Measuring
carbon stock
in peat soils

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Practical guidelines

MEASURING CARBON STOCK IN PEAT SOILS

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Glossary

Aboveground biomass. Biomass above ground level (above the soil surface), consisting of trees, other plants and animals (the latter are normally considered to be negligible).

Belowground biomass. Biomass below the soil surface, consisting of plant roots and soil biota.

Biomass. The total mass of living matter—plants and animals—in a unit area. It is normally quantified on the basis of dry weight and usually expressed in tonne per hectare (t/ha) or megagram per hectare (Mg/ha). 1 Mg = 1 t = 1,000,000 gram.

Carbon pool. A subsystem that can store or release carbon. Examples of carbon pools are plant biomass, necromass, soil and water.

Carbon budget. The balance of the transfer, during a specified time period, of carbon from one carbon pool to another in a carbon cycle, or from carbon pools to the atmosphere.

Carbon dioxide equivalent (CO_2eq). A measure used to compare the global warming potential (GWP) of certain greenhouse gases relative to the warming potential of CO_2; it combines differences in the heat-trapping effect as well as expected residence time in the atmosphere. For example, the GWP of methane (CH_4) during an accounting period of 100 years is 25 and for nitrous oxide (N_2O) it is 298. This means that emissions of 1 t of CH_4 and N_2O are equivalent to 25 and 298 t of CO_2, respectively.

Carbon dioxide. This is an odourless and colourless gas, expressed in the formula CO_2, that is formed from a variety of processes such as combustion and/or decomposition of organic matter and volcanic

eruptions. It is captured from the atmosphere, along with solar energy, by green plants through photosynthesis, and reemitted by respiration, releasing energy. Today's CO_2 concentration in the atmosphere is about 0.039% by volume or 388 mole ppm. The CO_2 concentration has increased over the past century owing to the use of fossil fuel and natural gas as well as the reduction of above- and belowground terrestrial carbon stocks. The molecular weight of CO_2 is 44 g; the atomic weight of carbon (C) is 12 g. Conversion of the weight of C to CO_2 is 44/12 or 3.67.

Carbon sequestration. The process of absorption of CO_2 from the atmosphere into plant tissues and soil.

Carbon stock. The mass of carbon stored in an ecosystem at any given time, either in the form of biomass, necromass (dead organisms) or soil carbon.

Carbon. Non-metallic chemical element expressed with the atomic symbol 'C', which is widely available in all organic (C bound to H and O) and inorganic (elemental C) matter. Carbon has the atomic number 6 and typical atomic weight of 12 g/mol, but a stable C13 and radioactive C14 also occur in small amounts.

Emissions. The process of releasing greenhouse gases into the atmosphere.

Fibric. Early stage of peat decomposition where recognizable plant fibres dominate (Table 4).

Forest. A vegetation (land-cover) type dominated by trees, which is recognized through various definitions that, for example, restrict the minimum area, give the minimum crown cover in current or potential stages and express restrictions on the type of woody vegetation that is included in the concept of 'trees'.

Flux. The flow (of greenhouse gases) between pools, for example, from the soil into the atmosphere in the unit weight of gas per unit surface area, expressed as, for example, $mg/(m^2 \text{ hour})$.

Hemic. Intermediate stage of peat decomposition, between fibric and sapric (Table 4).

Histosol. Peat soil.

Land cover. The vegetation on the Earth's surface, such as forests, half-open woodlands, grasslands and open fields.

Land use. This term refers to the classification of land-cover types based on human activities, such as plantation forestry, tree crops, field crops, urban and conservation areas (please note that a term such as 'forest' can refer to both land cover and land use, depending on context).

Necromass (dead organic matter). The weight of dead organisms (mostly plants) in a unit land area, usually expressed as dry weight in t/ha or Mg/ha. Aboveground necromass includes dead trees (standing or on the surface), the litter layer of dead leaves, twigs and branches and crop residues. Belowground necromass includes dead roots and crop residues buried by soil tillage that have not yet been converted into soil organic matter.

Organic matter. Material derived from living matter that can decompose or be the result of decomposition or materials consisting of organic compounds.

Peat (as substrate). Soil dominated by partially decomposed plant residues, with an organic C content of more than 18% (organic matter content of more than 30%).

Peat soil (as soil type). Soils with at least 50 cm of peat. Peat soil has a thickness ranging from 0.5 m (by definition) to more than 15 m. Large areas of tropical peats have thicknesses ranging 2–8 m.

Peatland (as ecosystem). A land system dominated by peat soils. Peatland is usually found in wetland conditions but not all wetlands are peatlands. Mosses, grasses, shrubs and trees can contribute to the formation of peat in water-saturated conditions, with the term 'bog' reserved for peatland dominated by moss.

Sapric. Advanced stage of peat decomposition into organic-matter-rich 'earth' without visible fibres (Table 4).

Soil bulk density (BD). Dry weight of soil per unit volume (including volume of soil solids and pores filled with gas and water).

Soil organic carbon content (C_{org}). The mass of carbon per unit weight of soil. Its units are percentage by weight or gram per kilogram (g organic C/kg soil), tonne per tonne (t /t) or megagram per megagram (Mg/Mg). If laboratory analysis only provides data on organic matter content (for example, by the method of loss on ignition (LOI)), the Corg content of the soil is normally assumed to be 1/1.724 of soil organic matter content. If the peat soil has an organic matter content of 98% then the C_{org} = 98%/1.724 = 57% = 570 g/kg = 0.57 Mg/Mg = 0.57 t/t or simply 0.57.

Soil organic matter content. The mass of soil organic matter per unit weight of dry soil. Usually expressed as percentage by weight or gram per kilogram (g organic matter/kg dry soil) tonne per tonne (t /t) or megagram per megagram (Mg/Mg). Organic matter content of 98% by weight = 980 g/kg = 0.98 Mg/Mg = 0.98 t/t.

Foreword

Peatland is one of the largest terrestrial carbon storehouses. However, the carbon it contains is only protected from decomposition by the wet conditions of the peat. Under special conditions where decomposition is slow owing to low oxygen supply (water saturated), low nutrient concentrations, and acidity, dead organic matter from trees or other vegetation can start to pile up and accumulate, creating conditions that further slow decomposition. Specialized trees, sedges and other vegetation start to dominate and a peat swamp forest is formed. When this starts to hold enough water, it can become a semi-autonomous landscape unit, depending on rainfall and atmospheric nutrient inputs, independent of the mineral soil and groundwater. The belowground carbon stocks can reach 10–100 times those of the most lush tropical forest. However, when the forest is cleared and the peat is drained the stored carbon is readily decomposed and released as CO_2, the most important greenhouse gas. In addition, excessive drainage of peatland increases its vulnerability to fires and, in turn, the peat loses its function of buffering the surrounding environment from drought by the gradual release of water stored in the peat 'dome'. What took thousands of years to accumulate can be burnt within a few days and decompose in a few years or decades.

With the increase of human populations, land resources are becoming scarcer. Peatlands that were once formerly regarded as wasteland are increasingly being developed for various economic purposes such as agriculture and settlements. As a consequence, the carbon sink of actively growing peat becomes one of the most important carbon sources associated with land uses, land-use changes and forestry. Tropical peat alone is estimated to contribute 1–3% of global CO_2 emissions owing to human activity. In Indonesia, the country that has

the largest area of tropical peat, emissions from peatland are around one-third of the total, although the exact numbers are debated and uncertain. Therefore, in the context of Nationally Appropriate Mitigation Actions (NAMAs) and efforts to Reduce Emissions from Deforestation and Degradation (REDD+), conservation and sustainable management of peatland has become one of the main concerns.

One of the requirements of any scheme to reduce carbon emissions through REDD+ and NAMA is a credible monitoring, reporting and verifying (MRV) system. MRV systems document, report on and verify changes in carbon stocks in a transparent, consistent and accurate manner. An MRV system must be supported by a reliable method for measuring carbon stocks and changes in them, both above- and belowground. This booklet provides practical guidance on peat sampling and analysis, calculation of the amount of carbon and data interpretation. It also explains the relationship between changes in carbon stock and CO_2 emissions.

We thank the various people and organizations who have assisted in writing and publishing this book. Hopefully, it will be useful for people who are engaged in the MRV of carbon stocks in peatland.

The conversion of peat forests into agricultural areas requires the construction of drainage canals to facilitate root growth. The drainage depth should be carefully regulated and managed to minimize CO_2 emission.

Soil is one of the three carbon pools on land. Other pools include biomass and necromass (IPCC 2006). Carbon stocks in natural forestland around the world have been estimated to total about 1146 gigatonne (Gt). The world's peatlands are thought to contain 180 to 455 Gt C on only a fraction of the total land area. The carbon stocks in natural forests in the tropical parts of Asia are larger than in sub-tropical regions, with an average range of 41–54 Gt C aboveground and about 43 Gt in the soil or an average range of 132–174 t/ha in plant biomass and 139 t/ha in the soil (Dixon et al. 1994).

Indonesia and several other countries in tropical regions, particularly Malaysia, Papua New Guinea and Brunei Darussalam, as well as having mineral soils also have peat soils (Histosols). Peat soils store much more carbon per unit area than mineral soils. The amount could be more than ten times the carbon stored in upland (mineral) soils, depending on the peat thickness.

Peatlands store carbon in plant biomass and necromass (above the surface and in the soil). In the soil, the carbon is stored in peat layers and in the elevated carbon content of the mineral soil layer below the peat layer (substratum). Of the various carbon stores, the largest stock in peatland is in the peat soil itself, followed by the plant biomass. In uplands, the carbon stored in plant biomass can exceed the carbon stored in the soil, depending on the type and density of crops covering the land (Hairiah and Rahayu 2010).

The concentration of carbon in peat soils ranges 30–70 kg/m^3 (or 30–70 g/dm^3), which is equivalent to 30–700 t/ha/m of peat depth. Thus, if a peat soil has a thickness of 10 m, then the carbon stock in it is likely to be around 3000–7000 t/ha (Agus and Subiksa 2008). In upland conditions, carbon stock in the 0–100 cm soil layer ranged 20–300 t/ha (Shofiyati et al. 2010) but at a depth of more than 100 cm the amount of carbon stored is so low that it

usually can be ignored. Peat thickness varied from 0.5 m to deeper than 15 m but the commonly found thickness was 2–8 m.

Formation of peatland often starts in a basin or shallow lake that gradually fills with organic material from dead plants. On further expansion the peatland may form a 'peat dome'. The edges of the dome tend to be thinner with less carbon stock whereas the central parts tend to be thicker and contain more carbon stock (Figure 1). However, this situation does not apply to all areas of peat. Often the relief of the bottom of the peat is not flat, but bumpy. Furthermore, not all landscapes of peat form a dome. Occasionally, peat formation ceases before a dome is formed, for example, owing to the influence of drainage and land clearing. Other peat areas develop in former river beds and the subsoil may still have traces of the meandering river, with a correspondingly high variability of peat depth, even though the surface appears to be even.

At the micro-spatial level, soil carbon content in the peat varies both vertically and horizontally. Linked to the process of peat formation there may be voids with very low bulk density that become covered. But next to such a void there may be dead trees that have not completely decayed and have high carbon density. This variation is a source of uncertainty in measuring peat carbon stock and a challenge. For example, if we are attempting to take samples using an auger and encounter dead wood we must abandon the place for one nearby, which may introduce a bias in the results.

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1.1.   Difference between peat and mineral soils

Peat soils differ from mineral soils in C_{org} content, structure, bulk density, distribution of carbon in the soil profile and the ease of burning and oxidation (Table 1). Therefore, the tools used for soil sampling and the soil depths that are sampled are also different between the two soil types.
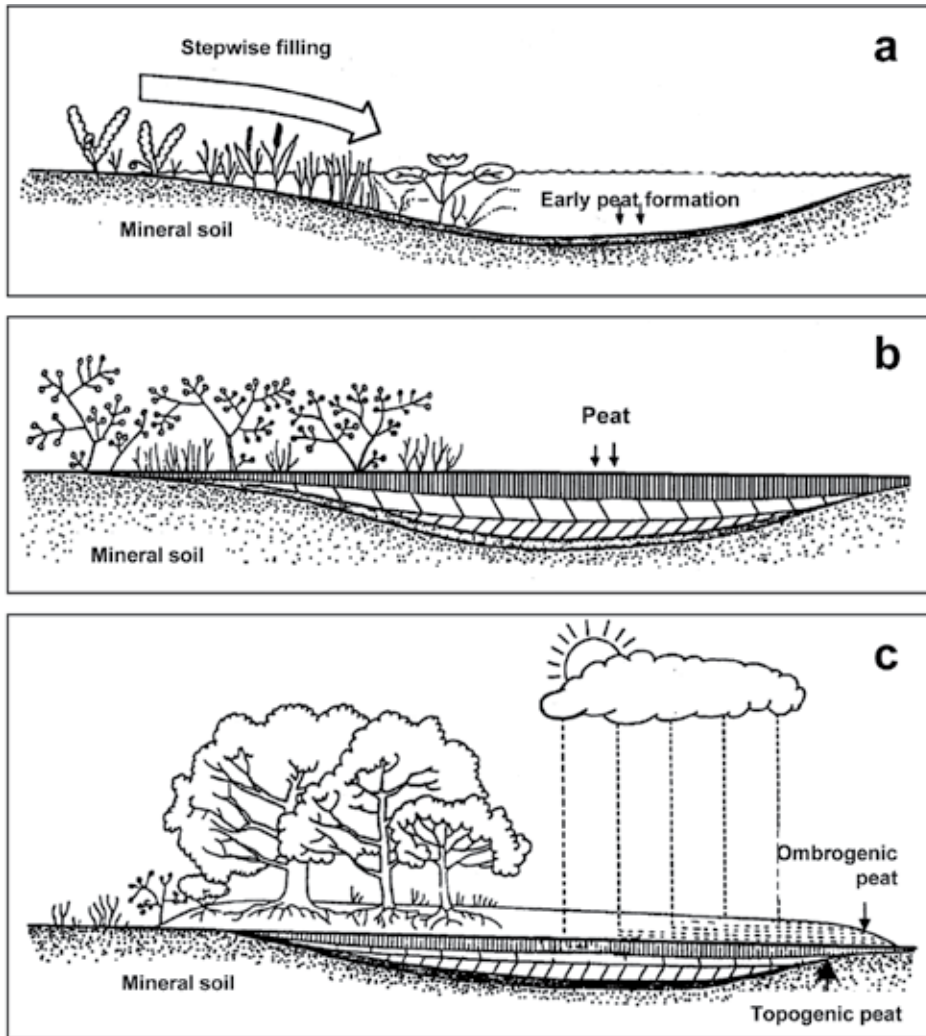
Figure 1. Schematic process of the formation and development of peat in a wetland basin landscape
a) Encroachment of shallow lake by wetland vegetation; b) Topogenic peat formation; and c) Formation of ombrogenic peat dome above topogenic peat.
Source: Noor 2001 from van de Meene 1984

Table 1. Some differences in the characteristics of peat and upland soils

Characteristics	Peat soil	Mineral soil
1. C_{org} content	Ranges 18–60%	Ranges 0.5–6% on most upland soils; around 10% on recent volcanic Andisols; and 8–20% on submerged wetland soils
2. Structure	Structureless and does not form clods	Depending on texture and degree of compaction, ranges from loose and aggregated to massive
3. Bulk density (BD)	Ranges 0.03–0.3 g/cm³ and under extreme conditions can be between <0.01 and >0.4 g/cm³.	Ranges 0.6–1.6 g/cm³, with values below 1 g/cm³ for undisturbed forest soils
4. Carbon distribution in the profile	High carbon content, homogeneously distributed from soil surface to the mineral soil interface at peat bottom	Mostly concentrated in the 0–30 cm layer
5. Ease of burning	Easily burned when dry; can be used as fuel	Not easily burned
5. Type of soil analysis for determining carbon stock	Carbon content and BD by layer from the soil surface to the bottom of the peat	Carbon content and bulk density by layers to a depth of 30–100 cm
7. Devise used for sampling for BD analysis	Peat auger. For BD, the unsaturated surface peat layer can be retrieved using sample rings. Soil blocks can be used to assess bias in the use of augers for bulk density estimates	Sample rings or small soil blocks

1.2. Carbon emissions from Indonesian peatlands

Under natural forest conditions, peatlands behave as carbon sinks. Natural peat forests, which are not affected by drainage (and prolonged droughts), grow slowly at a rate of 0–3 mm/year because of accumulation of dead tree trunks or branches on top of the soil and decompose slowly. But if the forest

is cleared and drained, the peatland changes from a sink to a CO_2 source. There are several factors that can alter the function of peatland from a sink into a CO_2 source.

1. Land clearing that increases the amount of sunlight onto the peat surface so that soil temperature and the activity of decomposing microorganisms increase. Felling of trees also increases the availability of fresh organic matter that easily decomposes into CO_2 under aerobic, and CH_4 under anaerobic, conditions. Thus, in addition to emissions from tree biomass, logging also accelerates decomposition of organic matter.

2. Drainage that decreases the peat watertable on the site and surrounding areas that are under agricultural and forest covers. Drainage changes the soil conditions from anaerobic (water saturated) to aerobic (unsaturated) and increases CO_2 emissions. Recession of the watertable can also occur naturally, such as under the influence of drought, but a high watertable dominates humid areas where peat is formed.

3. Peat fires. Fires increase CO_2 emissions owing to burning or oxidation of one or a combination of plant biomass, necromass and peat layers. Fires often occur during land-use change from forest to agriculture or other land uses. Fires can also occur during long drought periods. Under traditional farming practices, burning can be done intentionally to reduce soil acidity and improve soil fertility. But, on the other hand, this practice increases the contribution of peat to CO_2 emissions.

4. The addition of fertilizers and ameliorants. The addition of fertilizers, such as nitrogen fertilizers, lowers the ratio of soil C/N and encourages the decomposition of organic matter by microorganisms, followed by the release of CO_2. Nitrogen fertilizer can also contribute to N_2O emission. Fertilizing with manure or the addition of ameliorants that increase the pH of peat can also accelerate peat decomposition.

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Indonesia has about 15 million ha of peatland with belowground carbon stock of about 20-30 Gt. This is a revision of earlier peatland map by Wahyunto et al. 2004, 2005, 2006 using soil survey data. However, with increasing population and the demands of economic development, the exploitation of peat for various development purposes has also increased so that the amount of CO_2 emissions from peatlands is increasing. It has been estimated that CO_2 emissions from peat and related forest land uses

and land-use changes is more than 50% of the total emissions of Indonesia (Hooijer et al. 2010, Boer et al. 2010).

The Reducing Emissions from Deforestation and Forest Degradation (REDD) schemes currently in testing phases require that the carbon balance is measureable, reportable and verifiable according to international standards. This booklet provides a step-by-step guide to measurement of carbon stocks in peat soils, including examples of carbon stocks and emissions calculations. The last chapter describes the relationship between carbon stocks and CO_2 emissions from peat soils.

The measurement of carbon stocks in peatland as described in this booklet is supplementary to the carbon stock measurement technique according to the Rapid Carbon Stock Appraisal method developed by the World Agroforestry Centre Southeast Asia Regional Program (Hairiah and Rahayu 2007), with a focus on measurement at field level and its extrapolation to landscape level (Hairiah et al. 2011a, b).

The exposure of woody roots aboveground is direct proof of the subsidence of peat caused by peat decomposition and compaction (consolidation) under drainage conditions.

Carbon-stock-related peat properties

The main data needed to calculate carbon stocks in a peat landscape are:

- Bulk Density (*BD*), [g/cm³ or kg/dm³ or t/m³]
- Organic carbon content (C_{org}), [% by weight or g/g or kg/kg]
- Peat thickness. If the samples consist of many layers, the thickness of each layer with its respective *BD* and C_{org}, needs to be measured [cm or m]
- Area of land in which the carbon stock is to be estimated [ha or km²]

In addition to the above data, additional information on peat maturity or fibre content will be helpful.

2.1. Bulk density

Bulk density (*BD*) is the mass of soil solid phase (M_s) divided by the total soil volume (V_t). The total volume of soil is the sum of the volume of soil solid phase and the volume of soil pores (air filled and water filled) in an undisturbed (as in the field) condition. The BD determination of peat soils in principle is the same as that of mineral soils (see Chapter 2.4.2. in Hairiah et al. 2011a), but the sampling and handling procedures are different because of the different properties of the two types of soils.

M_s is determined from oven dry weight at 105 °C for 48 hours or more, until constant weight is achieved (no reduction in sample weight when the samples are dried for a longer time). Often the samples taken from the field are very wet and when a sub-sample is taken for drying it tends to cause substantial errors in the *BD* measurement. For that reason, usually the whole sample taken with a peat auger is quantitatively transferred into an aluminium can for drying at 105 °C for 48–96 hours to reach the constant weight.

BD values of peat soils generally range between 0.03 and 0.3 g/cm^3. However, within a peat profile, sometimes pockets may exist which are nearly empty of peat and filled with water, with a *BD* of < 0.01 g/cm^3. This condition is often found in natural peat forests. By contrast, the *BD* of a peat surface layer under several years of agricultural use may increase to as high as 0.3 to 0.4 g/cm^3.

BD is determined in the laboratory by a gravimetric method of weighing the oven dry weight of a known volume of peat. The samples used for the analysis may be samples taken using a peat auger (Ejkelkamp model), ring sample or cubical sample as long as the sample volume can be determined easily.

According to Maswar (2011), division by a correction factor of 1.136 is needed to correct for compaction that occurs at the sampling stage. This correction factor was established by comparison of auger samples and large blocks of peat obtained from soil pits and is considered to represent the real condition in the field.

2.2. Soil carbon content

The organic carbon content of soil can be determined by one of several methods, namely, dry combustion (loss on ignition (LOI)), Walkley and Black procedure (1934) or CN auto-analyzer. For peat soil, the CN autoanalyzer or LOI techniques are more preferable than the Walkley and Black. The LOI method is relatively simple but nevertheless gives a fairly accurate figure for determining the ash content (inorganic material) and peat organic matter because with this method the soil organic matter can be burned completely. However, LOI technique semi-quantitatively estimate peat carbon content by multiplying peat organic matter content with a constant of 0.58. On the other hand, under the Walkley and Black technique, there is a possibility of incomplete digestion of organic matter, leading to underestimating the carbon content value. The CN autoanalyzer is a direct method (measuring carbon or CO_2), however, the amount of sample analyzed is very small (a few milligram), such that ensuring the representativeness of the sample is critical and duplicate measurements are needed. In this booklet, we limit explanation to the LOI technique only , although for the quantitative analysis the CN auto-analyzer technique is preferable.

2.3. Peat maturity

Peat maturity observation is useful for assessing peat fertility and carbon content. The more mature the peat, the generally more fertile, although many other factors also determine fertility, including clay or ash mixture. The more mature peats also tend to have a higher carbon content per volume. Observation of peat maturity can be done in the field or in the laboratory based on fibre content, which will be discussed in the next section.

3

Peat soils differ in properties from mineral soils and require different methods and tools for sampling.

Carbon stock determination of peat soil

Measurement of carbon stocks in a landscape or peat dome consists of three stages.

1. Determination of sampling points
2. Peat soil sampling
3. Analysis of samples and calculation of carbon stocks

3.1. Determination of sampling points

For mapping the carbon stocks in a landscape or dome, the points of sampling may be according to 'grid' or from multiple transects across the peat dome, for example, north–south, east–west, northeast–southwest and northwest–southeast so that a range of peat thicknesses will be represented. Usually, the peat tends to be thicker closer to the centre of a dome. However, the surface of the underlying mineral soil at the bottom of the peat is usually irregular, tending to be bumpy. The more irregular the surface of the underlying mineral substratum the higher the variation of thickness and carbon stocks. This requires a more intensive sampling.

Figure 2 shows the two approaches to determine sampling points. Sampling using the grid system requires more observation points. The number of observation points and the total area represented by each grid is determined by the scale of the map or the level of accuracy required in the measurement. For the mapping scales of 1:10 000, 1:25 000, 1:50 000 and 1:250 000 an ideal sampling intensity is one sampling point for 1 ha, 6.25 ha, 25 ha and 625 ha, respectively. However, this approach will require a very high number of soil samples. This method is less popular nowadays, even

for mapping mineral soils, unless the area to be mapped is relatively small. A more frequently used approach is the 'terrain' technique, which is based on physiographic conditions, grouping land of similar properties (Aguilar et al. 2005). For peatland, we encourage the use of the transect approach (Figure 2B) so that the number of samples can be reduced without compromising quality.

Distance between observation points in a transect is determined by the scale of the map and the variation of peat thickness and properties. For large areas, additional transects (observation points) may be added between existing transects. When detailed observation is required, then the distance between one point to another in the grid or within each should be approximately 500 m. Our experience in several locations indicates that within 50 m distance the variation in peat thickness can range 10–50 cm, indicating that a more intensive sampling may be necessary.

The coordinates of each point of measurement must be recorded by using a global positioning system (GPS). Based on the pair of sampling points coordinates and the peat thickness, we can generate a contour map of peat thickness by using a geographic information system (GIS) with a schematic model, as presented in Figure 3. For the assessment of carbon stocks in a landscape or peat dome, the peat *BD* and organic matter content data will be required in addition to the peat thickness contour map.

At all selected observation points, the observation of carbon stocks aboveground (plant biomass and necromass) should also be determined according to the procedure of the Rapid Carbon Stock Appraisal (RaCSA) method, which is described in Hairiah et al. (2011a). To generate the pairs of data of plant biomass, necromass and peat (belowground) carbon, peat samples can be taken in the middle of the small plots (5 x 40 m) or large plots (20 x 100 m) when there are large trees with diameter greater than 30 cm, depending on the plot used in the measurement of biomass and necromass (Figure 4). Should intensive carbon stock observation be required, then the peat soil sampling may be distributed within the RaCSA plots.
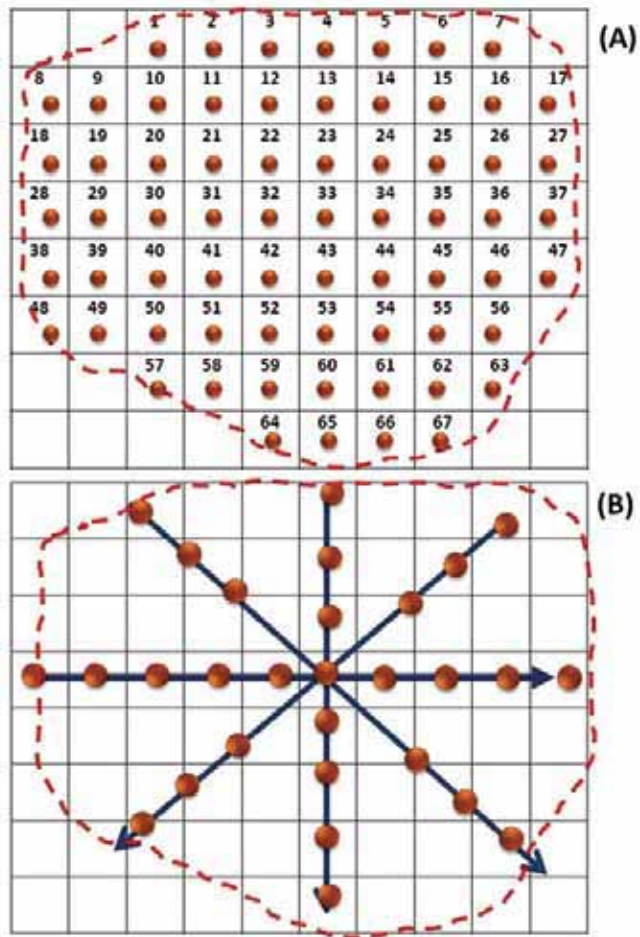
Figure 2. Schematic diagram of sampling points within a peat dome using the grid or transects methods
(A) Grid or regular sampling points; (B) transects north–south, east–west, northwest–southeast, northeast–southwest. ● = Point of observation determined by GPS
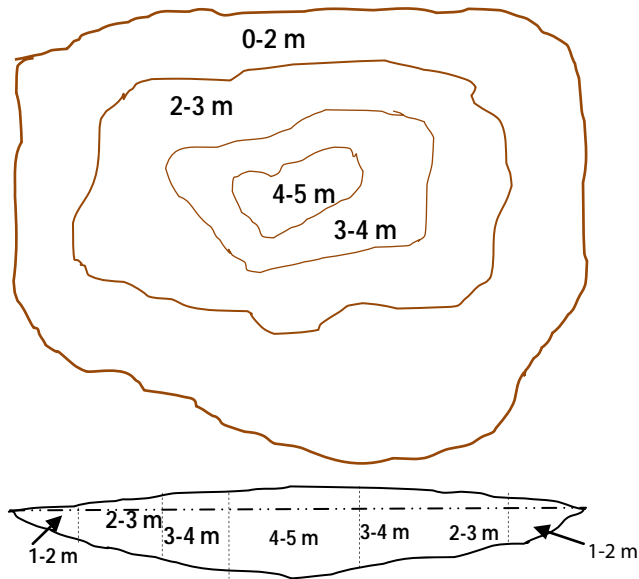
Figure 3. Peat thickness maps
Sample maps based on west–east transect: (top) peat thickness contours; (bottom) cross-sectional thickness
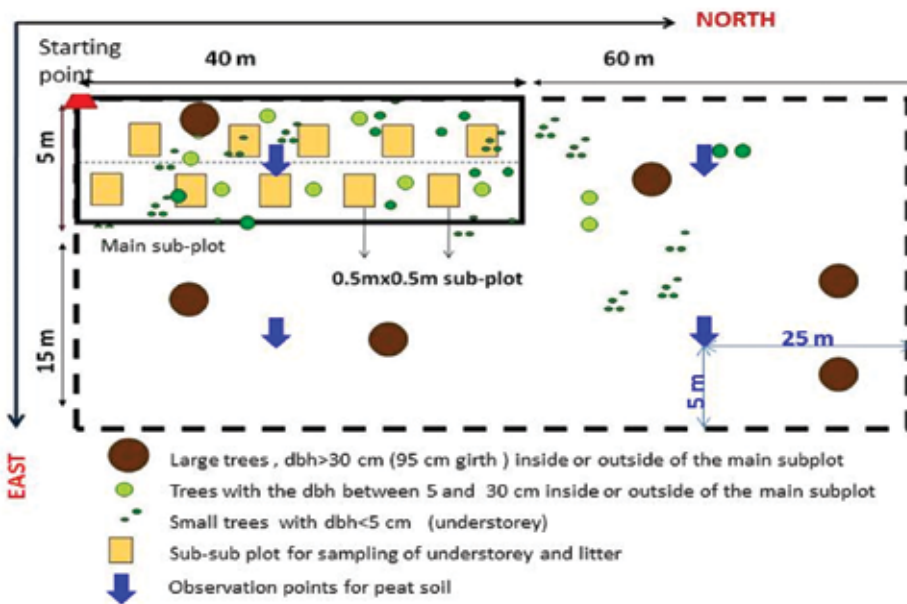
Figure 4. Observation plots of biomass and necromass (Hairiah et al. 2011a) and peat sampling point placement

3.2. Peat soil sampling

3.2.1. The kinds of peat samples

In general, soil samples taken in the field can be divided into two kinds, that is, intact (undisturbed) and disturbed soil samples.

Undisturbed soil samples are those which structure is similar to the actual structure of the peat in the field. Disturbed soil samples are those which structure is different from the original structure because of disturbance during sampling, handling and transportation. (Nearly) undisturbed soil samples can be obtained using a peat auger or soil core (hollow tube, which is also known as 'soil rings'). Disturbed soil samples can be taken with a regular soil auger, hoe, shovel or machete.

For peat sampling, the use of peat auger is recommended (Figure 5, left) because it can be used to sample almost undisturbed soil from the top to bottom layers. A peat auger can be used even under inundated conditions. Samples taken by a peat auger can be used for the analysis of bulk density, water content (% volume) and chemical properties including the carbon content.

Soil cores can be used for sampling the mature surface layer of peat under unsaturated condition. Soil cores cannot be used for fibric (immature) peat or when the peat is saturated. As with the use of soil cores, cube-shaped samples can only be taken for the surface layer of mature (sapric maturity) unsaturated peat.

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3.2.2. Peat sampling using peat auger

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Box 1. Tools and materials

a)   Peat auger (see pic below), consisting of peat sampler, extension rods and one handle

b)   Number 23 spanner or wrench (2 pcs) to install and disassemble the extension rods

c)   Metre stick or tape (2 m long) for measuring the thickness of the peat layers, the depth of charcoal or clay layers (if any) and the watertable.

d)   Fifty-metre-long metre tape for measuring the distance between observation points on a transect

e)   Knife or plastic spatula

f)   Brush and cloths for cleaning the auger

g)   Bucket

h)   Plastic bags

i)   Labeling cards

j)   Markers

k)   GPS device

Extension rods

Handle

Gouge and fin
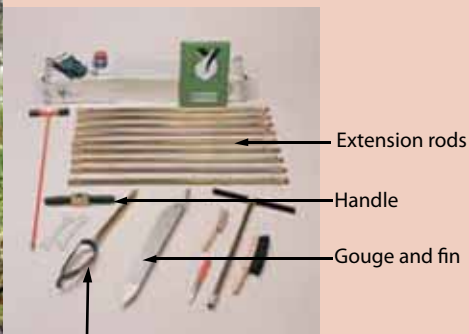
Edelman auger

</div>

Box 2. The main parts of a peat auger (Eijkelkamp model)

The main section (sampler) of a peat auger consists of a hooked blade (fin) and a half-cylindrical tube (gouge) that has one sharp edge to cut the peat. The sampler can be easily connected to the extension rods and auger handle using two no. 23 spanners or wrenches.

Figure 6. The peat auger
The stainless steel bottom part of the peat sampler has an auger body consisting of a half-cylindrical sampler containing a section or 'gouge' (1) with a large cone (2) at its bottom end. The gouge has one cutting edge and is sealed by a hooked blade or 'fin' (3) hinged on the auger body. The blade's top and bottom ends' width are identical to the auger's width but is wider in the middle. The protruding, rounded side has a cutting edge

The large cone serves to push aside the soil when the sampler is inserted. At that stage, the blade seals off the gouge. When the auger is given a half turn (180°) to fill, the resistance will cause the blade to remain in position. When the auger is hoisted, the other side of the blade seals off the gouge.

3.2.3. Procedure for peat sampling
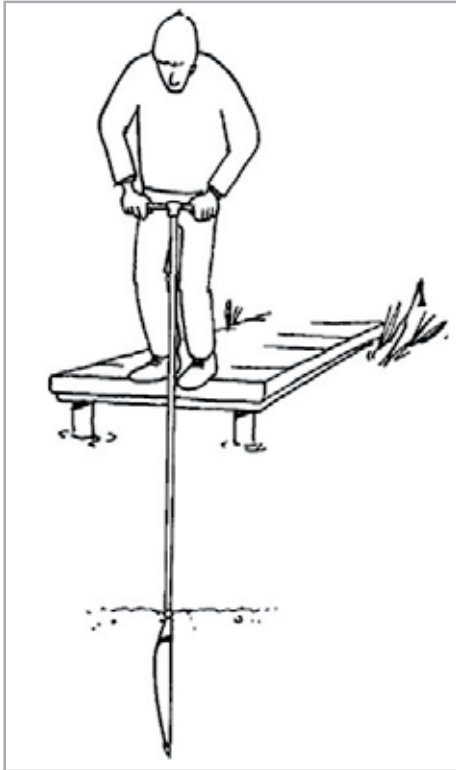
Figure 7. Using the peat auger on inundated peat

1) Attach the handle and the extension rods according to the desired depth of sampling.

2) Connect the main bottom part of the auger to the extension rods using two no. 23 spanners or wrenches to tighten the connection.

3) Turn the fin to have the concave part facing the outside of the tube.

4) Drive the auger vertically into the peat without turning it until the desired depth is reached. The fin closes the gouge such that no sample enters the gouge at this stage. The cone at the bottom of the auger pushes the peat aside.

5) If a hard layer is found, do not force the auger using a hammer as it will damage the auger.

6) After the auger reaches the desired depth, turn it clockwise at least 180˚. While the gouge rotates, the fin stays at its position, the gouge is filled with peat and the fin closes so that no additional peat enters the gouge.

7) Pull the auger slowly out and lay it on a plain surface covered by a plastic sheet with the fin facing upward. Turn the fin until the samples appears on top of the concave surface (Figure 8).

Figure 8. Peat sample appearing from the gouge on the fin's surface
Peat in the bottom picture is more mature than that in the top picture

8)   Store the peat samples in accordance with their intended uses. For example, for peat carbon dating, the samples can be stored in a PVC pipe cut in half and covered with aluminium foil. For the determination of water content (% volume) and BD, the peat and water from the auger must be quantitatively transferred into plastic bags (Figure 9) so that no fluid is spilled and the volume does not change (from 500 cm^3). Sometimes the 50 cm-long samples need to be cut into 2–3 parts if, for example, there are differences in maturity or if there is a layer of clay or ash at certain depths. Each piece of 10 cm length has a volume of 100 cm^3.

Figure 9. Peat samples
Labelled and sealed in plastic bags, ready for transportation to the laboratory for analysis

Notes

- Mark the extension rod with masking tape for each 50 cm increment of augering depth so that the error in depth determination can be minimized.

- Sampling with a peat auger will enable separation of samples at various depths as needed. An auger set of nine extension rods can be used to take samples to a depth of 10 m. Peat sampling to a depth of 400 cm is relatively easy to do but sampling at deeper depth will be more difficult.

- If the auger fin enters a hard or stony layer, or undecomposed large roots, the gouge may not be filled and the fin may not close properly. In such circumstances, the augering needs to be repeated at another point nearby otherwise the volume of sample will be < 500 cm^3.

- Do not use a peat auger in hard layers because they can damage the auger. Use an ordinary soil auger (Edelman auger) to penetrate hard layers above the intended peat sampling depth.

- Using Edelman auger to penetrate the sampling layer would disturb the peat so that they were no longer suitable for bulk density determination.

Box 3. Maintenance of peat auger

- The auger must be kept clean. After use, wash the auger with fresh water.

- Use a brush to clean the threads at each end of the extension rods.

- Dry the auger using a dry cloth and let it completely dry under the sun.

- Keep the auger in its bag or box.

3.2.4. Undisturbed soil sampling using soil core

The method of peat sampling using soil cores is the same as for mineral soils. However, only mature and relatively dry peat can be sampled using a soil ring. Stages of sampling using the rings are shown in Figure 11 (modified from Suganda et al. 2007).

1. Clean the soil surface of litter and small plants.

2. Dig a circle with a diameter of about 20 cm to a desired depth. For example, to 5 cm if the sample is to be taken from a depth of 5–10 cm. Trim the soil with a knife or a machete.

3. Put a ring on the ground vertically.

4. Put a small block of wood on the ring, press slowly until three-quarters of the ring is inserted into the soil.

5. Put another ring on top of the first one, and press until about 1 cm of the second ring is inserted in the soil.

6. Separate the upper ring from the bottom ring slowly.

7. Dig the ring using a shovel or a machete. In digging, the tip of the shovel should be deeper than the lower end of the ring so that 1 or 2 cm of the soil beneath the ring is lifted up.

8. Slice excess soil on top of the ring with caution and close the ring using a plastic cap that attaches snugly to the ring. Then slice the excess soil at the bottom of the ring and close it with another cap.

9. Attach a paper label to the cap of the ring that gives the sample's location, date of sampling and depth of sample.

Figure 10. Soil core (soil ring) for undisturbed soil sampling
Soil rings with and without caps. Ring diameters typically range 5–7.5 cm and
heights 2.5–6 cm. Rings of small diameter may cause more damage to soil samples.

Figure 11. Stages of undisturbed soil sampling using soil core
(From top left to bottom right)

3.2.5. Soil sampling using hollow box of galvanized iron sheet

Similar to sampling with a soil ring, this method is only applicable for
mature and dry peat. Alternatively, a peat cube can be created with a knife
or machete (Figure 12) without the use of soil core or soil sampling box. The
method of sampling with a metal box is similar to that using a soil ring. The
detail is described in Hairiah et al. (2011a).

> **Note:**
>
> The main purpose of using a metal box or ring for peat sampling is to take soil samples with known volumes under field conditions. For the BD or water content (% volume) measurements, each sample from the soil core can be quantitatively transferred into a plastic bag so that the same ring can be used to take more samples. But for analysis of soil water tension (pF), samples must be maintained in the ring so that the structure is not disturbed.

Figure 12. Cubical and fluid peat samples
Cubical (left) and fluid (right) samples taken with an Eldeman auger from depths below the watertable

3.3. Measurement of bulk density and organic matter content

For the determination of carbon stocks in peat soil the data of BD, C_{org}, the thickness of the peat and area of the landscape or dome are required.

3.3.1. Bulk density

Peat BD is determined in the laboratory by a gravimetric method. Samples to be used for BD analysis can be taken using a peat auger (for example, Ejkelkamp model), a soil core or hollow metal box, each with associated sample volume. The method of soil sampling is as described above.

Determination of BD

1. Transfer each sample obtained with peat auger or ring quantitatively into an aluminium cup. If using a soil core, each sample can either be removed from the core or the core with sample inside can be placed in an aluminium can for oven drying.

2. If the data of soil moisture content is required, then weigh the wet soil inside the cup. The mass of wet soil (M_t) is $M_w + M_s$, where Ms is the mass of the dry soil and Mw is the mass of water contained in the soil matrix (Figure 13).

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3. Dry the soil samples in an oven at 105 °C for 2 x 24 hours or until the constant weight is achieved. If the sample is very wet, it may take 4–5 x 24 hours to reach the constant weight. The constant weight is obtained when the sample weight does not decrease after subsequent drying. For example, if the weight of sample that is dried for 2 x 24 hours is still higher than the sample that was dried for 3 x 24 hours, then the drying should be continued.

4. Put the dry soil within the aluminium can in a desiccator for about 10 minutes.

5. Weigh the dry weight of the soil (M_s) plus the can weight (M_c).

6. Save the soil samples for analysis of organic materials with the LOI method. If the carbon content is to be determined by CN analyzer or Walkley and Black method, the oven-dried soil samples cannot be used, instead air dried samples must be used.

Determine the volume of soil samples, V_t. If soil samples are taken with the soil ring, then $V_t = \pi r^2 t$, where r is the inside radius and t is the height of the ring. If the samples are from an Eijkelkamp peat auger with a thickness (sample length) of 50 cm, then $V_t = 0.5$ dm³ $= 500$ cm³. If a 20 cm-long peat sample was taken from the peat auger, then $V_t = 200$ cm³.

Calculate *BD* as

$$DB = \frac{M_s}{V_t} = \frac{(M_s + M_c) - (M_c)}{V_t} \qquad [1]$$

$$V_t = V_s + V_w + V_a$$
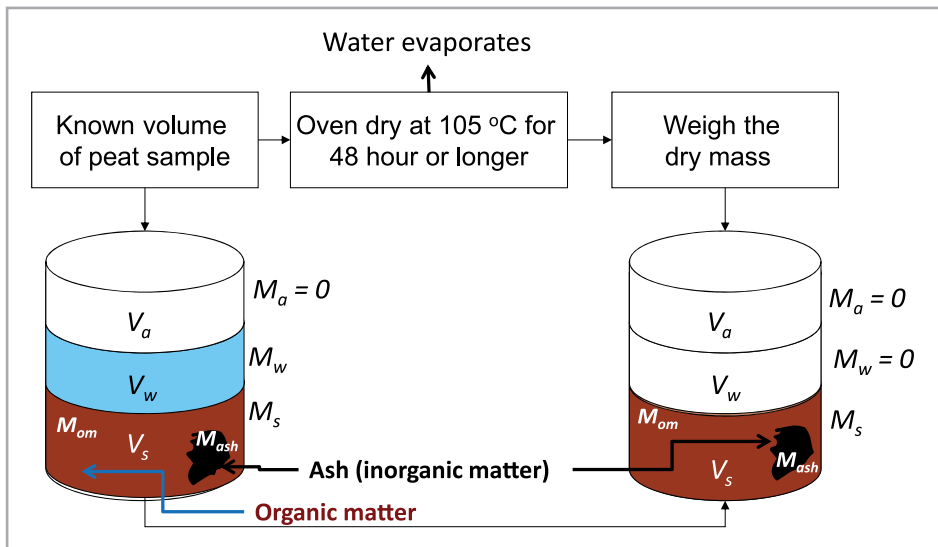
Figure 13. Illustration of peat soil volume
Peat soil volume consists of the volume of soil solids (V_s), liquid (V_w) and gas (V_a) and the mass of soil solids (M_s), water (M_w) and air (M_a). The mass of soil solids, M_s, is the sum of the mass of organic matter, M_{om}, and ash M_{ash}

If the unit weight is gram (g) and unit volume is cm³ then the unit for *BD* is g/cm³. This unit is equivalent with kg/dm³ or t/m³.

Wash and dry the cans in the oven at 105 °C for 1 2 hours. Weigh each can, M_c. Soil water content (by volume), KA_v, can be calculated as:

$$KA_v = \frac{V_w}{V_t} = \frac{\{(M_s + M_w + M_c) - (M_s + M_c)\} / \rho_w}{V_t} \qquad [2a]$$

Water content by weight, K_{Am},

$$KA_m = \frac{M_w}{M_s} = \frac{M_t - M_s}{M_s} \qquad [2b]$$

Units used are cm³/cm³ and g/g to give an indication that the water content was calculated based on volume and weight, respectively. The unit can be written in the form of %.

The value of water content by volume (KA_v) can be converted into water content by weight (KA_m) with the formula:

$$KA_m = KA_v * \rho_w / BD \qquad [3]$$

Where ρ_w is water density which is approximately 1 g/cm³

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3.3.2. Soil organic carbon content

Determination of soil organic matter content with the LOI method.

The mass of soil solids, M_s, as illustrated in Figure 13, consists of the mass of organic matter, M_{om}, and the mass of ash, M_{ash}. In the LOI method, all organic matter present in the soil sample is burned at a temperature of 550 °C for 6 hours. The burned organic matter will evaporate and the remaining material is inorganic matter such as clay, silt and other non-combustible substances that are collectively called ash for the purpose of this analysis. The mass lost from the sample equals the mass loss of organic matter. Conversion of organic matter to organic carbon content uses the conversion factor of 1/1.724. This method is a semi-quantitative one, since the mass lost during

the conversion reflects only the organic matter content and the conversion factor of 1/1.724 is a generalized relationship between organic matter and carbon content.

Procedure of LOI

1) Grind thoroughly one tablespoon of oven-dried soil (from Step 6, section 3.3.1 above) by using a porcelain mortar and pestle (Figure 14).

2) Weigh a 1 or 2 g fine peat sample and transfer quantitatively into a porcelain cup of known weight, M_c.

3) Arrange the porcelain cups containing the samples in a furnace (Figure 15).

4) Close the furnace and gradually raise the temperature. Leave for one hour for every 100 °C increase of temperature until the temperature reaches 550 °C. Let the ignition take place at 550 °C for 6 hours.

5) Turn off the furnace and allow to cool down for approximately 8 hours.

6) Weigh the weight of ash remaining in the cup, M_{ash}.

Figure 14. Porcelain mortar and pestle
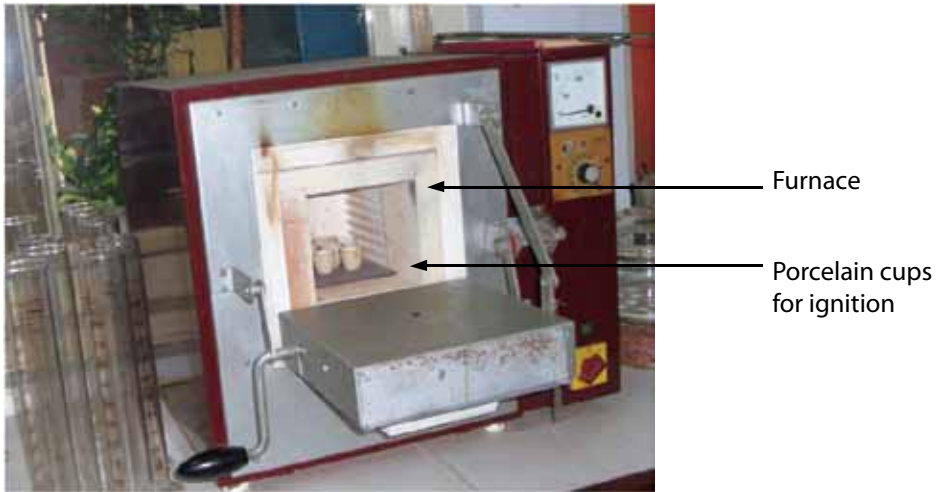
Figure 15. Porcelain cups inside a furnace

7) Weigh about 3 g (BB = wet weight) fine sample from Step 1 of this procedure into an aluminium can of known weight. Oven dry for 2 4 hours at 105 °C and weigh the dry weight (BK). Calculate the water content as:

$$KA_m = \frac{BB - BK}{BK} * 100\% = \frac{(M_s + M_w) - M_s}{M_s} * 100\% \qquad [4]$$

Equation [4] is identical with Equation [2b] where $M_s + M_w = M_t$.

Calculate the soil sample dry mass as,

$$M_s = M_t * (1 - KA_m) \qquad [5]$$

M_t in this case is the 1 or 2 g sample used in the ignition (Procedure 2) above. Equation [5] applies when using the unit mass fraction of KA_m (the mass of water/the mass of dry soil). However, when KAm uses the % by weight unit then equation [5] becomes,

$$M_s = M_t * (100\% - KA_m\%)$$

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Calculate organic carbon content, C_{org}, based on dry weight (g of C/g of dry soil):

$$C_{org} = \left\{ \frac{M_s - M_{ash}}{M_s} \right\} / 1.724 = \left\{ 1 - \frac{M_{ash}}{M_s} \right\} / 1.724 \qquad [6]$$

The ash content can be calculated as:

$$\text{Ash content (\%)} = M_{ash}/M_s * 100\% = 100\% - C_{org}\% \qquad [7]$$

C_{org} content is usually expressed in % by weight or weight fraction of organic matter to total dry weight. Organic matter content by soil volume, C_v, can be calculated as:

$$C_v = BD * C_{org} \qquad [8]$$

C_v is expressed in g/cm³ or kg/dm³ or t/m³ (Mg/m³). C_v is the weight of organic carbon per unit volume of soil.

Page et al. (2002) suggest an average value of C_v of 0.06 t/m³. However, observation of hundreds of peat samples that originated from Sumatra and Kalimantan (Agus et al. 2011a; Table 2) shows a high variation of C_v value by peat maturity. C_v ranged 0.082 ± 0.035 t/m³ for peat with sapric maturity, 0.057 ± 0.026 t/m³ for hemic maturity and 0.046 ± 0.025 t/m³ for peat with fibric maturity. Thus, the recommended value of Page et al. (2002) approaches the value for peat with hemic (medium) maturity. Generalization of C_v value results in errors in carbon stocks and emissions estimates using the subsidence approach (described further in Chapter 4).

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Table 2. Mean and standard deviation of selected peat properties based on samples from Sumatra and Kalimantan

Peat properties	Maturity*								
	Sapric (n = 263)			Hemic (n = 904)			Fibric (n = 659)		
C organic (%)	48.90	±	8.91	52.27	±	8.52	53.56	±	6.48
Bulk density (t/m³)	0.174	±	0.082	0.117	±	0.073	0.089	±	0.058
Ash content (%)	9.98	±	13.67	8.89	±	12.67	5.69	±	9.25
C_v (t/m³)	0.082	±	0.035	0.057	±	0.026	0.046	±	0.025

* Method of peat maturity determination is explained in section 3.3.3. Source: Agus et al. 2011

The range of peat BD is generally about 0.02–0.3 t/m³ depending on maturity and compaction, as well as the the ash content. C_{org} content of peat ranges 18–58% if the analysis is using the LOI method. If C_{org} is analyzed by direct methods, such as CN autoanalyzer, then the maximum C_{org} can be slightly greater than 60%.

Example of calculation:

(i) Determination of carbon stocks at one point of observation

Given that the soil *BD* of peat layers 0–20 cm, 20–50 cm, 50–100 cm, 100–150 cm and 150–180 cm, respectively are 0.12; 0.10, 0.09; 0.11 and 0.15 t/m³ and the consecutive ash content is 4%, 3%, 2%, 2% and 15%, what is the carbon stock for each layer and what is the total carbon stock of this peat per hectare?

Solution:

BD data and ash content of the soil for each layer and the calculation are presented in Table 3.

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Table 3. Example of calculation of carbon stocks in peat soil from one point of observation

Layer (cm)	Thickness per layer (m)	Volume per layer (m³/ha)	BD (t/m³)	Ash content (%)	C_{org} (%)	C_v (t/m³)	C stock per layer (t/ha)
A	B	C	D	E	F	G	H
	Given	Column B x 10 000	Given (from soil analysis)	Given (from soil analysis)	(100% - column E)/1.724	Column D x (column F /100)	Column C x column G
0–20	0.2	2000	0.12	4	55.68	0.067	134
20–50	0.3	3000	0.10	3	56.26	0.056	169
50–100	0.5	5000	0.09	2	56.84	0.051	256
100–150	0.5	5000	0.11	2	56.84	0.063	313
150–180	0.3	3000	0.15	15	49.30	0.074	222
						Total	1093

C_{org} is calculated by the equation [6] or = 100% - ash content (%); C_v is calculated by the equation [8] and C stock equals C_v * soil volume. From this calculation it was found that the soil carbon stock in this location was about 1093 t/ha from the surface to 180 cm depth.

(ii) Calculation of carbon stocks in a landscape or peat dome

Carbon stocks in a landscape of peat soil can be calculated by using the data of area of each class of peat depth (A_i), the average thickness of the peat in each thickness class (h_i) and the average data for *BD* and C_{org} for each peat layer and peat area. Peatland area for each thickness class can be calculated using a thickness contour map (Figure 3 above) by using a GIS tool.

$$C_{stock} = \Sigma (A_i * h_i * BD * C_{org}) = \Sigma (A_i * h_i * C_v) \qquad [9]$$

Determination of peat maturity

Peat maturity level is divided into three classes: sapric, hemic and fibric. In practice, there are three indicators used for field evaluation and one indicator for laboratory evaluation (Table 4).

Table 4. Indicators used for differentiating peat maturity in the field and in the laboratory

Indicators	Fibric (immature) peat	Hemic (medium) maturity	Sapric (mature) peat
1. Decomposition stage	Peat at early decomposition stage, with its original materials still recognizable	Half-decomposed peat, with some original materials are still recognizable	Decomposed peat in which the original materials are no longer recognizable
2. Colour	Brown–light brown	Brown	Dark brown–black
3. When squeezed in the palm the amount of fibre remaining	More than two-thirds of the initial amount	One-to-two-thirds of the initial amount	Less than one-third of the initial amount
4. Fibre content (%) using laboratory method	> 75	15–75	< 15

Determination of peat maturity with field technique

The method of determining the maturity of peat in the field is quite simple but it provides very useful and relatively accurate information when determined by an experienced technician.

Take a handful of peat from the desired depth and squeeze in the palm of the hand.

- Fibric (immature) peat is peat at early maturity stage with original materials still recognizable, brown to light brown in colour and when squeezed in the palm, more than two-thirds of its original amount remains in hand.

- Hemic (medium) maturity is half-decomposed peat with some of the original materials still recognizable, brown in colour and when squeezed in the palm between one-third and two-thirds of the original amount remain.

- Sapric (mature) peat is at an advanced stage of decomposition with original materials not recognizable, is dark brown to black in colour and when squeezed in the palm less than one-third of the original amount remains.

Figure 16. Determination of peat maturity in the field
Simply squeeze a handful of peat. The sample in the right hand of the surveyor is fibric and the one in the left is hemic

Determination of peat maturity in the laboratory

1) Fill a 10 ml or 25 ml syringe (Figure 17) with peat sample

2) Press the sample using the syringe pump and record the volume, *Vol 1*, when the sample can no longer be compressed

3) Transfer the sample into a 150 μm or 0.0059 inch sieve

Figure 17. 10 ml syringe (left) and a sieve (right)

4) Use a shower spray or a rinsing bottle to wash out the fine materials

5) After the fine materials have been thoroughly washed out of the sieve, transfer the coarse fibre again into the syringe and press. Record the volume, *Vol 2*

6) Calculate the fibre content = *Vol 2/Vol 1* X 100%

7) Group the peat maturity based on the criteria:

- Sapric peat is decomposed peat with a fibre content less than 15%

- Hemic peat is half-decomposed peat with fibre content 15–75%

- Fibric peat is immature peat with fibre content greater than 75%.

4

Burning is often still used in land clearing and preparation. If the watert¬able is below 30 cm and the peat is dry, fire can burn surface peat layers and decrease the carbon stock.

Estimation of greenhouse gas emissions

A reduction of carbon stock translates to carbon emissions and an increase in carbon stock translates to carbon sequestration. Carbon emissions data are normally expressed as CO_2-e (CO_2 equivalent).

Peatland emits greenhouse gases in the forms of CO_2, CH_4 (methane) and N_2O. Of the three gases, CO_2 is the most important because it forms the highest amount emitted by peatland, especially converted peat forest to agriculture or settlements. CH_4 is measurable in peat forests that are normally saturated or submerged. CO_2 emissions dominate drained peat, whereas CH_4 emissions decrease significantly or even become undetectable in drained peatland. N_2O emissions occur from nitrogen-rich soils. Part of the leached nitrate into the anaerobic layer is reduced into N_2O. In general, CO_2 emissions from peat soil can be calculated based on the change in carbon stocks within a given period of time.

Carbon storage in peatlands is the largest in (belowground) peat soil, second, in the plant biomass and, third, in the necromass. Each component of carbon stock may be increased or decreased depending on natural factors and human intervention. Droughts result in a decreased watertable, which could subsequently accelerate CO_2 emissions from peat soils. Agricultural land management practices on peatland, such as burning, construction of drainage and fertilization affect CO_2 emission levels. Peat fires can lower the carbon stock in plant biomass and in the peat, which translates to increased emissions from both sources. Fertilization can increase emissions owing to increased microbial activity. On the other hand, reducing the depth of the watertable in drained peatland through installation of canal blocking is likely to reduce the amount of emissions.

Plant growth is a process of CO_2 captured from the atmosphere through photosynthesis and stored as carbon in plant tissue. The process of plant growth, especially of tree crops, increases carbon stocks in a landscape.

Therefore, the amount of CO2 emissions at a certain time interval can be estimated by the formula:

$$E = \frac{(E_a + E_{bb} + E_{bo} - S_a)}{\Delta t}$$

[10]

E_a = Emissions owing to aboveground biomass decomposition

$$E_a = C_b \times 3.67$$

Where C_b is the biomass (and necromass) carbon stocks that are subjected to decomposition upon land-use conversion. The index 3.67 is the conversion factor from C to CO_2. According to the IPCC (2006), when land is cleared it is assumed that all (100%) of plant biomass carbon is oxidized into CO_2 through either burning or decomposition by microbes or a combination of both. Supposing that a peat forest is cleared with aboveground carbon stock in the plant biomass as high as 100 t/ha, then the amount of emissions from this source are

$$E_a = 100 \text{ t/ha C} \times 3.67 \text{ } CO_2/C = 367 \text{ t/ha } CO_2.$$

If the total forest area that was cleared was 6000 ha, then the emissions from the plant biomass would be

$$Ea = 367 \text{ t/ha } CO_2 \times 6{,}000 \text{ ha} = 2{,}202{,}000 \text{ t } CO_2.$$

The method for determining carbon stock in plant biomass is elaborated in Hairiah et al. (2011a).

E_{bb} = CO_2 emissions owing to peat fire. When a layer of peat is completely burned, then the organic matter will be oxidized, resulting in CO_2 and H_2O and a number of other gases.

E_{bb} = Volume of burnt peat (m³) x BD (t/m³) x C_{org} (t/t) x 3.67 CO_2/C

= Volume of burnt peat (m³) x C_v (t/m³) x 3,67 CO_2/C

The volume of burnt peat can be estimated by measuring the volume of the peat basin formed after the fire, with the basin being the portion of initial peat that is completely burned.

For example, if 6000 ha of peat with properties similar to the example in Table 2 burnt evenly to a depth of 30 cm, then

The volume of burnt peat from the 0–20 cm layer = 0.2 m x 6000 ha x 10 000 m²/ha = 12 000 000 m³.

E_{bb} (the amount of CO_2 emissions from the 0–20 cm layer)

= Volume of burnt peat x C_v x 3,67

= 12 000 000 m³ x 0.067 t/m³ C x 3.67 CO_2/C

= 2 950 680 t CO_2

The volume of burnt peat from the 20–30 cm depth = 0.1 m x 6000 ha x 10 000 m²/ha = 6 000 000 m³.

E_{bb} (the amount of CO_2 emissions from 20–30 cm layer)

= 6 000 000 m³ * 0.056 t/m³ C x 3.67 CO_2/C

= 1 233 120 t CO^2

Total emission from the 0–30 cm layer

= 2 950 680 t CO_2 + 1 233 120 t CO_2 = 4 183 800 t CO_2

Note: In reality the burning is never evenly distributed. It can enter into a few metres of dry peat while some parts of the surface are only partially burnt.

E_{bo} = Emissions from peat decomposition. There are various factors that affect the rate of peat decomposition. The most important one is the depth of the watertable, but under the same watertable emission rates can be different depending on the maturity of the peat, fertilizer application and the influence of plant root respiration. Plant root respiration must be discounted from emission calculations because it is compensated by CO_2 absorption through photosynthesis.

E_{bo} can be measured or estimated by several approaches, for example:
- Measurement of greenhouse gas fluxes using CO_2 Infra-Red Gas

Analyzer (IRGA) or Gas Chromatography (GC)

- o By using IRGA the gas from a closed chamber flows into the IRGA (Figure 18) by using a pressure pump and CO_2 concentration is directly read by the IRGA every second for approximately 2.5 minutes. A linear relationship between time of observations with the concentration of CO_2 gas is used to calculate the CO_2 flux to the ground surface.

- o If using a GC, the gas samples are collected from closed chambers using syringes (Figure 19) and then the gas concentration is measured by a GC (Hue et al. 2000).

Closed chamber

PC or data logger
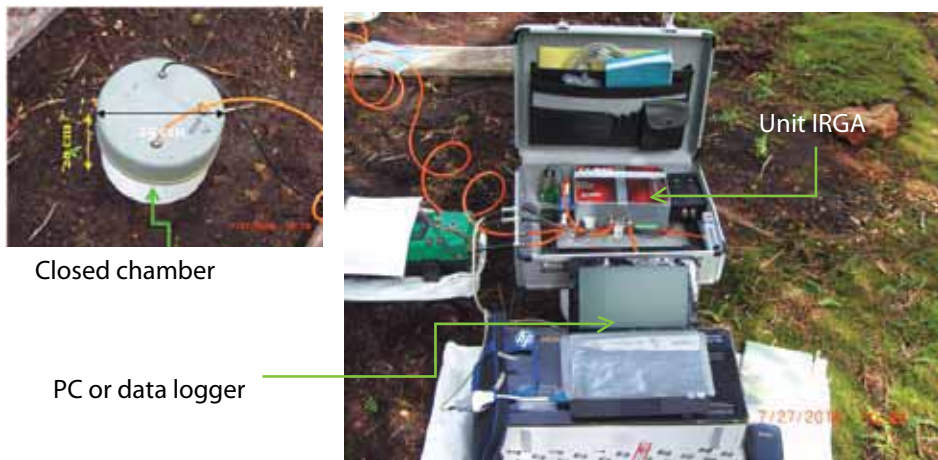
Figure 18. Infra-Red Gas Analyzer (IRGA) and the closed chamber for measuring CO_2 gas flux emitted from the soil

Empirical relationship of land management and emissions

From a review of publications based on research in Sarawak, Malaysia, and (mainly) Kalimantan, Indonesia, Hooijer et al. (2006, 2010) developed a linear relationship between the depth of drainage, DD, and CO_2 emissions:

$$E_{bo} \text{ (t } CO_2/\text{ha/yr)} = 0,91 \; DD \text{ (cm)} \tag{11}$$

Figure 19. Gas sampling from a closed chamber for gas concentration measurement using gas chromatography

The equation applies to *DD* between 30 and 120 cm. However, the literature referred to by Hooijer et al. (2006, 2010) did not separate the CO_2 from root respiration to the emissions caused by peat decomposition. Emissions from root respiration in certain circumstances can be very high. Handayani (2009) reported that for oil palm plantations on peatland in West Aceh district, the root respiration contribution was about 30% of the measured CO_2 based on closed chamber measurement. Thus, Agus et al. (2010) suggest that Hooijer (2010) be modified as

$$E_{bo} \text{ (t } CO_2/\text{ha/year)} = 0.7 \times 0.91 \, DD \text{ (cm)} \qquad \text{[12]}$$

For example, if the undrained natural peatland is converted to plantations with a depth of drainage of 60 cm there will be an

increase of CO_2 emissions:

E_{bo} = 0.7 x 0.91 t CO^2/ ha / yr / cm x 60 cm = 38.22 t CO_2/ ha / yr.

If the area of the converted land is 6000 ha for an oil palm plantation cycle of 25 years then

E_{bo} = 0.7 x 0.91 t CO_2 /ha/yr/cm x 60 cm x 6000 ha x 25 yr

= 5 733 000 t CO_2 = 5.7 Mt CO_2

Estimate based on peat subsidence

According to Wösten et al. (1997), subsidence takes place very rapidly in the first few years after the drainage is initiated and achieves stability at the rate of about 2 cm/yr (Figure 20). They explained further that, assuming that there is no fire, then the decomposition accounts for 60% of subsidence, while compaction (consolidation) accounts for 40%. In contrast, Couwenberg (2010) estimated that the decomposition of peat accounted for approximately 40% of subsidence. That is, if subsidence occurs as thick as 10 cm, 4 cm is attributable to peat decomposition and 6 cm due to compaction and consolidation.

Based on Couwenberg (2010), supposing that within 25 years a landscape of peat undergoes 50 cm subsidence, then 40% x 50 cm = 20 cm of the subsidence is caused by peat decomposition. If the volume-based carbon content, C_v = 0.06 t /m^3, then from the 6000 ha of peatland, emissions that occur during 25 years would be

E_{bo} = 0.20 m x 0.06 t/m^3 C x 3.67 t CO_2/t C x 6000 ha x 10 000 m^2/ha

= 2 642 000 t CO^2 = 2.6 Mt CO^2

Estimation based on changes in carbon stocks in peat

This estimate is based on the difference in carbon stocks in peat at time t_1, for example, when peatland is still covered by natural forest and at time t_2, after a few years of drainage. Carbon content and *BD* measurements were done by layers from the surface to the peat bottom at time t_1 and t_2. Sample calculations in Table 5 provide the data of *BD* and C_{org}, at t_1 and t_2 in 1990 and 2015, respectively. This approach provides an estimate of emissions as much as 5.8 million t CO_2 over 25 years (Table 5).
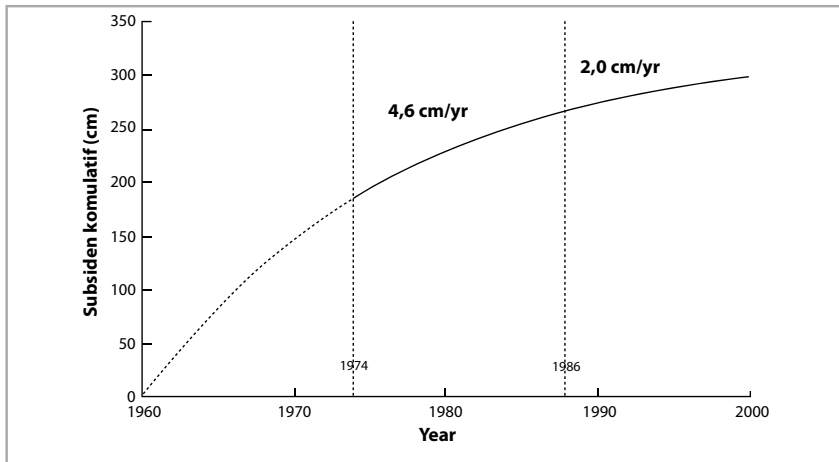
Figure 20. The rate of subsidence of drained peat as a function of time since the drainage starts (Wösten et al. 1997)

Table 5. Calculation of the change in peat carbon stocks based on bulk density (*BD*) and organic carbon content (C_{org}) data by layer

No.	Observation in 1990					Hypothetical observation in 2015				
	Peat depth (cm)	BD (t/m³)	%C_{org}	C_v (t/m³)	C stock (t/ha)	Peat depth (cm)	BD (t/m³)	%C_{org}	C_v (t/m³)	C stock (t/ha)
1	0-40	0.10	30	0.03	120	0-30	0.35	25	0.09	263
2	40-100	0.15	40	0.06	360	30-80	0.30	35	0.11	525
3	100-160	0.12	40	0.05	288	80-140	0.20	40	0.08	480
4	160-200	0.15	45	0.07	270	140-200	0.15	45	0.07	405
5	200-250	0.16	35	0.06	280	200-250	0.16	35	0.06	280
6	250-300	0.14	50	0.07	350	250-300	0.14	50	0.07	350
7	300-350	0.13	58	0.08	377	300-350	0.13	58	0.08	377
8	350-355	0.12	50	0.06	330	350-390	0.12	30	0.04	144
9	355-400	0.14	50	0.07	315					
10	400-450	0.12	55	0.07	330					
11	450-470	0.13	25	0.03	65					
Average		0.13	43	0.06			0.19	40	0.07	
Total (t/ha C)					3,085					2,824
Decrease in carbon stock in 25 years (t/ha C)										262
Emissions = Decrease in carbon stock in 25 years on 6000 ha (t CO_2) = 262 t/ha * 6000 ha *3.67										5,758,230

S_a = Sequestration or CO_2 uptake by plants = the time-averaged carbon stock in the biomass and necromass of the succeeding plants (t/ha) x 3.67. For example, if the time-averaged carbon stock from one economic time cycle of 25 years of oil palm = 40 t/ha C, then for 6000 ha of land, its contribution in reducing CO_2 in the atmosphere = 40 t/ha C ha x 6000 x 3.67 t CO_2/C = 880 800 t CO_2.

Δt = The time period for the calculation, which depends on the purpose of the analysis. It could be 1 minute or 1 hour in terms of gas flux, 1 year or several years for plant growth, as long as all factors in the calculation (Equation 10) use the same time period. For carbon trading, a long time scale of, for example, 10–20 years, is normally used.

By using the above calculation and Table 5 for E_{bo}, and combining them to Equation [10], then

$$E = \frac{(E_a + E_{bb} + E_{bo} - S_a)}{\Delta t}$$
$$E = \ (2{,}202{,}000 + 4{,}183{,}800 + 5{,}758{,}230 - 880{,}800) \text{ t } CO_2/25 \text{ years}$$

$$= 11{,}262{,}430 \text{ t } CO_2/25 \text{ yr}/6{,}000 \text{ ha, and this is equivalent with}$$

$$= 75 \text{ t } CO_2/\text{ha/year}$$

From this calculation it can be interpreted that about 11 million tonne (M_t) of CO_2 would be emitted within 25 years from the 6000 ha peat forest that was converted to plantation. From the perspective of REDD, it can be stated that about 11 Mt CO_2/25 yr/6000 ha can be reduced by maintaining the peat forest as is (by avoiding deforestation).

Discussion

In REDD or any similar emission reduction scheme, the service providers of carbon conservation are entitled for payment from the carbon service buyers based on a formal agreement. The amount of payment may be based on the internationally published price of carbon or on the 'opportunity cost' of forgone benefits from alternative business on the land.

What should a country, a province or district consider prior to engagement in carbon trading? They should first understand and convince themselves of several issues.

- Whether the price of carbon offered by the buyers can cover the opportunity and transaction costs. In other words, whether the seller of the service is willing to accept the amount of payment.

- Whether government at national and sub-national levels, as well as the local community, can obey the long-term commitment (in this example, 25 years, but it may be 10, 20 or longer than 25) not to cut or drain the peat forest.

- Whether avoiding deforestation on the land under contract can avoid 'leakage', that is, an increase in deforestation and land conversion in surrounding areas.

If the answer to each of the three question is 'yes', it indicates that both the carbon buyers and sellers are ready for carbon trading.

Apart from carbon trading, a decrease in carbon stock is associated with peat subsidence. Peat subsidence is highly related to sustainability of farming on peatland. Before using peatlands for agriculture we need to consider the sustainability and environmental aspects (Agus and Subiksa 2008). For those lands that have been used for agriculture, it is imperative to implement the best management techniques for sustaining the business. Given the relatively low productivity of peatlands and their important role as a buffer of environmental quality, then the future development of peatland for agriculture should be kept to a minimum.

Drainage canals are used not only to reduce soil saturation but also for transportation. Maintenance of a high watertable in the canal is important for transport functions but also reduces CO_2 emissions.

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Appendix. Record sheet for peat observation

No.	Name of Surveyor	No. of landscape photo:
1	Date	
2	Code/Observation Number	
3	Location (village, subdistrict, district, province)	
4	Coordinates/GPS position	
5	Peat thickness(cm)	
6	Type of underlying layer	Clay/quartz sand/acid sulphate
7	Drainage pattern	Natural/artificial. Explain! . . . .
8	Distance of observation point from the drainage canal (cm)	Primary canal/secondary canal/tertiary canal/field drain
9	Watertable at the canal (cm)	At present . . . . cm. In wet season . . . .. cm. In dry season . . . cm
10	Watertable at the observation point (observed from the auger hole) (cm)	
11	Land use	
	What year was the drainage canal constructed?	
	Previous land use	
	Year of conversion to present land use	

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12	Sample code and numbering for each layer (must appear on this form and in the sample plastic bags)			
No.	Code and date	Depth (cm)	Maturity	Remarks (e.g. in case of the presence of clay or charcoal layer, record at what depth and how thick)
1				
2				
3				
4				
5				
6				
7				
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