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# Further results on comparison of methods for quantifying soil carbon in tropical peats

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ABSTRACT

We present an alternative equation for estimating carbon density of tropical peatlands. We compiled a dataset of tropical peatlands with various land uses and found that when carbon content is greater than 0.5 g g$^{-1}$, there is no relationship between carbon content and bulk density. Thus, carbon density can be estimated from an average carbon content ($0.5501 \pm 0.0225$ g g$^{-1}$) multiplied by the measured bulk density. This simple model is in contrast with previous studies, where a linear regression model is fitted to the carbon density and bulk density data. We tested the model to the data and demonstrated its high accuracy and applicability across land uses.
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## 1. Introduction

Tropical peats have the highest terrestrial carbon store per unit area of land (Moore et al., 2013; Page et al., 2011) and estimation of their carbon stocks is essential for both conservation and management practices. Thus, it is useful to have a simple soil carbon estimation or pedotransfer function for tropical peatlands where access to laboratory analysis can be difficult or expensive. In mineral soils, bulk density is known to be affected by organic matter content, and pedotransfer functions have been proposed to estimate bulk density from soil organic matter content as measured by the loss on ignition (LoI) method (Adams, 1973; Jeffrey, 1970). Adams (1973) observed that bulk density decreases exponentially with an increasing organic matter content until a value of 75% where the relationship doesn't hold. Warren et al. (2012) noted that there is no expected relationship between bulk density and carbon content for peat soils as mineral fractions are very low.

Farmer et al. (2014) proposed new equations for predicting carbon content and carbon density for tropical peats, which include:

1. A new factor conversion value for predicting carbon content, $C_c$ from its ash content as measured by the loss on ignition (LoI) method, based on a relationship between LoI and elemental analysis data;
2. A linear equation for predicting carbon density, $C_d$ (in kg m$^{-3}$) from its bulk density, BD (in g cm$^{-3}$):

$$C_d = (515.44 \times \mathrm{BD}) + 3.01 \tag{1}$$

which is an extension of the equation proposed by Warren et al. (2012):

$$C_d = (468.72 \times \mathrm{BD}) + 5.82 \tag{2}$$

The slope of Eqs. (1) and (2) represents an average carbon content ($C_c$) of tropical peats, i.e. 0.5154 and 0.4687 g g$^{-1}$, respectively. Both Farmer et al. (2014) and Warren et al. (2012) provided uncertainty estimates of the regression models. Eqs. (1) and (2) aimed to circumvent the need for a more expensive laboratory analysis of C content, as BD can be determined relatively easy using a standard oven.

Warren et al. (2012) derived their model from peat forests data and stated that Eq. (2) is valid for well-developed peats having carbon content greater than 0.4 g g$^{-1}$ (or 40%). Farmer et al. (2014) showed that the accuracy of Warren's Eq. (2) equation decreased with increasing bulk density and they suggested that the equation was applicable for bulk density values between 0.05 to 0.16 g cm$^{-3}$. Meanwhile, Farmer's Eq. (1) was developed for peat soils affected by mechanical compaction (e.g. under oil palm plantations).

In this communication, we would like to propose an alternative simple relationship for predicting $C_d$ directly from $C_c$ which considers the uncertainty of the data. In addition, we will define the applicable range of bulk density for this relationship based on a new data set of tropical peatlands with diverse land use.

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## 2. Dataset

We compiled a dataset of carbon content and bulk density from various tropical peatlands in Indonesia, Malaysia and Peru with different land uses (i.e., primary and secondary forest, natural timber production, planted forest *Acacia crassicarpa* and oil palm) published in the literature and from our past studies. The details of the location, the number of observations, land use, observed depth ranges, and methods used for determining carbon content are listed in Table 1. Carbon content from our studies used the loss on ignition (LoI) method (Agus et al., 2011; Farmer et al., 2014), while data from the literature used either LoI or elemental analysis technique. Bulk density was measured using the gravimetric method.

## 3. Results and discussion

In total, our compiled dataset has 577 observations with bulk density values between 0.013 and 0.572 g $cm^{-3}$, and carbon content ranges between 0.11 and 0.62 g $g^{-1}$ (Table 2). Fig. 1 shows the plot of bulk density, BD vs. carbon content, $C_c$ with their histogram. The plot shows that when carbon content values are above 0.5 g $g^{-1}$ (N = 483 or 84% of the data), there is no relationship between $C_c$ and BD. And within this data range ($C_c$ > 0.5 g $g^{-1}$), 95% of the data have BD values less than 0.25 g $cm^{-3}$.

We then separated out the data where BD is less than 0.25 g $cm^{-3}$ and $C_c$ is greater than 0.5 g $g^{-1}$. In this subset of data, we calculated an average value of $C_c$ of 0.5501 g $g^{-1}$ (or 55.01%) with a standard deviation of 0.0225 g $g^{-1}$ (or 2.25%), and within these values, $C_c$ values are constant with varying BD values (Fig. 2a).

Since $C_d$ is a dot product of $C_c$ and BD ($C_d = C_c \times BD$), and there is no relationship between $C_c$ and BD, we can estimate $C_c$ directly from its average value ($\overline{C_c}$ in g $g^{-1}$):

$$C_d = \bar{C}_c \times BD = 0.5501 \pm 0.0225 \times BD \qquad (.(3))$$

where the units of $C_d$ and BD should both either in g $cm^{-3}$ (Mg $m^{-3}$) or kg $m^{-3}$. This method is in contrast with the regression approach of Warren et al. (2012) and Farmer et al. (2014) where they fitted a linear regression $C_d = a + b \times BD$ to the data relating BD to $C_d$. We believe that the regression approach has a couple of shortcomings: firstly, this regression presents co-dependent variables ($C_c \times$ BD vs. BD), and thus the estimate of the slope depends on both $C_c$ and BD and there could

**Table 1**
Data of tropical peatlands' carbon content and bulk density obtained from the literature and authors' studies.

| Location | Number of observations | Depth ranges (cm) | Land use | Method of carbon measurement | Source |
|---|---|---|---|---|---|
| Bengkalis, Riau, Indonesia | 6 | 5–30 | 2nd rotation of planted forest *Acacia crassicarpa* | CHNS autoanalyzer | Sumawinata et al. (2014) |
| Central Kalimantan, Indonesia | 16 | | Virgin or secondary forested including riverine, terrace, basin, marginal, floodplain, coastal | CHN elemental analyzer | Shimada et al. (2001). Average value |
| Demeni, Central Amazon, Brazil | 3 | 30–140 | Forest | CN analyzer | Lähteenoja et al. (2013) |
| Zalalá, Central Amazon, Brazil | 4 | 30–170 | Semi-open | | |
| Daracuá, Central Amazon, Brazil | 3 | 30–210 | Forest | | |
| Calibuqui, Central Amazon, Brazil | 2 | 30–70 | Open | | |
| Jambi, Indonesia | 6 | 0–65 | 2nd rotation of planted forest *Acacia crassicarpa* | CHNS autoanalyzer | Sumawinata et al. (2014) |
| Katingan, Central Kalimantan, Indonesia | 12 | 20 | Secondary forest | Loss on ignition | Boehm and Frank (2008) |
| Kubu Raya, West Kalimantan, Indonesia | 131 | 5–75 | Secondary forest and planted forest *Acacia crassicarpa* | Loss on ignition, conversion factor = 1.724 | Our data collection |
| Miraflores-Amazon Peru | 5 | 30–290 | Forest | CN analyzer | Lähteenoja and Page (2011) |
| Nueva York-Amazon Peru | 5 | 30–290 | Forest | | |
| Aucayacu | 15 | 30–730 | Forest | | |
| Roca Fuerte | 11 | 30–520 | Center: forested, | | |
| Nueva Alianza | 4 | 30–190 | High canopy; edge: floodplain forest | | |
| Maquía | 7 | 30–390 | Open, scattered *M. flexuosa* | | |
| San Roque | 3 | 30–540 | Open, scattered *M. flexuosa* | | |
| Buena Vista del Maquía | 2 | 30–140 | *M. flexuosa* palm swamp *M. flexuosa* palm swamp | | |
| Ogan Komering Ilir, South Sumatra, Indonesia | 6 | 5–10 | Secondary forest and planted forest *Acacia crassicarpa* | Loss on ignition, conversion factor = 1.724 | Our data collection |
| Ogan Komering Ilir, South Sumatra, Indonesia | 7 | 10–70 | Planted forest *Acacia crassicarpa* | CHNS autoanalyzer | Sumawinata et al. (2014) |
| Ogan Komering Ilir, South Sumatra, Indonesia | 16 | | Oil palm | Loss on ignition, conversion factor = 1.724 | Prayitno et al. (2013) |
| Pontianak, West Kalimantan, Indonesia | 36 | | Secondary forest | Loss on ignition, conversion factor = 1.724 | Our data collection |
| Padang Sugihan, South Sumatra | 2 | 0–40 | Primary forest | Elemental analyzer | Brady (1997) |
| Sugihan East, South Sumatra | 2 | 0–40 | Primary forest | | |
| Padang Island, Riau, Indonesia | 6 | 0–40 | Primary forest | | |
| Quistococha, Peruvian lowland Amazonia, Peru | 5 | 70–400 | Forest | Leco Analyzer | Lähteenoja et al. (2009) |
| Rinón | 4 | 90–380 | Open peatland | | |
| San Jorge | 6 | 70–570 | *M. flexuosa* palm swamp and forested | | |
| Rasau Jaya, Kubu Raya, West Kalimantan, Indonesia | 11 | 0–700 | | | Dariah et al. (2011) |
| Rokan Hilir, Riau, Indonesia | 20 | | Tropical rainforest (natural timber production) | Walkley and Black | Yuono (2009) |
| Sarawak, Malaysia | 3 | | Forest, sago, oil palm | | Melling et al. (2005) Average value |
| Sebangau, Central Kalimantan, Indonesia | 57 | 3–960 | | Leco Analyzer | Page et al. (2004) |
| Siak, Riau, Indonesia | 131 | 10–300 | Secondary forest | Loss on ignition | Our data collection |
| *Total* | *577* | | | | |

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