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A cost-efficient method to assess carbon stocks in tropical peat soil

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Abstract

Estimation of soil carbon stocks in tropical wetlands requires costly laboratory analyses and suitable facilities, which are often lacking in developing nations where most tropical wetlands are found. It is therefore beneficial to develop simple yet robust analytical tools to assess soil carbon stocks where financial and technical limitations are common. Here we use published and original data to describe soil carbon density (gC cm^{-3}; C$_d$) as a function of bulk density (g dry soil cm^{-3}; B$_d$), which can be used to estimate belowground carbon storage using Bd measurements only. Predicted carbon densities and stocks are compared with those obtained from direct carbon analysis for ten peat swamp forest stands in three national parks of Indonesia. Analysis of soil carbon density and bulk density from the literature indicated a strong linear relationship ($C_d = B_d \times 0.49 + 4.61$, $R^2 = 0.96$, $n = 94$) for soils with an organic C content >40 %. As organic C content decreases, the relationship between C$_d$ and B$_d$ becomes less predictable as soil texture becomes an important determinant of C$_d$. The equation predicted soil C stocks to within 0.39 % to 7.20 % of observed values. When original data were included in the analysis, the revised equation: $C_d = B_d \times 0.48 + 4.28$, $R^2 = 0.96$, $n = 678$ was well within the 95 % confidence intervals of the original equation, and tended to decrease C$_d$ estimates slightly. We recommend this last equation for a rapid estimation of soil C stocks for well developed peat soils where C content >40 %.

1 Introduction

Tropical wetland forests containing organic soils – mangroves and freshwater peat swamps – are significant global carbon (C) stores (Donato et al., 2011). Page et al. (2011) estimated 88.6 PgC is stored in tropical peatlands worldwide, with 68.5 PgC (77 %) occurring in Southeast Asia. Similarly, Donato et al. (2011) estimated mangroves may contain up to 20 PgC globally. Tropical wetland forests are susceptible to large-scale C losses, due to their high C storage and rapid rates of deforestation

(Langner et al., 2007; Miettinen and Liew, 2010a, b). Of further concern is the vulnerability of tropical wetland C pools exacerbated by predicted consequences of global climate change: ENSO-related droughts and subsequent fires, altered precipitation patterns, increasing frequency and severity of tropical cyclones, and sea level rise (Ellison and Stoddart, 1991; Li et al., 2007; Field et al., 2009).

Tropical wetlands are also well known for their numerous ecosystem services and unique biodiversity. Because of these values and vulnerabilities tropical wetland forests are of particular interest in climate change mitigation strategies such as reduced emissions from deforestation and degradation (REDD+; Murdiyarso et al., 2010; Hergoualc'h and Verchot, 2011). However, data deficiencies preclude the rigorous C accounting necessary for the successful implementation of REDD+ activities in tropical wetlands (IPCC, 2006). There is a pressing need for accurate C assessments in tropical wetland ecosystems to establish baseline C stocks, and real and potential C losses from disturbance.

Belowground carbon pools of tropical wetlands are quite high. Chimner and Ewel (2005) estimated 330–775 Mg ha^{-1} of belowground peat C for forests on Kosrae, and 1077 MgC ha^{-1} were reported for riverine peat forests over shallow peat horizons in Tanjung Puting, Indonesia (Murdiyarso et al., 2009). Jaenicke et al. (2008) estimated up to 3130 MgC ha^{-1} for the Sebangau peat formation in Indonesia, and Page et al. (2011) calculated a global average of 2009 MgC ha^{-1} for all tropical peatlands. By comparison, the soil carbon pools of upland tropical forests have been shown to range from 76 MgC ha^{-1} in dry forests with shallow soils <60 cm in depth to about 268 MgC ha^{-1} in wet forests (Kauffman et al., 2009). Kauffman et al. (2009) reported total ecosystem C pools (aboveground + belowground pools) in upland Neotropical forests ranged from 141 Mg ha^{-1} in tropical dry forest to 571 Mg ha^{-1} in lower montane moist forests.

Land conversion on peatlands results in immediate massive C fluxes to the atmosphere due to drainage, deforestation and burning followed by longer term oxidative losses contingent on hydrological conditions (Hooijer et al., 2010; Murdiyarso et al., 2010; Hergoualc'h and Verchot, 2011). Murdiyarso et al. (2010) estimated 25 % of all C emissions from converting peat forest to industrial plantations (a dominant land use transition of tropical peatlands in Indonesia; Koh et al., 2011) occur from initial burning to clear land. During the unusually severe fire season of 1997, drought conditions prompted opportunistic and uncontrolled burning which eventually affected over 2 Mha of wetland ecosystems throughout Indonesia, resulting in C losses commensurate with the 1.5 PgC average annual flux from global land use change from 1990–2005 (Taconni, 2003; Le Quéré et al., 2009; Page et al., 2002; Langmann and Heil, 2004).

The large estimates of greenhouse gas emissions from altered tropical wetlands are of particular concern considering their rapid deforestation rates (Langner et al., 2007; Miettinen and Liew, 2010a, 2010b). Langner et al. (2007) estimated that annual deforestation rates of mangroves and peat swamp forests on the island of Borneo were 7.92 % and 2.24 % (respectively) for the years 2002–2005. The deforestation rates of wetland forests exceeded that of any other forest type. Similarly, Posa et al. (2011) suggested that only about 37 % of Southeast Asia's initial 182 541 km^2 of peat swamp forests remain, and Miettinen and Liew (2010b) estimated that half of the peat swamp forest area mapped in peninsular Malaysia, Borneo and Sumatra in 1990 had been converted to other land uses by 2008, implying large scale C emissions from land use change.

The uncertainties of ecosystem carbon stocks of tropical wetlands and emissions from land cover change as well as their difficulties in measurement are well known and recognized, and limit the accuracy of large scale C stock and flux estimates (Hergoualc'h and Verchot, 2011). The widespread estimation of soil C stocks in tropical wetlands has been partly limited by lack of access to suitable technical facilities and analytical equipment in remote developing areas. Induction furnace C analyzers are costly and depend on infrastructure and the availability of consumables to be run properly. Other methods of C analysis (such as Walkley-Black wet combustion and loss on ignition; LOI) are only semi-quantitative and lose precision when soil organic matter content is very high (Nelson and Sommers, 1982). Therefore, it is beneficial to derive simple analytical tools to partially overcome these challenges and provide a method to accurately estimate soil C storage without the need for complicated laboratory analyses.

Soil carbon stocks (per unit area) are estimated as the product of carbon concentration (%C), bulk density ($\mathrm{g\,cm^{-3}}$), and soil volume ($\mathrm{m^3}$). These properties cannot be measured directly from satellite or airborne sensors, and therefore rely on intensive field sampling for data acquisition. Reliable depth estimates require numerous point measurements in the field, which do not exist for most areas, and many large-scale peat volume estimates use average depths from point samples without spatial interpolation or area-weighted means (but see Jaenicke et al., 2008). Measurements of bulk density and C concentration require careful sample extraction in the field and subsequent analysis using laboratory equipment. Bulk density and C concentration can vary spatially and throughout the vertical peat profile, resulting in complicated three dimensional C storage patterns (Page et al., 2004). Therefore, multiple measurements of carbon concentration and bulk density from samples taken at various depths in the soil profile are needed to accurately determine the soil carbon stocks (Donato et al., 2011; Kauffman et al., 2011; Murdiyarso et al., 2010).

Considering the technical hurdles that must be overcome to successfully measure and monitor belowground C pools in tropical wetlands, it would be useful to develop analytical approaches using well correlated soil properties for localized and rapid yet accurate C assessments. Here, we use published and original data to determine the relationship of volumetric C density and bulk density for tropical peat soils of Indonesian forests. Our objective was to determine if a universal equation developed from more easily sampled variables of bulk density and peat depth is sufficient to estimate peat C stocks rapidly and accurately. If so, the method could be useful for estimating soil carbon in the framework of wetland forest carbon inventories and greenhouse gas mitigation programs.

2 Methods

Data for this study were compiled from peer reviewed research articles, previous reviews, a doctoral thesis, and data that we collected from Indonesian peat forests (Table 1). The following variables were assembled: sample region, site and/or peat type, sample depth, carbon content (%C), bulk density and total carbon mass of the peat layers. Data was only included if carbon content was determined by induction furnace methods. Elemental C analysis is considered the most accurate and avoids error associated with other semi-quantitative methods of C determination including loss on ignition (LOI) or wet combustion (Kauffman and Donato, 2012). Values for carbon density (C_d; gC cm^{-3} soil) were included from the original data sources or calculated from published bulk densities and C contents.

Original data included in this study were collected using modified methods described by Kauffman et al. (2011) and Kauffman and Donato (2012). Peat samples were taken as part of an extensive survey of ecosystem C stocks in peat swamp forests throughout Indonesia including four sites at Danau Sentarum National Park (W. Kalimantan Province), four sites at Sabangau Natural Laboratory for Peat Swamp Forest (NLPSF; C. Kalimantan Province), and two sites at Berbak National Park (Jambi Province, Sumatra). At each of these sites three to six peat cores were extracted from 10 m diameter subplots established along 250 m transects using a Russian peat sampler (Jowsey, 1966). Minimum distance between peat cores was 50 m, and between sites was 700 m. Peat samples taken from the organic-mineral boundary horizons were not included in the analysis, and distinguished as transitional soil horizons in the field by the presence of mineral soil mixing with the organic peat fraction and associated changes in texture and color.

In Danau Sentarum National Park, transects were located in the vicinity of the Hutan Nung (0°46′20″ S; 112° 07′ 00″ E) forest, accessible from Bukit Tekenang research station. Peat cores were taken at 0, 100, and 150 m points along transects. Peat samples were removed from the auger in 10 cm increments and sampled until underlying mineral substrate was reached. Four sites were sampled, with 3 cores per site (12 peat sample cores). Peat depth ranged from 2.1 to 12.7 m across the four sites, and a total of 434 peat samples were collected. Peat samples were transported to the soil laboratory at Tanjungpura University within one week for drying at 70 °C and weighing for bulk density determination.

In the Sabangau and Berbak sites, 5 cm peat samples were taken from the midpoint of 0–15, 15–30, 30–50, 50–100, 100–300 cm depth increments, and every 50 cm thereafter for depths >300 cm (Kauffman et al., 2011). Sampling was biased to the upper peat layers that are most likely impacted by land uses (Ballhorn et al., 2009; Anshari et al., 2010). Samples were transferred directly to a 70° drying oven as soon as possible, usually within 72 h.

Peat samples from Sabangau were collected within the NLPSF (2°19′00″ S, 113°54′29″ E) managed by the Centre for the International Cooperation in Sustainable Management of Tropical Peatlands (CIMTROP) based at the University of Palangka Raya. Sampling design was the same as for Danau Sentarum, with four transects sampled and peat cores extracted at 0, 100, and 250 m resulting in 12 cores ranging from 1.9 to 4.2 m depth. A total of 104 peat samples were collected from the Sabangau NLPSF, with 8 samples from the mineral-organic interface, not included in this analysis.

In Berbak National Park, two transects were sampled in the forest area surrounding a field camp managed by the Zoological Society of London's Sumatran tiger conservation program. In one transect, peat cores were taken every 50 m resulting in 6 cores to assess the scale of variation along the 250 m transect. A total of 9 peat cores were extracted from Berbak National Park ranging from 4.1 to 6.2 m in depth, with a total 70 peat samples collected. Two samples were from the organic-mineral transition horizon and excluded from analysis.

Dried peat samples from all sites were ground, homogenized, and analyzed for C concentration using a LECO TruSpec induction furnace C analyzer (LECO Corporation, St. Joseph MI, USA).

The linear equation describing carbon density (C_d) as a function of dry bulk density (B_d) was determined with linear regression using data collated from the literature review. Since C_d is the product of B_d and C concentration, a linear relationship was expected with a slope equal to the average C concentration of the peat samples and an intercept of 0, assuming the C fraction of peat varies randomly with bulk density. Although there is a negative relationship between soil organic C concentration and bulk density for mineral soils, this relationship was not expected for organic peat soils since mineral fractions are extremely low. To validate the model and provide proof of concept, C_d was predicted for each sample collected in the field using measured bulk density values and the linear equation derived from literature review. The measured C_d of each sample calculated from bulk density and C concentration was then compared with predicted values and the 95 % confidence intervals of the linear model. As a final step, we compared peat C stock estimates (MgC ha^{-1}) using predicted C_d values with those calculated from measured C_d.

3 Results

A total of 119 values for bulk density, C density, and C concentration were available in the literature for tropical wetland soils and met our criteria (Table 1). Data included in the analysis span numerous sites, organic soil types, and land uses throughout Indonesia and three Peruvian sites. Published C contents ranged from 4.4 to 62.0 %, with a mean of 48.59 %. Bulk densities ranged from 0.030 to 0.565 g cm^{-3}, with a mean of 0.130 g cm^{-3}. Soils with lower C content and higher bulk densities were associated with mangroves and shallow peats which contain a high mineral fraction and are distinct from deeper, well developed organic peat swamp soils with no detectable mineral fraction.

The relationship between B_d and C_d for organic soils with C concentration exceeding 40 % is described by the equation (Table 2):

$$C_d = B_d \times 0.49 + 4.61; R^2 = 0.96, p < 0.001 \quad (1)$$

Where C_d is C density (kg m^{-3}) and B_d is dry bulk density (kg m^{-3}). The equation to predict carbon density is applicable but limited to peat soils with low mineral content, typical of well developed ombrotrophic peat swamp forests that do not receive deposits of allocthonous sediments. The clear relationship between C_d and B_d diminishes when soil C concentration falls below 40 % (Fig. 1). As the mineral fraction of the soil increases, C_d becomes less predictable as soil physical properties (such as clay content) play a larger role in determining carbon content. Organic soils with higher mineral content and lower C concentration (<40 %) frequently occur at the interface of peat and underlying mineral substrate, in shallower (<60 cm) peats, and in floodplains and estuaries where mineral alluvium is deposited periodically over organic material.

The linear equation which describes C_d as a function of B_d (Eq. 1) was used to predict C_d values for 597 peat samples collected in the Danau Sentarum, Sabangau, and Berbak sites. Of the 597 samples that were classified as peat in the field, and close to 100 % organic in composition, only six violated the assumption of C content >40 %. The carbon content of these six samples ranged from 30.92 to 39.92 %. Carbon content of field samples ranged from 30.92 to 60.71 % with a mean of 51.33 %. Bulk density ranged from 0.054–0.415 g cm^{-3} with a mean of 0.127 g cm^{-3}. Using the equation to predict C_d based upon B_d derived from the literature (Eq. 1) resulted in slight overestimates of C_d for some samples (Fig. 2). Of the 597 peat samples, 89.4 % fell within the 95 % confidence intervals of Eq. (1) (Table 2). The equation describing C_d as a function of B_d calculated from field data in addition to data obtained from literature review (Table 2):

$$C_d = B_d \times 0.48 + 4.28; R^2 = 0.96, p < 0.001 \quad (2)$$

is also well within the 95 % confidence intervals of Eq. (1) (Table 2). The tendency of Eq.1 to overestimate C_d was only apparent for two of the ten transects when comparing estimates of overall peat C stocks (Fig. 3). Predicted peat C storage (Fig. 3) was close to mean measured values, and within one standard deviation of the measured means with the exception of Sentarum transect 4, where the predicted C stock was 23.71 MgC ha^{-1} more than the measured mean + 1 SD. Sentarum transect 4 was the deepest peat layer sampled, with peat depths in excess of 12 m. Differences in peat C stocks estimated using predicted C_d from Eq. (1) and those estimated using measured C_d ranged from 0.39–7.20 % (Table 3). The error using predicted C_d values was less than 5 % for eight of the ten sites.

4 Discussion

Guidelines for estimating greenhouse gas (GHG) emissions from agriculture, forestry, and other land uses are provided by the Intergovernmental Panel on Climate Change. The IPCC guidance includes specific details for estimating C stocks of upland forest ecosystems, however specific provisions for tropical wetland organic soils and peatlands are lacking (IPCC, 2006). The close relationship between C density and bulk density across a wide range of values allows for a reasonably accurate estimation of peat C stocks for tropical organic soils with C concentration >40 % (Fig. 3). The overestimation of C stocks in Danau Sentarum transect 4 and Berbak transect 2, is partly corrected by applying Eq. (2), which includes the complete set of literature and field data points, and is a more precise C density estimate. Because of the larger sample size and more precise estimate of C_d, we recommend Eq. (2) for rapid estimation of soil organic C stocks for well developed peat soils where C content >40 % can be assumed. Upper and lower prediction intervals for C density can also be calculated by applying the 95 % confidence intervals of Eq. (2) (Table 2).

Direct measurement of carbon concentration in organic wetland soil samples is expensive and requires access to induction furnace elemental analyzers, which can be limited in many tropical remote areas. The equations described here provide an alternative method for calculating organic soil C stocks to partially overcome the economic and technical limitations frequently encountered in less developed countries. These equations are meant to provide a means for rapid belowground C assessment in tropical peatlands. Similar to other default methodologies suggested under IPCC guidelines, the equation describing C_d as a function of B_d using the complete data set (Eq. 2) could be useful for estimating and comparing C stocks in surface peat layers which are most vulnerable to impacts from fire and land use/cover change.

Current estimates of tropical peat C stocks and fluxes often rely on assumed default values for B_d (usually around $0.1\,\mathrm{g\,cm^{-3}}$), C content (54–58 %) and average peat depth, despite known variation in all of these variables among peat types and depth profiles of single peat cores (Ballhorn et al., 2009; Jaenicke et al., 2008; Murdiyarso et al., 2010; Page et al., 2002, 2004, 2011). Average peat depth values probably contribute the most uncertainty to C estimations, since peat C storage is scaled volumetrically and values used are often calculated from relatively few samples which may not represent the heterogeneity of peat forests forming under distinct geomorphic, environmental, and biological conditions. Furthermore, substantial quantities of carbon may exist in mineral soils underlying peat layers especially in shallow peats (Murdiyarso et al., 2009). Using Eq. (2) to estimate potential C storage at a given site could be accomplished by determining the size of the representative area, using peat depth measurements to estimate volume, and obtaining measurements of B_d throughout the vertical peat profile. These measurements only require peat augers, accurate sample volume measurements, an analytical balance and a drying oven, all of which can be easily employed in remote settings. Carbon stocks estimated in this way should be considered preliminary in preparation of a more detailed assessment for C accounting purposes. Initial estimates could then be followed up and verified by measuring C density directly using a C analyzer, and more sophisticated three dimensional spatial modeling of the peat deposit (Jaenicke et al., 2008).

The advantage of using the C density equations presented here is the possibility of calculating C stocks empirically without the need for expensive analytical equipment. However, the validity of the C density equations depends entirely on the accurate assumption that the peat sampled has an organic C content >40 % which is not problematic for most ombrotrophic fibric and hemic peats in geomorphic settings that preclude allocthonous sources of mineral sediments. Only six of the 597 peat samples obtained from ten sites across three Indonesian national parks in this study violated the assumption of C content >40 %. The equations presented here to calculate C_d from B_d cannot be used for many organic soils in transitional, floodplain, and mangrove forests, as they are likely to have organic C content <40 %. Reliable field identification and classification of organic tropical wetland soils is necessary to correctly apply the equations presented, and the assumption of %C>40 should be validated for a minimum set of subsamples at any given site. Although limited, predicting C density from bulk density measurements using the general Eq. (2) (Table 2) is a useful tool for rapid and accurate belowground C stock estimation for highly organic tropical peat soils common throughout the freshwater wetlands of Indonesia and elsewhere.

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Table 1. Source and locations of data used for this study.

Source	Country	Region	Notes
Anshari et al. (2010)	Indonesia	W. Kalimantan	Includes coastal and inland peat forests, logged peat forest, industrial timber, community agriculture, and oil palm plantations. Chemical analysis performed up to 200 cm depth.
Brady (1997)	Indonesia	Sumatra: S. Sumatra and Riau	Three primary peat forest sites. Data for upper and lower acrotelm layers, 0–40 cm depth.
Kauffman et al. (2011); Murdiyarso et al. (2009) unpublished data	Indonesia/ Federated States of Micronesia	C. Kalimantan/Kosrae	C. Kalimantan: Riverine peat swamp forests characterized by shallow (<1 m) peats, higher B_d (mean = 460 kg m^{-3}) and low %C (25.4 %). Kosrae: Coastal peat forest sampled in five locations, also with C content generally lower than 50 %. Sample depths to ca. 200 cm.
Lahteenoja et al. (2009)	Peru	Lowland Peruvian Amazon	Three floodplain sites including open peatland, palm swamp forest, peat forest. Sample depths up to 570 cm.
Melling et al. (2005)	Malaysia	Sarawak	Includes three sites: drained forest, Sago, and Oil Palm plantations.
Page et al. (2004)	Indonesia	C. Kalimantan	Incremental data for a single continuous core to 960 cm depth. A single value for depth 0–90 cm was derived using average profile B_d reported in text and average %C value 0–90 cm.
Shimada et al. (2001)	Indonesia	C. Kalimantan	Includes terrace, basin/domed, riverine, floodplain and marginal peatland. Also cites data from Neuzil (1997) for Sumatran and W. Kalimantan sites. Values reported are averages of normalized profile depth.
This study	Indonesia	W. Kalimantan C. Kalimantan Jambi, Sumatra	Includes peat cores extracted from ten peat swamp forest sites across three national parks of Indonesia. Peat depths ranged from 1.75 to 12.7 m. 597 peat samples were used to compare predicted and measured carbon density values and estimated C stocks.

Table 2. Parameters of the linear relationship $C_d = B_d \times a + b$ between dry bulk density B_d ($\mathrm{kg\,m^{-3}}$) and carbon density C_d ($\mathrm{kg\,m^{-3}}$) derived from literature values (Eq. 1) and including field data from this study (Eq. 2). Equations valid for C concentration >40 %.

					95 % Confidence Interval	
Eq. (1)		df	Coefficient	Standard Error	Lower	Upper
	Intercept	92	4.61	1.34	2.01	7.34
	Slope	92	0.49	0.01	0.47	0.52
Eq. (2)						
	Intercept	676	4.28	0.43	3.44	5.13
	Slope	676	0.48	0.004	0.47	0.48

Table 3. Comparisons of peat carbon stock estimates using measured C_d and predicted C_d using Eq. (1). Estimates are for ten sites across three national parks of Indonesia.

Site	Average peat depth (m)	Measured peat C stock (MgC ha^{-1})	SE	Predicted peat C stock (MgC ha^{-1})	SE	% Difference
Sentarum1	9.17	5709.60	956.75	6110.96	1201.65	7.03
Sentarum2	6.17	3830.00	461.36	4013.65	514.07	4.80
Sentarum3	2.28	1698.61	129.34	1688.70	118.54	0.58
Sentarum4	12.07	7888.88	120.45	8121.20	156.28	2.95
Berbak1	4.30	2252.81	66.13	2414.95	68.72	7.20
Berbak2	6.32	3164.21	121.14	3151.90	113.67	0.39
Sabangau1	2.68	1719.09	383.55	1742.86	399.95	1.38
Sabangau2	2.67	1424.61	80.23	1402.94	61.53	1.52
Sabangau3	3.75	2501.16	144.83	2569.93	173.56	2.75
Sabangau4	3.73	2612.55	359.14	2630.70	401.88	0.69

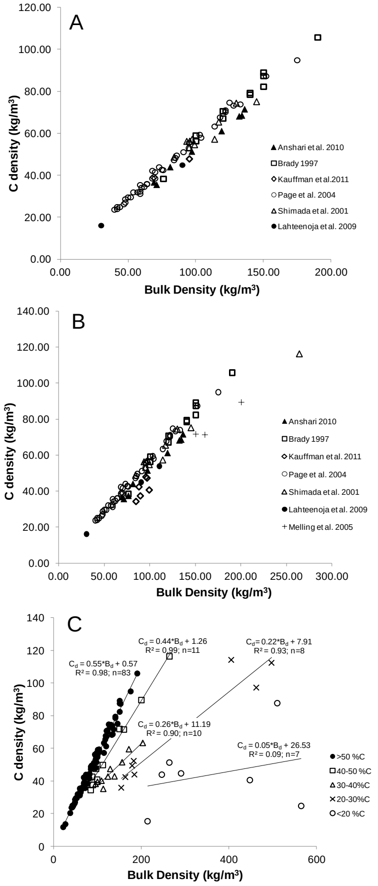

Fig. 1. (Caption on next page.)

Fig. 1. Linear relationships between C density and dry bulk density for peat soils >50 % C **(A)**, >40 % C **(B)**, and soils >20 % C **(C)**. Carbon density can be calculated from dry bulk density and scaled volumetrically with peat area and depth measurements for a rapid assessment of total belowground C stocks assuming C>40 %. A robust linear relationship breaks down when C content falls below 40 % (panel **C**) and soil texture plays a larger role in determining C storage at higher bulk densities. To convert bulk density expressed in kg m^{-3} to g cm^{-3}, multiply by 0.001.

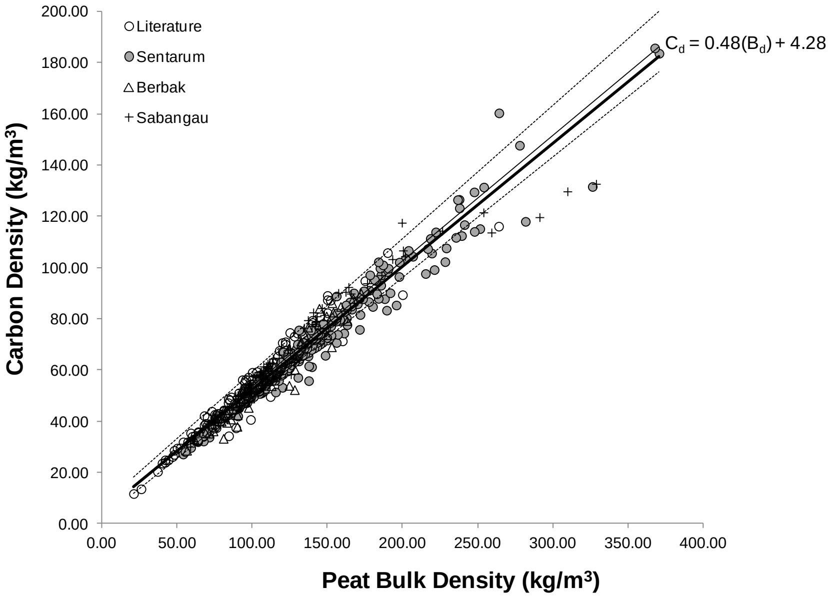

Fig. 2. The linear relationship between peat bulk density and carbon density for 678 data points collected from literature review and three national parks in Indonesia. Mixed organic/mineral samples were excluded from the analysis since they are likely to have %C<40. Thin solid and dotted lines represent the equation: $C_d = 0.49\ (B_d) + 4.61$ with upper and lower 95 % confidence intervals calculated from data collected from published literature. The bold line represents the equation: $C_d = 0.48\ (B_d) + 4.28$, calculated from the complete data set of literature values and original measurements.

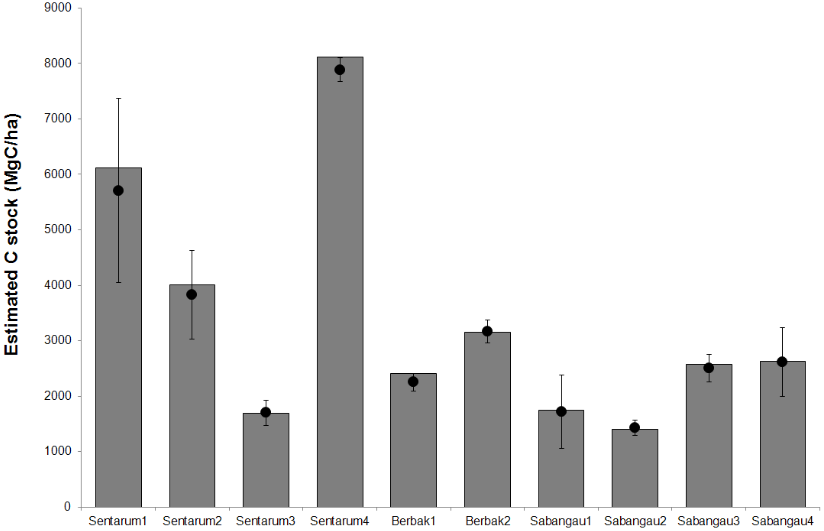

Fig. 3. Soil C stock estimates for ten peat swamp forest sites across three national parks of Indonesia. Black circles and error bars indicate measured means ±SD of 3–6 subplots along 250 m transects. Grey bars indicate means estimated from bulk density only, using the standard equation derived from literature values: Carbon Density = Bulk Density ×0.49 + 4.61. Estimates are for the organic peat layer, and do not include transitional/boundary horizons where soil organic C<40 %.