6–18 cores were sampled at each site to quantify depth, density and concentration (Figure 4). The sampling location of core samples is at or close to the plot center (Figure 4). It is very important to select an undisturbed place for soil sampling. Walking on the peat can compact the soil, affecting the bulk density measurement and overall C stock estimation.

Soil augers designed to sample deep peats such as a Russian auger or an open-faced peat auger have been used to successfully extract soil cores in peat forests for carbon stock measurements (Figures 18 and 19). These augers are especially designed to cut through roots and fibrous materials and retrieve a relatively intact soil sample. With extensions to the auger, deep samples (3–12 m) can be collected. The Russian auger encloses the peat sample, thus preventing soil loss during removal (Figures 19 and 20). The open-faced peat auger has an open side and bottom, allowing for efficient collection of a large sample. The drawback of the open-faced auger is that sample extraction can be difficult in saturated sites with very low bulk density and little cohesion (Figure 17).

Figure 17. An open-faced auger is quite efficient for sampling in shallow peats.

Note: Such augers have allowed soils at depths as great as 5 m to be collected efficiently.

Figure 18. Extracting a sample of peat soil using a Russian peat auger.

For deep peat sampling and in sites of low bulk density and low soil cohesion, this is a most efficient type of auger.

To accurately characterize the soil peat carbon pool, samples should be collected at regular intervals throughout the peat profile. Soils closer to the soil surface are often sampled with greater intensity as these are most susceptible to disturbance due to land use and these effects can be better detected with intensive sampling. Many studies in peat forests and mangroves have partitioned the peat soil profile into the following depth layers: 0–15 cm, 15–30 cm, 30–50 cm, 50–100 cm, 100–300 cm, and increments of 200 cm for peats exceeding 300 cm depth (Figure 19). Usually, sampling extends to the limits of the peat horizons. Peat depth should be considered as the depth to the organic–mineral transitional horizon.

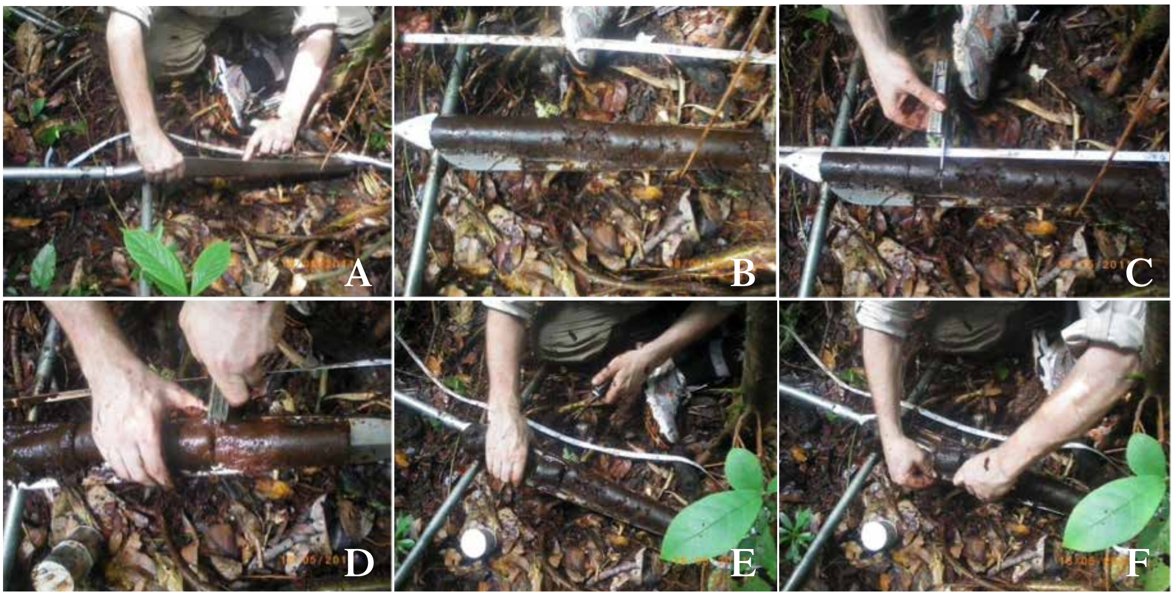


Figure 19. Collection of soil samples from peat auger.

A: Opening the auger. B: Cleaned, flat surface of soil core. C: Measuring and marking the depth intervals. D: Cutting a sample. E: Removing sample from auger. F: Collecting sample in a numbered container.
Photos by Sofyan Kurnianto, OSU.

At the center of each depth increment, a subsample is collected for laboratory analysis. The subsample should be large enough for bulk density and all chemical analyses to be conducted – usually at least a 100 g sample from the field (wet weight). The peat sample should be carefully cut and removed from the core, and then placed in an appropriate container such as a labeled metal soil can. Plastic bags and aluminum foil can also be used for collection. The key critical point is to extract a precise volume of peat soil to accurately determine both bulk and carbon density. It is important to know the area and volume of the soil sampler before making the collections. It is most efficient when all samples are the exact same volume. Extracting a core of 5 cm in length from the center of the selected depth range has been found to be a sufficient sample for all analyses (Kauffman et al. 2016; Novita 2016).

5 Laboratory and data analyses

5.1 Biomass and carbon pools of vegetation

5.1.1 Live trees

The biomass of trees is determined utilizing allometric equations (Chave et al. 2005, 2014) and peat forests are no exception (Manuri et al. 2014). Such methods use the relationship between the biomass of whole trees (or their components) and readily measured parameters, such as main stem diameter, species and tree height. As previously mentioned, the main stem diameter is usually expressed as the diameter at 1.3 m in height (DBH) or the diameter above the area of buttresses or other flared tree bases (Figure 7). Although not necessary, species identification is desired as it allows the use of equations that use wood density (or specific gravity) in the allometric equation. Given the differences in structure and wood density among species, equations that include wood density are likely to yield greater accuracy than equations that only include diameter.

Few references for allometric equations for peat forest biomass exist (Table 3). Before deciding which biomass equation to use, consider the geographic origin and species that composed the data set from which the equation was derived. If possible, it is best to use an equation developed in the same region as where the inventory is taken. There is a great deal of variation in wood density, morphology and height–diameter relationships between sites, which can affect the accuracy and utility of any given equation. It is also critical to note the maximum and minimum diameter of the trees sampled from which the equation was derived. Applying the equation to trees with a larger diameter than those from which the equation was derived (i.e. extrapolation) can lead to significant errors – often overestimating the biomass of large trees.

Different equations will yield different biomass predictions (Figure 20). The differences in biomass estimation are most apparent in the biomass predictions of the largest individuals (i.e. those with the largest diameter; Figure 20).

5.1.2 Standing dead trees

While the method used for calculating the biomass of standing dead trees is similar to that used for live trees, modifications must be made to account for biomass loss due to decay. The biomass of recently dead trees (i.e. those with fine branches still attached; decay Status 1 in Figure 9) can be estimated using live tree equations. The only difference is that leaves should be subtracted from the biomass estimate. This can be accomplished either using a leaf biomass equation to determine the quantity of leaves to be subtracted or by subtracting an estimated constant of 2.5% of the aboveground biomass estimate of the tree. Status 2 dead trees can be calculated in a similar manner, subtracting away a portion of the biomass; however, because they have also lost some branches in addition to leaves, both leaf biomass and branch loss must be considered. Commonly, an estimated total of 10–20 percent of biomass (accounting for both leaves and some branches) is subtracted.

Different analyses are required for dead trees in later stages of decay. Decay Status 3 trees (Figure 10) have often lost a significant portion of their volume due to advanced breakage, and these variable losses cannot be accurately subtracted from the live-tree biomass estimates. Instead, the tree's volume may be calculated using an equation for a frustum (truncated cone). The top diameter must be estimated using a taper equation, using the base-diameter and height measurements that are taken in the field for Status 3 trees.

Table 3. **Allometric equations to determine live tree biomass for tropical peat swamp forests.**

Equation	R^2	Sample size	Min–max diameter (cm)	Species	Location	Source
$\ln(W) = -2.36 + 2.58 \ln(D)$	0.99	20	5–40	*Shorea teysmaniana*	Central Kalimantan	Akbar and Priyanto 2011
$W = 0.107D^{2.486}$	0.90		2–35	Mixed	Central Kalimantan	Jaya et al. 2007
$W = 0.1032D^{2.4695}$	0.96	30	20–54.1	Mixed	Central Kalimantan	Dharmawan et al. 2013
$W = 0.0145D^3 - 0.4659D^2 + 30.64D - 263.32$	0.95	38	>10	Mixed	Riau	Istomo 2006
$W = 0.30D^{2.29}$	0.97	20	5–40	*Cotylelobium burckii*	Central Kalimantan	Akbar and Priyanto 2011
$W = 0.217D^{2.38}$	0.96	20	5–40	*Dipterocarpus kerrii*	Central Kalimantan	Akbar and Priyanto 2011
$W = 0.09D^{2.58}$	0.99	20	5–40	*Shorea parvifolia*	Central Kalimantan	Akbar and Priyanto 2011
$W = 0.153D^{2.40}$	0.98	20	2–30.2	Mixed secondary peat forest	South Sumatra	Widyasari 2010
$W = 0.206D^{2.45}$	0.98	30	5–64	Mixed secondary peat forest	South Sumatra	Novita 2010
$W = 0.136D^{2.51}$	0.97	148	2–167	Mixed	Sumatra, Kalimantan	Manuri et al. 2014
$W = 0.0673 \text{ x } (rD^2H)$		4004	5–212	Upland tropical forests	global data	Chave et al. 2014
$W = \rho \text{ x } \exp(-1.499 + 2.148 \ln(D) + 0.207 (\ln(D)^2) - 0.0281(\ln(D)^3)$	0.99	2410	5–187	Upland tropical forests	global data	Chave et al. 2005

Variables in the equations are: W = tree mass (kg); D = diameter (cm); ρ = wood density (g cm^{-3}); and H= height (m).

Taper equation for estimating the top diameter of a broken-topped dead tree (Pearson et al. 2005; Walker et al. 2012):

$$d_{top} = d_{base} - \left[100 * ht * \left(d_{base} - \frac{DBH}{130}\right)\right]$$

where:
d_{top} = estimated diameter at the top of the tree (cm)
d_{base} = the basal trunk diameter (cm)
ht = tree height (m)
DBH = tree DBH (cm).

Then, volume is determined by assuming the tree is a truncated cone:

$$\text{Volume (cm}^3) = \left(\frac{\pi * (100 * ht)}{12}\right) * \left(d^2_{base} + d^2_{top} + \left(d_{base} * d_{top}\right)\right)$$

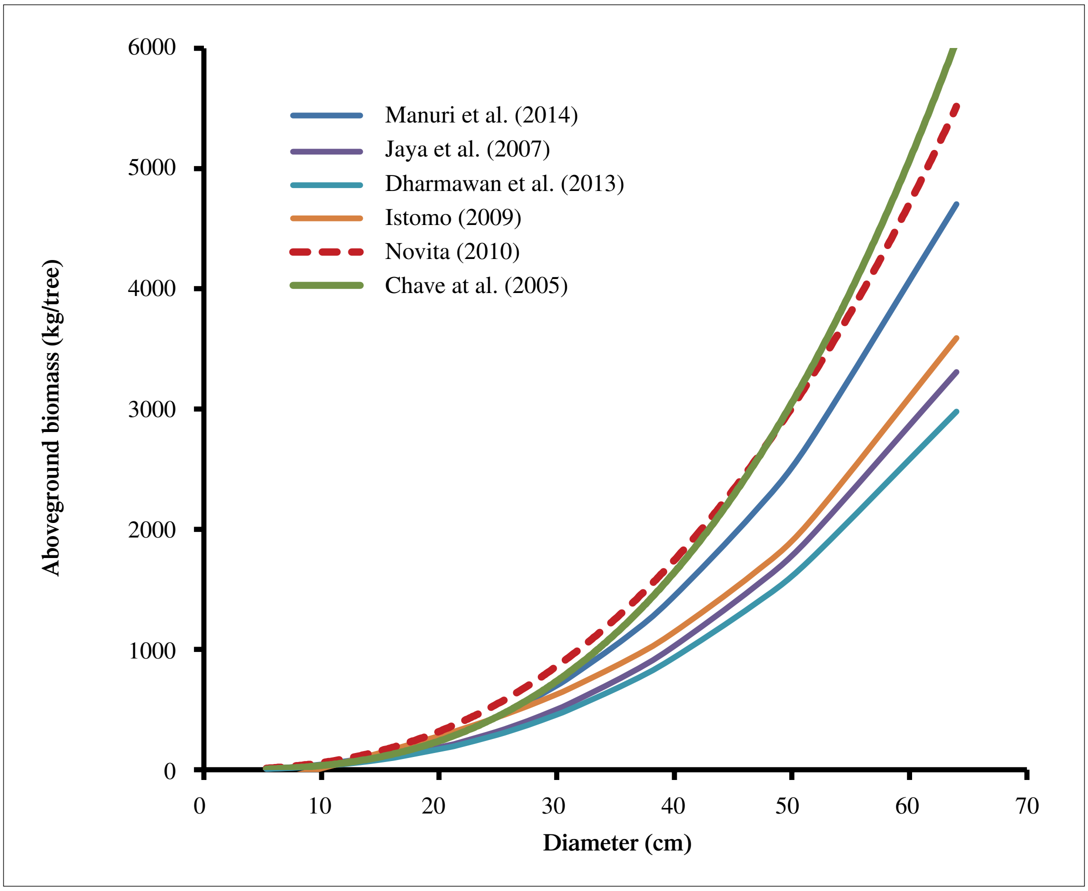


Figure 20. The relationships between tree diameter and predicted biomass using the same sample of trees (n = 146) from peat swamp forests of Sumatra and Kalimantan, Indonesia.

The range in predicted mass of large trees (≈60 cm) using these equations ranged from 3000 kg to >6000 kg. It is apparent that the choice of equation can have a huge bearing on biomass/carbon pool estimates of live trees. The equations on which these curves are based and the range of tree diameters from which the equations were derived are listed in Table 3.

where:
ht = tree height (m)
d_{base} = the basal diameter (cm)
d_{top} = the diameter at the top (cm) estimated from the taper equation (if the taper equation results in a negative number, use 0.1 for d_{top}).

Dead tree biomass (g) is then determined by multiplying its volume (cm^3) by its wood density ($g\ cm^{-3}$). Wood density of dead standing trees in the ecosystem will need to be determined.

The carbon mass of dead trees can be determined if the mean carbon concentration for this component has been established. The carbon concentration of dead wood is usually around 50% (e.g. Kauffman et al. 1995) and a default value for C concentrations of dead trees is recommended as 0.50.

5.1.3 Belowground plant mass (roots)

Few allometric equations have been developed that accurately predict belowground plant mass in peat swamp forests. Two general belowground mass equations for tropical forests have been provided by Cairns et al. (1997) and Mokany et al. (2006).

These equations are:

$$\text{Root biomass} = 0.489 AGB^{0.890}$$

($R^2 = 0.93$; Cairns et al. 1997)

$$\text{Root biomass} = \exp\left[-1.0850 + 0.9256(\ln AGB)\right]$$

($R^2 = 0.83$; Mokany et al. 2006),

where AGB is aboveground biomass (kg).

An equation for root biomass in peat swamp forest was developed by Suwarna et al. (2012) in Sumatra:

$$\text{Root biomass (kg tree}^{-1}) = 0.064 \times DBH^{2.252}$$

where *DBH* is the diameter at breast height (cm).

Root/shoot ratios, calculated as the ratio between total root biomass and tree aboveground is another means to determine belowground biomass. Cairns et al. (1997) reports that the mean root/shoot ratio in tropical forests is 0.24 (± 0.14). Mokany et al. (2006) reports the root/shoot ratio is 0.205 (± 0.036) for small trees and 0.235 (± 0.011) for large trees. In primary peat swamp forest in Sumatra, the root/shoot ratio is found to be 0.16 (± 0.01) (S. Persch, personal communication, 2015).

5.1.4 Downed wood

Analysis to determine downed wood mass using the line-intercept technique requires the data from the field measurements, data on wood density and mean diameters for the smaller size classes (Brown 1971). The average diameter within each size class can be derived from measurements of about 50–100 randomly selected individual pieces of downed wood of each size class. A digital caliper is recommended for these measurements. Use of the quadratic mean diameter (QMD) of the wood pieces is recommended to calculate volume rather than the mean diameter of wood classes (Brown and Roussopoulos 1974). The QMD is calculated as follows:

$$QMD = \sqrt{\frac{\Sigma d_i^2}{n}}$$

where d_i = the diameter of each sampled piece of wood in the size class, and n = the total number of pieces sampled.

Specific gravity or wood density must also be determined for each wood category sampled (fine, small, medium, large–sound, large–rotten). It is recommended that at least 20–25 pieces are collected for each size class, capturing a representative range of sizes, and the full range of species present in the sample (Table 4). As a rough guideline, each piece collected for specific gravity determination should have a mass of about 5–50 g. Pieces for determination of specific gravity should be randomly collected within the project area but not inside permanent sample plots to avoid undue disturbance. Specific gravity requires measurement of both the oven-dry mass and volume of each sampled piece. Volume is obtained via determination of each piece's mass when submerged in water. This is accomplished by placing a water container on a digital balance of a size sufficient to submerge each piece. Each piece of sampled wood is attached to a needle that is attached to a ring stand above the scale. The piece is then submerged (without touching the bottom and sides of the container) and the change in mass is recorded. Because the specific gravity of water is 1 g cm^{-3}, the resultant increase in mass shown on the scale is the volume displaced by the particle. To obtain wood density, the mass of each piece is divided by the volume, and then the mean for each size class is computed. These mean values will be used in later computations of biomass and/or carbon. In West Kalimantan, Indonesia, downed wood pieces were found to have specific gravities ranging from 0.40 to 0.53 g cm^{-3} (Basuki 2017; and Table 4).

Table 4. The specific gravity and mean diameter of the standard downed wood size classes used to estimate wood mass in West Kalimantan peat swamp forests (Basuki 2017).

Size class (cm diameter)	**Specific gravity** (g cm^{-3}) ± SE	**Sample size**
2.5–7.5	0.45 ± 0.03	28
>7.6 (Sound)	0.53 ± 0.02	24
>7.6 (Rotten)	0.40 ± 0.03	29

Downed wood volume is then calculated from line-intercept data using the following scaling equations.

Volume of fine, small and medium wood size classes based on counts of the numbers encountered on a transect:

$$\text{Volume } (\text{m}^3\text{ha}^{-1}) = \pi^2 * \left(\frac{N_i * QMD_i^2}{8 * L} \right)$$

where:
N_i = the count of intersecting woody debris pieces in size class i
QMD_i = the quadratic mean diameter of size class i (cm)
L = transect length (m), (van Wagner 1968; Brown 1971).

Volume of large (>7.6 cm diam) downed wood based on measurements of the diameter of each individual encountered on a transect:

$$\text{Volume } (\text{m}^3\text{ha}^{-1}) = \pi^2 * \left(\frac{d_1^2 + d_2^2 + d_3^2 + \cdots d_n^2}{8 * L} \right)$$

where:
d_1, d_2, etc. = diameters of intersecting pieces of large dead wood (cm)
L = the length of the transect line for large size class (m), (van Wagner 1968; Brown 1971).

Wood biomass is then calculated as the volume multiplied by its mean specific gravity. An example of the broad range of downed wood mass in peat swamp forests is given in Table 5.

The final step in the analysis is the conversion of downed wood biomass to C mass. It would be advisable to determine the carbon concentration of the wood for this measurement. An acceptable default value based on carbon concentrations of dead wood in tropical forests is 50%.

Table 5. Examples of downed wood mass (Mg ha^{-1}) by size class (diameter in cm) in tropical peat swamp forests. Data are from Novita (2106) and Basuki (2017).

Location	**≥7.6 cm sound**	**≥ 7.6 cm rotten**	**2.55–7.6 cm**	**Total mass**
Tanjung Puting	0.26 ± 1.44	2.50 ± 0.17	0.24 ± 0.13	3.00 ± 0.49
Ketapang, West Kalimantan	15.0 ± 5.4	15.0 ± 10.2	32.0 ± 8.5	62.0 ± 14.3

Note: Data are mean ± standard error. The mass calculated here used specific gravities and quadratic mean diameters from Table 6.

5.1.5 Forest floor vegetation and litter mass

Samples of the forest floor and vegetation that are sampled in the field must be dried to determine biomass and carbon mass on a dry weight basis. Upon collection, samples are transported to the laboratory and oven-dried at 60 °C to a constant mass. Mass of the subplot area (e.g. 50×50 cm) is then scaled to a per-hectare (or per meter) basis.

Carbon mass of these components is determined by multiplying mass by the carbon concentration. Mean carbon concentrations of tropical forest leaf litter have been reported as 38–49% (Kauffman et al. 1993, 1995). Novita (2016) reports that mean carbon concentration of forest litter in Tanjung Puting, Indonesia, was 48.4 ± 0.4%. Therefore, a conversion factor of 0.48 is recommended.

5.2 Soils/peats

5.2.1 Bulk density

After collection in the field, the peat samples should be oven-dried as soon as is practical. If this is not possible, such as when sampling takes place in remote areas, air drying samples to slow microbial activity is recommended. Upon returning to the laboratory, soil samples should be oven-dried to a constant mass at ≤60 °C. Higher temperatures may alter or reduce the carbon and nitrogen in the sample and this should be avoided. In many protocols, drying at 105 °C is recommended for bulk density determination, to boil away any water from the sample. However, this would require collecting a second sample from each depth interval, since samples to be analyzed for carbon should not be exposed to such a high temperature. The authors have determined that peat soil bulk density, derived from drying at 60 °C, is within 1% of that derived from drying at 105 °C. Given this almost negligible difference, the effort of double sample collection can be avoided. Typically, it requires at least 48 hours for samples to attain a constant dry mass when dried at 60 °C. Caution should be taken to ensure that samples are thoroughly dried before undertaking bulk density and carbon analysis. Carefully breaking up the sample into smaller pieces improves the drying process.

Figure 21. After drying samples to a constant weight in a drying oven at temperatures ≤ 60 °C, samples are then weighed with a digital balance. As the sample consists of a known field volume, the bulk density can now be determined.

Bulk density is determined by dividing the mass of the oven-dried soil sample (Figure 21) by the volume of the sample. The bulk density equation is as follows:

$$BD = \frac{m}{V}$$

where *BD* is bulk density (g cm^{-3}), *m* is oven-dried sample mass (g) and *V* is the fresh peat sample volume (cm^{-3}).

Bulk density may be used with measures of peat depth to indirectly estimate peat mass. Warren et al. (2012) found that peat bulk density could be used to predict carbon density. They found a significant linear relationship between peat bulk density and the carbon density ($r^2 = 0.95$) (Figure 22). C density (C_d) of peat forest (kg C m^{-3}) could be estimated with the following equation:

$$C_d = (468.76 \times BD) + 5.82 \; \left(R^2 = 0.95\right)$$

where: C_d is carbon density (kg C m^{-3})
BD is bulk density (g cm^{-3}),

In oil palm plantations where the peat has been compacted, Farmer et al. (2014) find that C density (kg C m^{-3}) could be estimated with the following equation:

$$C_d = (515.44 \times BD) + 3.01 \; \left(R^2 = 0.94\right)$$

where: C_d is carbon density (kg C m^{-3})
BD is bulk density (g cm^{-3}),

In contrast, Basuki (2017) finds a wide variation in carbon concentrations of forest peat samples with low bulk densities and urges caution in using such equations to estimate carbon density.

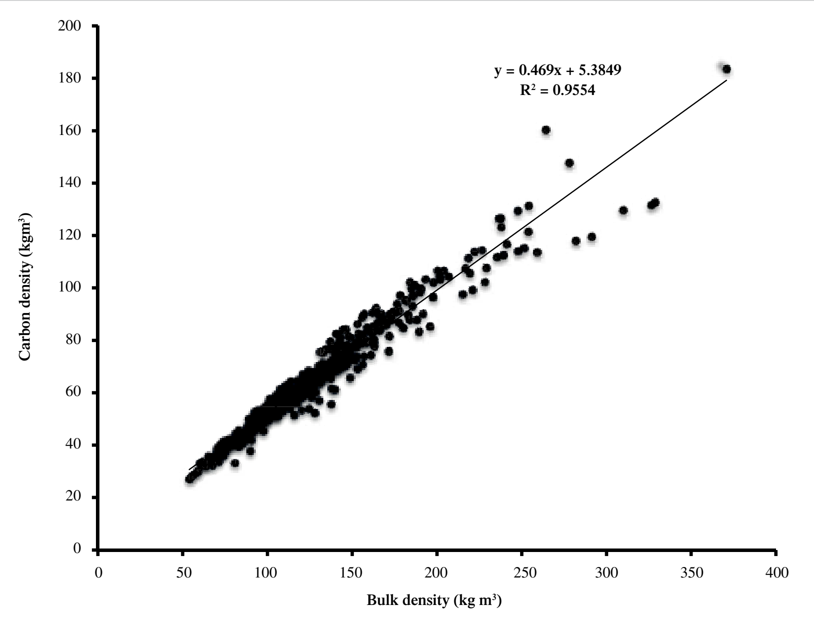


Figure 22. The linear relationship between bulk density and carbon density from 588 soil samples collected from peat forests of Berbak, Sebangau and Sentarum National Parks, Indonesia (see also Warren et al. 2012).

5.2.2 Soil carbon concentration

Soil samples should be sent to a reliable and experienced laboratory for analysis of carbon concentration. The laboratory should follow commonly accepted standard procedures with respect to sample preparation and carbon analysis approaches. Dry combustion with an elemental analyzer and wet combustion are the two basic approaches used to quantify total carbon in soils (Nelson and Sommers 1996; Schumacher 2002). Dry combustion is the most suitable method for routine analysis of total carbon (Sollins et al. 1999). This method uses a high temperature induction furnace. Wet combustion via the Walkley–Black method is also commonly used because it is simple and requires minimal equipment. However, the results obtained cannot be considered quantitative (Nelson and Sommers 1996), and the process also produces toxic wastes (Sollins et al. 1999).

Another method that is less direct, but is rapid, is the loss on ignition (LOI) method, which determines soil organic matter through combustion of the soil sample at high temperatures (Nelson and Sommers 1996). The best way to determine carbon concentration via the LOI is to develop an allometric equation where carbon concentration is the dependent variable and LOI is the independent variable (Fourqurean et al. 2015). LOI can be determined with the following equation (Chambers et al. 2010):

$$LOI = \frac{\text{dry weight} - \text{weight after combustion}}{\text{dry weight}}$$

The ash content (%) is the proportion of mass remaining after combustion in a muffle furnace. Carbon concentration is negatively correlated with the ash content (Figure 23). However, Basuki (2017) finds that there is a large variation (poor relationship) between carbon concentration and ash content at low percentages (i.e. the left side of Figure 23).

Carbon concentration in Indonesian tropical peat forests may range from ~20% carbon to almost 60% carbon (Table 6).

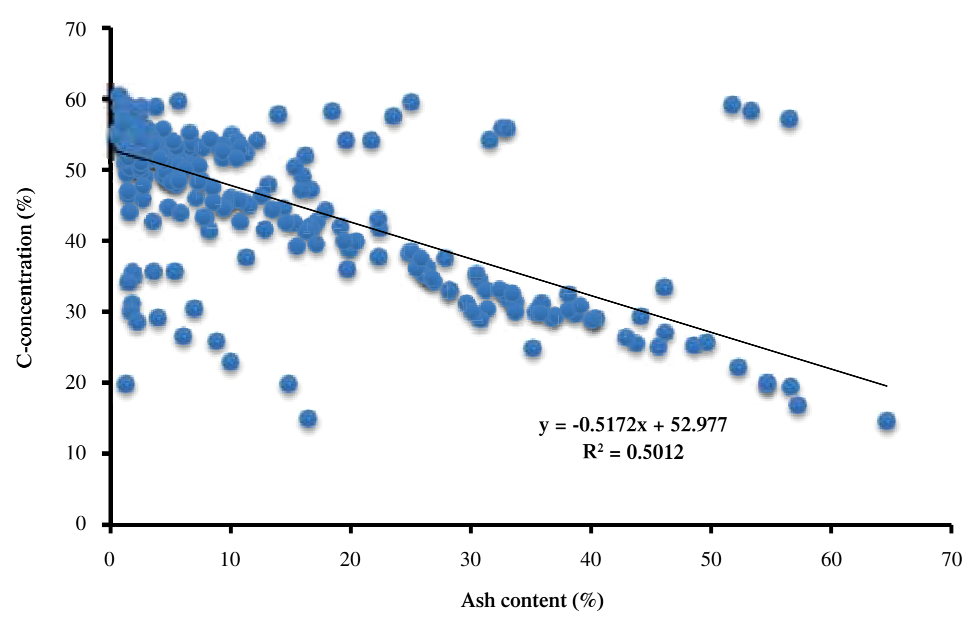


Figure 23. The relationship between ash content and carbon concentration from the peat samples from West Kalimantan, Indonesia.

Table 6. Examples of soil properties from tropical peat swamp forests, Indonesia.

Site	Peat depth (m)	Bulk density (g cm^{-3})	C (%)	N (%)	Refs
Tanjung Puting, Central Kalimantan	1.57 ± 0.17	0.20 ± 0.03	45.44 ± 7.69	1.18 ± 0.23	Novita 2016
Danau Sentarum NP, West Kalimantan	2.1–12.7	0.131 ± 0.043	50.7 ± 2.2		Warren et al. 2012
Sebangau, Central Kalimantan	1.9–4.2	0.122 ± 0.052	54.0 ± 3.3		Warren et al. 2012
Berbak, Jambi	4.1–6.4	0.106 ± 0.028	51.6 ± 3.6		Warren et al. 2012
Ketapang, West Kalimantan	8.54 ± 0.64	0.08 ± 0.001	57.3 ± 1.5	1.15 ± 0.11	Basuki 2017

5.2.3 Carbon density

Carbon density (carbon mass per unit volume of soil) is calculated by multiplying soil C concentration by soil bulk density (Kauffman et al. 2014). This is a frequently reported value in carbon stocks studies. The average carbon density collected from three peat formations in Indonesia and literature values is 0.64 g cm^{-3} (64.2 ± 20.9 kg m^{-3}; Warren et al. 2012). However, soil compaction due to land use can lead to increased bulk density and can increase carbon density even while carbon concentrations may be lower. For interpretation of changes caused by land use, it is important to include changes in bulk density, carbon concentration, and carbon density as well as declines in overall peat depth.

5.2.4 Soil carbon pools

The soil carbon mass per sampled depth interval is calculated through multiplication of the carbon concentration by the bulk density. The total soil carbon pool or mass is then determined by summing the carbon mass of each of the sampled soil depths. Ideally, the entire organic soil carbon pool (to bedrock or mineral soil) is accounted for. Frequently, only depths to 50–150 cm are reported. This can result in great underestimates in soil carbon pools and may result in underestimates of carbon emissions, as land use in tropical wetlands has been shown to affect soil carbon pools at depths >1 m (Kauffman et al. 2014, 2016; Basuki 2017;).

5.3 Total ecosystem carbon stocks

The total carbon stock or pool is determined by adding all of the component pools. First, each component pool is averaged across all plots (e.g. trees, wood, soil, etc.). These average values are then summed to obtain the total.

The equation for total ecosystem carbon stocks is:

$$\text{Total carbon stock (Mg ha}^{-1}\text{) of the sampled stand} =$$
$$C_{\text{treeAG}} + C_{\text{deadtree}} + C_{\text{sap/seed}} + C_{\text{treeBG}} + C_{\text{deadsap/seed}} + C_{\text{nontreeveg}} + C_{\text{woodydebris}} + C_{\text{litter}} + C_{\text{soil}}$$

where:
C_{treeAG} = aboveground carbon pools of trees
C_{treeBG} = belowground vegetation carbon pool
C_{deadtree} = the dead tree pool
$C_{\text{sap/seed}}$ = saplings and seedling carbon pools
$C_{\text{nontreeveg}}$ = non-tree vegetation carbon pools (e.g. lianas, palms, etc.)
$C_{\text{woodydebris}}$ = downed wood carbon pool
C_{litter} = the surface litter layer carbon pool
C_{soil} is the total soil carbon pool.

Total ecosystem carbon stocks have been quantified following the protocols described in this manual in several locations in Indonesia and some examples can be found in Table 7. There is a tremendous range in the ecosystem carbon stocks of peat swamp forests and this is largely due to the ranges in peat depth. Ecosystem carbon stocks of peat forest range from 558 Mg C ha^{-1} in shallow riverine forests with peat depths of <1 m to 5591 Mg C ha^{-1} in peat forests with peat depths exceeding 8 m.

Land use decreases ecosystem carbon stocks, e.g. oil palm plantations had lower carbon stocks than adjacent forest due to declines in both aboveground and belowground carbon pools. For example, mean carbon stocks for peat forest at Ketapang was 4401 Mg C ha^{-1} compared with 3442 Mg C ha^{-1} for paired oil palm plantations (Basuki 2017).

Table 7. Carbon stocks of tropical peat swamp forests and oil palm plantations, Indonesia. All sites were sampled following protocols described in this manual. The carbon stocks include the entire peat profile to mineral soils.

Location and number of stands sampled	Cover type and sample size	Peat depth (cm) Mean ± SE (Max–Min)	Carbon stock (Mg ha^{-1}) Mean ± SE (Min–Max)	Source
Tanjung Puting National Park	Riverine peats (N=5)	46 ± 6.8 (≈25 –75 cm)	894 (558–1213)	Murdiyarso et al. (2009)
Tanjung Puting National Park	Peat forest (N=3)	157 ± 11 (27–290)	1770 ± 123 (1038–2502)	Novita (2016)
Tanjung Puting National Park	Oil palm (N=3)	38 ± 9(20–47)	759 ± 26 (567–893)	Novita (2016)
Ketapang, West Kalimantan (N=4)	Peat forest (N=4)	915 ± 25 (841–953)	4401 ± 281 (3801–5591)	Basuki (2017)
Oil palm, Ketapang West Kalimantan (N=5)	Oil palm (N=5)	700 ± 29 (608–737)	3442 ± 294 (2566–4389)	Basuki (2017)

Note: For a given project area, there would presumably be a sufficient number of sites sampled to characterize the carbon stocks of the region in an accurate, transparent and verifiable manner. If the project area has been stratified into different units (communities, land uses, geomorphic units, etc.), then obtaining the mean ecosystem carbon stock of each unit (as well as the degree of uncertainty) is the next step. Finally, the total carbon stock for the project area would be the sum of the carbon stocks for each of the units within the project area.

5.3.1 Quantifying uncertainty in carbon pools

For carbon assessments, it is essential that uncertainty is reported for each component pool, as well as total carbon stock. Uncertainty reflects the degree of precision in the dataset (i.e. the degree of variation around the mean value). For carbon assessments it is typically reported as a 95% confidence interval (CI), expressed as a percentage of the mean. For example, if the value is 100 Mg ha^{-1} and the 95% CI is 90–110 Mg ha^{-1}, the uncertainty in the estimate is ± 10%. Key definitions relevant to uncertainty in forest carbon inventories can be reviewed in GOFC-GOLD (2015).

5.3.2 Uncertainty in component pools

The first step is to compute the confidence interval for each component pool (trees, downed wood, soil, etc.). A **confidence interval** is a range that encloses the true value of an unknown parameter with a specified confidence (probability). In the context of estimation of emissions and removals under the United Nations Framework Convention on Climate Change (UNFCCC), a 95% confidence interval is normally used (GOFC-Gold 2015). The 95% CI half-width is often used to express the uncertainty of each carbon pool as a percentage of the mean:

$$\text{Uncertainty } (\%) = 100 * \left(\frac{95\% \text{ CI half-width}}{mean} \right)$$

Uncertainty in total stand-level carbon stock

Calculating uncertainty for the total carbon stock requires accounting for the uncertainty of each of the component pools (trees, wood, soils, etc.). There are two methods for calculating the total uncertainty for carbon stocks (Pearson et al. 2005, 2007; GOFC-GOLD 2015). The first method uses simple error propagation through the square root of the sum of the squares of the component errors. The second method uses Monte Carlo simulations to propagate errors. The advantage of the first method is that it is simple to use and requires no additional computer software. The second method is used when substantial correlations exist between datasets (for example, between two carbon pools), when uncertainties are very large (e.g. greater than 100%), or when data distributions are strongly non-normal. In theory, it is always better to use Monte Carlo analysis because it is robust to almost any data structure. If data analysts knowledgeable of this method are available, this might be a preferred approach. However, the difference in results attained through the two methods is typically small, unless correlations and/or uncertainties are very high (Pearson et al. 2007). Thus, the simple error propagation method is often used and is detailed here for that reason.

The compilation of ecosystem carbon stocks entails addition of the carbon pools that compose the ecosystem carbon stock. Uncertainty of the carbon stock at the stand level can be determined with the following formula (GOFC-GOLD 2015):

$$U_{total} = \frac{\sqrt{(U_1 * X_1)^2 + (U_2 * X_2)^2 + \ldots (U_n * X_n)^2}}{X_1 + X_2 + \ldots X_n}$$

where:
U_i = percentage uncertainty (usually the 95% CI) associated with each of the parameters (e.g. live trees, dead wood, peat layers, etc.)
x_i = the value of the parameter (i.e. the mean mass of each carbon pool)
U_{total} = the percentage uncertainty in the sum of the parameters that comprise the carbon stock.

Uncertainty in total carbon stock of project areas, regions or other large areas

Quantifying the uncertainty in the carbon stocks of large areas follows the same general concept as calculations for stand-level carbon stock. However, the formula is slightly different because the estimate requires multiplication rather than addition of inputs (see equation for stand-level carbon stock in the previous paragraph).

The remote-sensing analysis of land cover types (e.g. peat swamp forest) should have an uncertainty estimate associated with it. This uncertainty should be combined with the uncertainty in stand-level carbon stock using the following equation (to determine uncertainty in the total carbon stock of a project area):

$$U_{total} = \sqrt{U_1^2 + U_2^2 + \ldots U_n^2}$$

where:
U_i = percentage uncertainty associated with each of the parameters (ecosystem carbon stocks of each cover type within the project)
U_{total} = the percentage uncertainty in the product of the parameters.

Similar to stand-level carbon stock, the uncertainty in total carbon stock over an area can be expressed as the actual interval, or as a percentage of the mean estimate.

5.4 Other parameters used to quantify structure and diversity

5.4.1 Basal area and density

In addition to biomass and carbon pools, a great deal of information can be derived about the structure and composition of forests from the measurements described in this manual. Common variables that represent tree species abundance in addition to biomass include tree density and basal area. Tree density is the number of trees per unit area (usually expressed as numbers per hectare). This can be derived from the total numbers of individual trees in the sampled plots:

$$\text{Density} = \frac{\text{total number of individuals of a species found}}{\text{total area examined}}$$

Basal area is the area occupied by the trunk or main stem and can be calculated from tree diameter data. For community structure analysis, tree basal area is summed to the plot level and then usually reported as m^2 ha^{-1}.

$$BA = \frac{\sum_{i=1}^{n} BA_i}{A}$$

where:
BA is the stand-level basal area (m^2)
BA_i is the basal area for individual i (m^2)
A is the area of the sampled plot(s) (m^2).

5.5 Determination of carbon sequestration and direct measurements of greenhouse gasses

The carbon cycle of tropical peatlands consists of CO_2 uptake via photosynthesis, carbon sequestration and storage in plants, and carbon losses via respiration, dissolved carbon exports, and disturbance processes (e.g. fire; Figure 24). It is exceedingly difficult to determine complete carbon budgets in ecosystems. Nevertheless, in order to participate in climate change mitigation and adaptation activities, it is imperative to understand the carbon cycle of the forests. The large green circles in Figure 26 represent the ecosystem carbon stocks of forests and oil palm (land use), and their measurement has been the principal goal of the methods explained thus far in this manual. Subtracting the differences in these pool sizes yields an estimate of the ecosystem carbon losses to the atmosphere (the large open arrow in Figure 24). This estimate is referred to as the stock difference or stock change approach (IPCC 2006; Kauffman et al. 2016).

To understand rates of carbon sequestration and pathways of losses, measurements of the rates of carbon uptake, respiration and decomposition are also needed. It is beyond the scope of this manual to describe the many complex methodologies and approaches used to quantify the multiple pathways of carbon flux in peat forest ecosystems. In this section, we provide a basic discussion of possible approaches to quantify carbon sequestration and losses via trace gas emissions.

5.5.1 Measurements of greenhouse gasses

Important trace gas fluxes from terrestrial ecosystems include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The largest greenhouse gas flux to the atmosphere is CO_2, which is produced during plant respiration (autotrophic respiration), decomposition (heterotrophic respiration) and rapid oxidation during fires (land cover change). The saturated soils and anaerobic nature of undisturbed

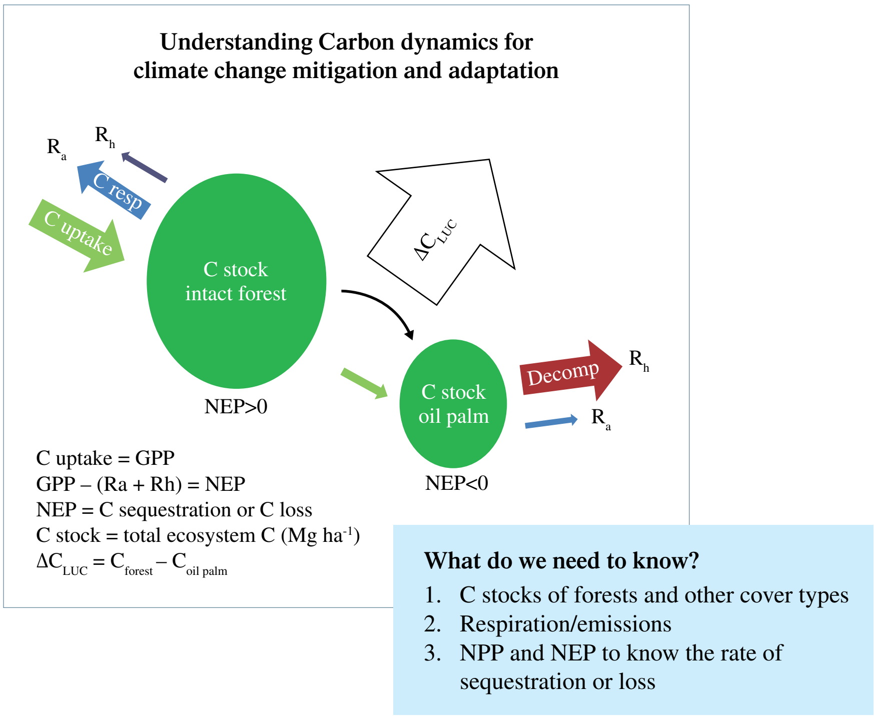


Figure 24. Participation in carbon markets requires quantification of the carbon dynamics of intact forests and how land use affects these dynamics.

In this example, carbon emissions via a stock change approach would be estimated by determining the differences in the two green circles that represent the carbon stocks at two different points in time (or space). A gain–loss method would examine the carbon gain and emissions to determine net sequestration or loss. A combination of the two approaches is truly needed to determine the carbon dynamics of tropical forests. In this figure, GPP = gross primary productivity, NEP = net primary productivity, LUC = land use change, NPP = net primary productivity. C resp = autotrophic respiration (Ra) and Decomp = heterotrophic respiration (Rh).

tropical peat swamp forests naturally release substantial amounts of CH_4 emissions into the atmosphere. Emissions of N_2O arising from tropical peat forests are negligible (Hadi et al. 2005; Novita 2016), but upon agricultural conversion and with use of fertilizers, N_2O emissions significantly increase (Toma et al. 2011; Novita 2016).

Chamber methods are relatively simple approaches for the direct measurements of greenhouse gasses arising from soils (e.g. Ishizuka et al. 2005; Jauhiainen et al. 2008; Comeau et al. 2013, Novita 2016). Chamber flux measurements are made with varying frequency over short periods using dark chambers to determine total respiration (Rt), which includes autotrophic (Ra) plus heterotrophic (Rh) respiration from the soil and litter. This approach may be utilized where more complex approaches such as eddy covariance towers are neither practical nor possible. The chamber techniques include both dynamic and static methods (Figure 25; Lou and Zhou 2006). Dynamic chamber methods make direct measures of trace gasses in the field using a portable infrared gas analyzer (IRGA), to measure CO_2 and/or CH_4 concentrations. The closed static chamber technique involves extraction of gas samples from a covered chamber over soils. The static chamber approach usually involves collecting air samples at three or more time intervals using a syringe and placing them in sterilized vials. The gas samples are then transported to the laboratory and analyzed with a gas chromatograph. To interpret the greenhouse gas fluxes, measurements of air and soil temperature, water table depth, soil moisture, substrate quality, and land use history are necessary.

A method for estimating greenhouse gas emissions at landscape levels is the eddy covariance technique (Figure 26; Baldocchi 2003). This method offers reliable estimates of total net gas fluxes at the ecosystem level, but there are many practical, ecosystem, infrastructure and capacity limitations that need to be considered (Baldocchi 2003), particularly in remote areas where many peat forests exist.

Figure 25. The measurement of CO_2 using a dynamic chamber method with portable infrared gas analyzer.

Photo credit: Dede Hendry, CIFOR.

Figure 26. An eddy flux tower in a forest.

Photo by Yosuke Oki, CIFOR.

5.6 Field methods for measuring carbon sequestration

Carbon sequestration is defined as the capture and storage of atmospheric carbon into long-lived C pools such as trees and soils (Lorenz and Lal 2010). Carbon sequestration in plant biomass can be estimated by measuring accumulated biomass in vegetation (Vesterdal et al. 2007) coupled with litterfall measurements. These parameters can be measured in the field. Ecosystem-level sequestration also requires measurements of carbon accumulation or loss in soils. Carbon gain in soils can be estimated using methods such as those involving surface-elevation transects and soil markers (Alongi 2008; Lovelock et al. 2011; Fourqurean et al. 2014).

5.6.1 Measurements of tree growth

Sampling permanent plots of forests at intervals of 2–10 years is a simple approach for determining the carbon being sequestered in trees. Carbon gain from these data are determined via a stock difference approach. For a more precise estimate in shorter time intervals, dendrometer bands can be used (Anderson-Teixeira et al. 2014; Figure 27). Dendrometer bands are permanently established expandable bands placed on trees that provide a measure of tree growth via trunk expansion. Measurements of tree diameter from these bands can be made to determine annual growth rates. Biomass increase can be derived by subtracting the biomass of the initial measure from the most recent measure. The same allometric equations and approaches of conversion of biomass to carbon stocks as mentioned in the tree analysis sections are used here.

Figure 27. A dendrometer band for measuring the tree diameter growth.

Photo by Imam Basuki.

5.6.2 Litterfall

Litterfall is another ecosystem variable used in the determination of net primary production (Clark et al. 2001). Litterfall is defined as leaves, wood, flowers fruits, seeds, and other parts of tree that fall to the forest floor (Anderson-Teixeira et al. 2014). Litterfall traps are devices with a known area that are placed in the field to measure this process (Figure 28). They are placed closed to the ground, and frequent collection of their contents facilitates measurement of the seasonal variability of litterfall as well as total inputs. Commonly, the contents of litterfall traps are collected monthly or more frequently to prevent loss and decomposition in the trap. Samples are placed in a bag and transported to the laboratory where they are oven-dried and weighed to calculate litterfall rates on a dry weight basis. The mean annual litterfall production in the primary forests in Tanjung Puting, Central Kalimantan, was 3.1 ± 0.1 Mg dry litter $ha^{-1}yr^{-1}$ (Novita 2016). Comeau et al. (personal communication, 2015) report annual litterfall rates in peat swamp forest in Sumatra of 9.6 ± 1. 5 Mg dry litter $ha^{-1}yr^{-1}$.

5.7 Chronosequence approaches to determine rates of carbon sequestration

When developing baselines, there is often a need to determine rates of carbon sequestration or emissions due to land use. This may include the need to develop rates of sequestration following re-vegetation. Substituting space for time or taking a chronosequence approach is a viable approach to

Figure 28. A litterfall trap in a primary peat swamp forest.

Photo by Imam Basuki.

determine carbon gain or loss in tropical forest ecosystems. Chronosequences can be established to determine the rate of sequestration following forest establishment (Hughes et al. 1999) as well as rates of emissions following deforestation (Hughes et al. 2000; Kauffman et al. 2009).

A chronosequence approach involves selecting stands of different ages but having similar soils, climate and topography. The assumptions are that in an undisturbed state, all samples sites would be similar and that the differences in carbon stocks are due to differences in time since the last disturbance. The same methods of carbon stock determination described in the manual would be applicable when it is desired to establish a chronosequence. The differences between sites can be used to determine rates of sequestration or loss.

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Tropical peat swamp forests contain among the largest terrestrial carbon stocks on Earth. They support unique biological diversity, providing habitats for such charismatic species as the orangutan, Sumatran tiger, the Java rhino and the clouded leopard. Paradoxically, these peat swamps are also being deforested at alarming rates and, as a result, have shifted from being carbon sinks to sources of atmospheric greenhouse gasses. Tropical peat forests are strong candidates for inclusion in any climate change mitigation action (e.g. Reduced emissions from Deforestation and Degradation + (REDD+) and Nationally Appropriate Mitigation Actions (NAMAs)) because of (1) their large carbon stocks; (2) the large emissions that arise from their conversion; and (3) the loss of other important ecosystem services when the forests are converted to other uses. The purpose of this publication is to provide a convenient resource for those wishing to undertake the necessary field measurements of ecosystem C dynamics in peat swamp forests – especially C stocks, biomass, structure and fluxes. General approaches to laboratory procedures and data analysis for estimating C stocks are included. As a reference document, the handbook can be taken to the field as a quick guide to the procedures for measuring major C pools as defined by the Intergovernmental Panel on Climate Change (IPCC). The ecosystem C pools covered by this handbook are: aboveground biomass, belowground biomass, standing and downed coarse wood (CWD), understory biomass, forest litter and soil organic carbon. Although these protocols were designed for peat swamp forests, they can easily be adapted to other land use types or disturbed sites on organic wetland soils. For example, with only slight modifications in approaches to plant sampling, these methods can also be used to quantify stocks and fluxes in oil palm and other plantations on peat soils. It is our hope that practitioners of ecosystem C assessments will find this handbook a useful resource when measuring ecosystem C storage in the field.

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