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Comparison of methods for quantifying soil carbon in tropical peats

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ABSTRACT

We test the applicability of two different methods for quantifying carbon (C) stocks in five tropical peat sites in Sumatra, Indonesia; two in an intact peat swamp forest, one in a logged forest and two in an oil palm plantation. Elemental analysis is used to quantify C contents and stocks in all samples, and is the standard to which the two methods are compared. The first method, loss on ignition (LoI), underestimates sample C stocks by 4.9 ± 0.8% compared to results from the elemental analysis across all samples. Loss on ignition is applied to three full peat cores in one of the intact forest sites and one oil palm site, using the standard factor of 1.922 to convert the organic matter (OM) result into C content. Evaluation against independent data suggests that a factor of 1.878 would be more appropriate. The second method, using the equation presented in Warren et al. (2012) for quantifying C density in peat swamp forest soils, shows no significant difference between the equation and elemental analysis derived results for the intact and logged forest sites. We suggest the use of a bulk density (BD) range to further define the limits of the equation. When applied to samples from oil palm sites, there was a significant difference in the results provided by the Warren equation and elemental analysis. Evaluation against independent data suggests that, in this land use, C density (kg C m^{-3}) is more accurately estimated by the equation $C_d = (515.44 \times BD) + 3.01$ ($R^2 = 0.94$). We also present a variable factor for the conversion of the organic matter (OM) to C content by merging the two methods. We recommend the use of the LoI method with the improved factor for conversion of OM to C content, or where bulk density is known the Warren equation for calculating accurate C density values across intact and logged forests on Indonesian peats, and our revised equation for oil palm sites.

1. Introduction

Tropical peats store substantial stocks of soil carbon (C), due to the anaerobic soil conditions restricting decomposition of organic matter (Page et al., 2011a, 2011b). Conversion of tropical peat swamp forests to plantation forestry and agriculture involves the installation of extensive drainage channels, resulting in a lowering of the water table which exposes the peat soil to oxygen and triggers microbial decomposition of the soil C (Miettinen et al., 2012). Quantification of the soil C stocks in tropical peats and the effect of land-use change on them are challenges; both in obtaining the field samples and in accurately analysing the soil C content.

There are a number of qualitative, semi-quantitative and quantitative methods for the analysis of the C content of soils, typically presented as a proportion of the soil organic matter (Schumacher, 2002). In tropical peats this analysis is usually undertaken using one of two methods; loss on ignition (LoI) (as found in Satrio et al., 2009; Ywih et al., 2009) or elemental analysis (as found in Brady, 1997; Shimada et al., 2001). Loss on ignition involves the dry combustion of the soil samples at 550 °C, where the residual ash content is used to determine the organic matter content, from which the organic C is calculated using a conversion factor (Agus et al., 2011). The second method, elemental analysis, is the most accurate of all methods available, but requires expensive, sensitive equipment which is often unavailable in the areas where these tropical peats are found. Analysis involves the combustion of samples at high temperatures (up to 1800 °C) with an accelerant, followed by gas chromatography or infrared detection of the C oxides. It quantifies the total soil C content which is similar to the organic C content in peat soils. Recent work by Warren et al. (2012) presents an equation for estimating the density of C in tropical peat swamp forest soils (presented as kg C m^{-3}) using bulk density (BD) values only, tested against ten sites in Indonesia where elemental analysis was originally used to establish the C stocks. With an R^2 of 0.95 for the regression between BD and C density, the equation provides an opportunity to quantify C stocks without the need for expensive and time consuming laboratory analysis.

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In this study we compare peat C content and C density estimates using LoI and Warren et al.'s (2012) general equation with results from elemental analysis for three land use types on peatlands in Sumatra, Indonesia. We also present recommendations on the most accurate and appropriate methods for quantifying soil C contents and stocks in tropical peats under intact forest, logged forest and oil palm land uses.

2. Methods

2.1. Sites

Five different sites on peat soil in Jambi province, Sumatra, Indonesia were sampled for this study. Three soil cores representing the entire peat profile were taken from an intact tropical peat swamp forest (IF2) located in Berbak National Park (Taman Nasional Berbak), approximately 2 km from the nearest waterway (Simpang Kubu) at −1°30′10.58″S latitude and 104°15′26.17″E longitude. Additional surface samples down to 150 cm depth were collected from an additional intact forest site location in Berbak National Park (IF1, at 1°27′48.31″S latitude and 104°21′29.92″E longitude).

Surface samples were also collected from a logged forest site on the edge of a commercial oil palm plantation, where samples from a four and seven year oil palm site were also taken (OP2007 and OP2004 respectively). In addition, three soil cores of the full peat depth were taken from the seven year old oil palm site. Initial drainage in the oil palm and logged forest sites took place in 2003–2004, and further drainage canals were installed as the plantation establishment took place. Charred woody debris in the sites indicated that burn events had occurred in the past. Prior to clearance for oil palm the site was forested and then logged. These sites were located around 1°38′31.78″S latitude and 103°49′59.74″E longitude.

Average rainfall and annual temperature in Jambi from 2006 to 2011 (NOAA, 2011) were 1770 mm^{-1} yr^{-1} and 27 °C, respectively.

2.2. Sampling

Sampling took place in October 2011. For the full profile cores, three randomly located cores were taken through the peat profile down to the mineral soil below. Peat cores were extracted using an Eijkelkamp peat auger. Each core was sampled in 50 cm increments, with the first 0–50 cm divided into samples of 0–15, 15–30 and 30–50 cm and the rest of the profile taken as 50 cm sample segments. The auger was cleaned after each sample was taken, to ensure no contamination between layers. Peat depth was recorded for each core. In all sites it was impossible to sample a complete core in one location, due to woody debris buried in the peat. When this occurred the auger was placed in a new location as close as possible to the original core and inserted to the required depth and the sample taken, hence peat C stocks may be slightly underestimated (although woody matter at depth in these peats has been shown to have similar BDs as that of the surrounding peat (Hooijer et al., 2012)). Each sample was placed into a labelled plastic bag and transported to a refrigerator where it was stored at 4 °C for no longer than a week until further analysis. For the sets of samples taken to 150 cm only, the same sampling procedure was followed, using the same depth increments.

2.3. Analysis

2.3.1. Bulk density

All wet samples were weighed and then oven dried to a steady dry weight which was recorded. Samples for LoI analysis were dried at 70 °C and for elemental analysis were pre-dried at 40 °C before being re-dried at 70 °C prior to analysis. The temperature of 70 °C was selected after Warren et al. (2012), and the similar temperature recommended by Page et al. (2011a, 2011b). The BD (g cm^{-3}) was calculated as described in Agus et al. (2011);

$$BD = M_{ds}/V_s \tag{1}$$

where M_{ds} is the sample dry weight (g) and V_s is the sample volume (cm^3). Once dried, samples were passed through a 2 mm sieve before being sent for further analysis.

2.3.2. Loss on ignition

Loss on ignition was used to determine the organic C content of the full core's samples only, in the laboratory of the Indonesian Soil Research Institute (ISRI) in Bogor, Java. For each sample, 1–2 g sub-samples underwent combustion at 550 °C in a muffle furnace for at least 6 h, after which the weight of the residual ash was recorded. The ash content (p_{ash}, %) was calculated as:

$$p_{ash} = \frac{M_{ash}}{M_{ds}} \times 100 \tag{2}$$

where M_{ash} is the ash mass after combustion (g) (Agus et al., 2011). The organic C in the sample was then calculated using the following equation:

$$C_{org} = \frac{100 - p_{ash}}{R_{OM:C}} \tag{3}$$

where C_{org} is the organic C content (%) and $R_{OM:C}$ is the currently preferred conversion factor used by ISRI to establish the C_{org} of the total organic matter in Indonesian peats (1.922), based on field research in West Aceh, Indonesia (Maswar, 2011). Historically this value used to be set at 1.724 (Agus et al., 2011).

A randomly selected sample of 50% of the whole dataset was used to calculate an improved conversion factor (x) from the C_{org} (%) derived from the elemental analysis and the organic matter contents from the LoI analysis (OM (%)). This gave a revised factor for converting the LoI derived OM to organic C_{org};

$$x = \frac{OM}{C_{org}}. \tag{4}$$

2.3.3. Elemental analysis

The samples from all five sites were sent to The James Hutton Institute laboratories, Scotland, for elemental analysis. The C_{org} of the samples was calculated from the area output of the mass spectrometer calibrated against National Institute of Standards and Technology (NIST) standard reference material 1547 peach leaves which was analysed with every batch of ten samples. Long term precision for a quality control standard (milled flour) gave a total C of 40.3 ± 0.4% (mean ± sd, n = 200) (Barry Thornton, personal communication).

2.3.4. Equation comparison

The empirical equation presented by Warren et al. (2012) (R^2 = 0.95, n = 714) was used to compute the C density from the BD values of all samples:

$$C_d = (BD \times 468.72) + 5.82 \tag{5}$$

where C_d is the C density (kg C m^{-3}) and BD is the sample bulk density (g soil cm^{-3}). From this the C_{org} (%) can be calculated as:

$$C_{org} = \frac{C_d}{BD \times 10}. \tag{6}$$

Eq. (5) is presented in Warren et al. (2012) as an improvement to an original equation they developed based on 151 literature values, with Eq. (5) based on inclusion of 714 additional samples from the field. This equation is yet to be evaluated against independent field data