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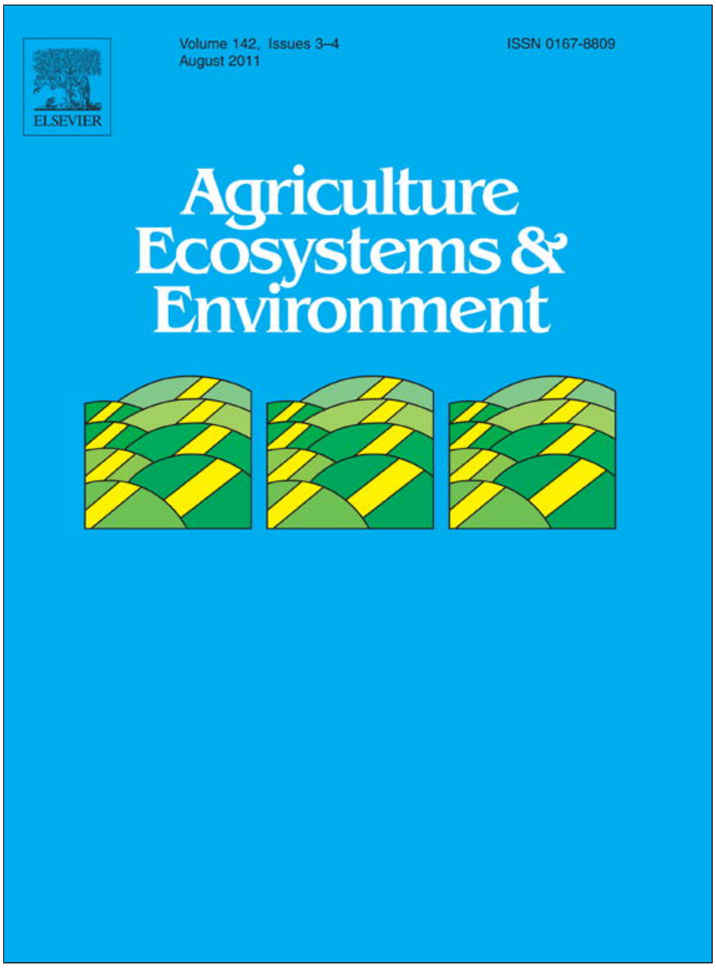
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ABSTRACT

The Carbon Benefits Project (CBP) is developing a standardized system for sustainable land management projects to measure, model and report changes in carbon stocks and greenhouse gas (GHG) emissions for use at varying scales. A global framework of soil organic carbon (SOC) stocks under native vegetation for application in data poor regions, using the simple assessment option of the CBP system, is presented. It considers default classes for climate and mineral soils as required for IPCC Tier 1 (empirical) level GHG inventories. Suitable soil profiles were extracted from an expanded version of the ISRIC-WISE database. Probable outliers within each climate–soil cluster were removed using a robust outlier-rejection procedure. Mean SOC stocks, to the IPCC reference depth of 30 cm (SOC_{30}), vary greatly within each cluster. Overall, present estimates of SOC_{30} are lower than those listed in the 2006 IPCC Guidelines (though not necessarily in the statistical sense) that drew on a smaller selection of profiles from a more limited geographic area. They represent globally averaged values of SOC stocks under native vegetation that may differ from country/region specific values. Finer criteria for defining climate zones and soil classes, and replacement of default reference stocks and stock change factors with region-specific values, will be necessary to reduce uncertainty.

1. Introduction

Carbon inventory assessments involve the estimation of stocks and net fluxes of carbon from different land use systems in a given area over a given period and under a given management system. Ultimately, the scale and objective of a project will determine the methods and data that should be used for the carbon inventory (Ravindranath and Ostwald, 2008). Typically, default data sets for predefined climate zones, land cover and soil classes will be used at national scale, in data poor countries, in combination with simple, empirical calculation approaches. More detailed data sets and increasingly complex modelling approaches will be required for inventories at sub-national down to project-level (IPCC, 2006; Milne et al., 2007). This difference has been expressed in terms of Tiers in the approach of the International Panel on Global Change (IPCC, 1996, 2006). A shift from lower Tier (1) to a higher Tier (3) is associated with an increased complexity in terms of data requirements (i.e., regional specificity of model parameters) and achievable accuracy. Essentially, empirical Tier 1 and 2 methods represent land-use and management impacts on soil carbon stocks as a linear shift from one equilibrium state to another, which is a simplification. Alternatively, Tier 3 methods involve the development of an advanced forecasting system, incorporating process-based models such as RothC and Century (e.g., Falloon and Smith, 2002; Del Grosso et al., 2005; Easter et al., 2007; Milne et al., 2007), to better represent the seasonal or annual variability in carbon dynamics and GHG fluxes. Tier 3 level approaches can also take into account the long-term effects of antecedent land use and management (e.g., Schulp and Verburg, 2009).

The Global Environmental Facility (GEF) co-funded Carbon Benefits Project (CBP), executed by the United Nations Environment Programme (UNEP-DEWA) and implemented by a large international consortium, will provide scientifically rigorous and cost-effective tools to establish the net carbon benefits of sustainable land management interventions in terms of protected or enhanced carbon stocks and reduced GHG emissions (Milne et al., 2010a,b). The CBP system will be applicable at various scales. Upon its completion, it will be made available freely as a web-accessible system (CBP, 2011).

The simple assessment option of the CBP system follows an IPCC Tier 1 approach. Stratification by broad climate region, land use/cover and soil class underlies such approaches. As indicated by Ravindranath and Ostwald (2008), IPCC Tier 1 methods are designed to be the simplest possible to use. Equations and default parameter values, for example for emission and stock change factors, are provided in the IPCC Guidelines for National Greenhouse

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Gas Inventories (2006) (Hereafter referred to as $IPCC_{2006}$ Guidelines). Alternatively, countries and projects with detailed data on climatic conditions, soil types and land use and management are encouraged to develop and use project-specific data sets for application at Tier 2 and 3 levels (IPCC, 2006; Ravindranath and Ostwald, 2008; GOFC-GOLD, 2009; Maia et al., 2010); such a capability will also be included in the CBP system (Milne et al., 2010a).

SOC stocks under undisturbed, native vegetation are usually considered to be in dynamic equilibrium with other terrestrial carbon pools; they are largely controlled by climate, terrain, vegetation, soil mineralogy, particle/aggregate size and their interactions (e.g., Jenny, 1941; Watson et al., 2000; Canadell et al., 2007). Subject to human intervention, such as changes in land use and management, carbon levels in terrestrial systems are prone to change leading to changes in greenhouse gas emissions. Historically, such changes have generally led to decreased SOC levels unless appropriate soil nutrient and water management practices were adopted (e.g., Mann, 1986; Lal and Kimble, 1994; Watson et al., 2000). As such, an important component of any inventory is to have baseline data for SOC stocks under native vegetation before agriculture or other human-induced changes (e.g., Ravindranath and Ostwald, 2008). Such baseline data may also be of use to climate modellers who study the dynamics of the global carbon cycle (e.g., Houghton et al., 2009; Scholes et al., 2009; Smith and Fang, 2010).

The aim of this study is to develop a revised global framework, compatible with $IPCC_{2006}$ Tier 1 type inventories, of SOC stocks to 30 cm depth (SOC_{30}) under native vegetation across the range of world climates and soil types for use with the simple assessment option of the CBP system in data poor countries. The default $IPCC_{2006}$ scheme for grouping climate and soil classes was maintained for this study – proposing new criteria for this would require the derivation of new reference carbon stocks and stock change factors (IPCC, 2006), which is beyond the scope of this study.

Tier 1 and 2 methods do not explicitly consider SOC stocks in organic soils; instead, the annual C-flux following drainage is estimated using an annual emission factor (IPCC, 2006, p. 2.35). Similarly, changes in soil carbonate carbon stock, also called inorganic carbon, are only considered if using a Tier 3 approach. Therefore, they are not considered in this study.

2. Data and methods

2.1. Climate and soil layers

IPCC climate zones are delineated based on elevation, mean annual temperature (MAT), mean annual precipitation (MAP), mean annual precipitation to potential evapotranspiration ratio (MAP/PET) and frost occurrence. The resulting global (GIS) map considers five broad climate zones (tropical, warm temperate, cool temperate, boreal and polar) and twelve subdivisions (IPCC, 2006, p. 3.39).

The $IPCC_{2006}$ Guidelines consider seven soil classes for Tier 1 level inventories: high activity clay (HAC; comprising slightly to moderately weathered soils dominated by 2:1 clay type minerals), low activity clay (LAC; representing highly weathered soil types dominated by 1:1 clay minerals and sesquioxides), sandy (SAN), spodic (POD), volcanic (VOL), wetland (WET), and organic (ORG). These broad classes are derived from soil classification either according to the World Reference Base for Soil Resources (WRB, 2006) or USDA Soil Taxonomy (Soil Survey Staff, 2010) using a strict sequential (IPCC, 2006, p. 3.40–3.41), yet pedologically unsophisticated, approach. Using the IPCC scheme in combination with information about the geographic distribution of WRB reference soil groups worldwide (see FAO/IIASA/ISRIC/ISSCAS/JRC, 2009), the CBP project has created a GIS map of default IPCC soil classes. The clustering procedure and associated uncertainties are discussed by Batjes (2010b).

2.2. Soil profile data

For many areas of the world, soil profile data derived from past surveys are the only source available for estimating pre-clearing SOC levels, for defined climate–soil regions, as required for IPCC Tier 1 inventories. The ISRIC-WISE database (~10 250 profiles, see Batjes, 2009), originally developed for a project entitled World Inventory of Soil Emissions Potentials (WISE, see Batjes and Bridges, 1994), complemented with ~1900 additional geo-referenced profiles provided the basis for this study. Most of the new (historic) additions come from temperate and boreal regions that, so far, were under-represented in WISE (Batjes, 2010a). Soil profiles were characterized according to the FAO Legends (FAO-Unesco, 1974; FAO, 1988) and at Reference Soil Group (WRB, 2006) level. Primary (analytical) data were screened in accordance with standard protocols (see Batjes, 2002, 2009).

Issues associated with the limited comparability of soil analytical procedures worldwide have been discussed by numerous authors (e.g., Pleijsier, 1989; Sombroek et al., 2000). An important issue with part of the available organic carbon data, for example, is the inaccuracy of the Walkley and Black (1934) wet-combustion method, associated with the incomplete oxidation of soil organic matter. The actual C-recovery can vary with climate, soil type, land use, management practices, vegetation type and soil depth (e.g., Skjemstad et al., 1990; Matus et al., 2009; Meersmans et al., 2009, 2011). By convention, however, most laboratories use a recovery factor of ~1.3 to account for the incomplete oxidation (van Reeuwijk, 2002; USDA-NRCS, 2004) and this factor is maintained here. Nowadays, carbon concentration in soil is increasingly obtained through dry combustion (e.g., LECO, 1996); SOC content is then determined from total soil carbon minus carbon held in carbonates (e.g., Soil Survey Staff, 1996).

Default climate at the site of the geo-referenced profiles was estimated using a GIS overlay with the IPCC climate zones map. Alternatively, the IPCC soil class was derived from the FAO soil classification as described by Batjes (2010a).

2.3. Flagging profiles under natural vegetation

Profiles in WISE were collected between 1925 and 2010; about two-thirds of the descriptions originate from the period 1955 to 1995. Changes in land use and management will directly affect the input and decomposition of organic matter in the soil and thereby influence soil organic carbon dynamics. For this study, it is necessary to know whether a soil was considered to be undisturbed (i.e., under natural vegetation), or disturbed (e.g., under cultivation, pasture, or degraded), at the time of profile description and sampling. However, as has been indicated by various researchers, there is still no unanimous acceptance of a single system for describing natural and semi-natural vegetations (Watson et al., 2000; IPCC, 2003; FAO, 2006). This makes the comparison and harmonization (i.e., conversion to a common terminology) of such classes cumbersome, particularly at the global level (Verburg et al., 2010). Selection of a particular classification system thus remains arbitrary. Land use and natural vegetation in WISE are characterized in accordance with international systems adopted for the Guidelines for Soil Profile Description (FAO/ISRIC, 1990; FAO, 2006) and World Soil and Terrain Database (Oldeman and van Engelen, 1993; van Engelen and Wen, 1995).

The information required for harmonizing data on land use and natural vegetation, according to the above systems, was extracted from the various source materials that underpin WISE. For many profiles, however, the primary information is rather scanty if not

Table 1
Main combinations of IPCC default climate regions and soil classes and the proportion of the World's land surface they cover.

IPCC climate zone	IPCC soil class (%)						
	HAC (HAC)	LAC (LAC)	Sandy (SAN)	Spodic (POD)	Volcanic (VOL)	Wetland (WET)	Organic (ORG)
T1 – Tropical Montane	0.86	0.84	0.20	–	0.04	0.07	0.01
T2 – Tropical Wet	1.70	3.58	0.26	0.05	0.05	0.61	0.22
T3 – Tropical Moist	3.45	6.03	0.64	–	0.02	0.67	0.05
T4 – Tropical Dry	10.24	0.91	2.40	–	–	0.14	0.01
W1 – Warm Temp. Moist	6.44	2.48	0.33	–	0.16	0.23	0.04
W2 – Warm Temp. Dry	12.82	0.21	3.02	–	0.02	0.11	0.01
C1 – Cool Temp. Moist	7.95	0.03	1.06	0.54	0.21	0.63	0.57
C2 – Cool Temperate Dry	5.27	–	0.46	–	0.05	0.14	–
Bx – Boreal, undiff.[a]	6.28	–	1.10	1.56	0.03	2.07	1.42
Px – Polar, undiff.	3.39	–	0.58	0.07	0.03	0.60	0.05
Total[b]	58.4	14.08	10.05	1.63	0.50	5.27	1.47

[a] The $IPCC_{2006}$ Guidelines do not differentiate between the Boreal Dry and Boreal Moist zones, respectively the Polar dry and Polar moist zones, in the reference SOC framework; hence the undifferentiated (undiff.) classes.
[b] Classes are only shown when they cover at least 0.01% of the world's land surface (some 137.8×10^6 km^2); data exclude some 13.4×10^6 km^2 for Antarctica, which is not shown on the IPCC climate map. Total adds up to some 93.5% of the land surface; the remaining 6.5% correspond with miscellaneous units of the FAO Legend (e.g., salt flats, rock outcrops, and not determined). Based on GIS overlay of broad scale IPCC climate zones and IPCC soil class map considering the full map unit composition (see Batjes, 2010a).

lacking altogether. Further, when provided, it has been presented according to a range of different classification schemes. Therefore, generalizations are prone to occur when the primary descriptions are converted to the broad land use and natural vegetation classes adopted for WISE, but the associated uncertainty cannot be quantified.

Based on simple decision rules (see Batjes, 2010a), the harmonized information on land use and natural vegetation was used to cluster profiles according to whether they were considered to be under "cultivation or disturbed conditions" or (semi)natural vegetation at the time of profile description/sampling. Profiles flagged as being under natural vegetation provided the basis for the subsequent analyses.

2.4. Computation of SOC stocks

The SOC stock for an individual profile with k layers is calculated according to Eq. (1) (Batjes, 1996):

$$T_d = \sum_{i=1}^{k} \rho_i P_i D_i (1 - S_i) \tag{1}$$

where T_d is the total amount of organic carbon over depth, d, (in Kg m^{-2}), ρ_i is the bulk density of layer i (Mg m^{-3}), P_i is the proportion of organic carbon in layer i (g C Kg^{-1}), D_i is the thickness of this layer (m), and S_i is the volume of the fraction of fragments >2 mm.

Only profiles with measured SOC data to at least 30 cm (the reference $IPCC_{2006}$ depth) are considered here. Gaps in the measured data for bulk density and volume of the fraction of fragments >2 mm were filled using consistent taxotransfer procedures (see Batjes et al., 2007). A *taxotransfer* function is a means of estimating soil parameters based on modal soil characteristics of soil units from a combination of their classification name – which by definition implies a certain range for various soil attributes – expert knowledge and empirical rules, and statistical analysis of a large number of soil profiles belonging to the same taxon (Batjes et al., 1997). The current procedure considers the Revised Legend (FAO, 1988) and clusters the corresponding soil profile data into five textural classes (from coarse to very fine) and five depth ranges (0–20, 20–40, 40–60, 60–80 and 80–100 cm). The cut-off point for defining and applying any taxotransfer rule was that there were at least 5 observations for the soil unit, depth zone, soil textural class, and attribute under consideration (i.e., $n_{WISE} < 5$). All taxotransfer rules have been flagged to provide an indication of the inferred confidence in the soil parameter estimates presented; a detailed discussion of the procedure is beyond the scope of this paper.

SOC_{30} stocks, computed for each profile, were analysed by functional group (e.g., "Sandy-Tropical Wet" or SAN-T2). Possible outliers within a given cluster were flagged using a robust, statistical outlier-rejection scheme. This procedure tests departure from the median, using $k = 1.5$ (Frigge et al., 1989), and subsequently excludes all flagged values from further analysis. Typically, for non-normal distributions, the median is more robust than the mean as well as more resistant to erratic extreme observations (Snedecor and Cochran, 1980, p. 136–137). Application of the outlier-rejection scheme led to the rejection of 0% up to 11% of the original cases (see Batjes, 2010a).

3. Results

3.1. Global distribution of dominant IPCC climate–soil clusters

Table 1 provides an indication of the clusters for which SOC_{30} data under native vegetation may be presented in the global SOC framework, keeping in mind the main soil forming factors (see Jenny, 1941; Post et al., 1985). In practice, however, filling of the framework will depend strongly on the availability of regionally representative profiles for the main climate–soil clusters.

3.2. Reference SOC stocks

3.2.1. By IPCC climate zone

SOC_{30} stocks vary greatly within each IPCC climate zone. Coefficients of variation (CV) range from 74% for the Tropical Wet zone (W2) to 127% for the Polar-undifferentiated (Px) zone (Table 2). The overall pattern is that mean SOC_{30} stocks are highest in cold, relatively moist areas decreasing in the sequence Bx (Boreal) > Px ∼ C1 (Cool temperate moist). Further, in tropical regions, mean SOC_{30} stocks decrease as the climate becomes drier. These broad patterns are consistent with those reported by other researchers (Jenny, 1941; Post et al., 1985).

3.2.2. By IPCC soil class

Subsequently, profiles under native vegetation were clustered by IPCC soil class, irrespective of climate zone (Table 3). Again, SOC_{30} stocks vary greatly within each class with coefficients of variation ranging from 54% for the organic class to 160% for the sandy class. The latter is to be expected here since the $IPCC_{2006}$ scheme

Table 2
Descriptive statistics for SOC_{30} stocks under native vegetation by IPCC climate zone.

IPCC climate zone	SOC_{30} (Mg C ha^{-1})							
	n[a]	MEA	SD	CV (%)	MED	MAD	MIN	MAX
T1 – Tropical Montane	246	61	52	86	47	20	5	483
T2 – Tropical Wet	525	61	45	74	51	20	5	422
T3 – Tropical Moist	738	50	54	110	36	15	3	909
T4 – Tropical Dry	948	22	23	102	16	8	1	280
W1 – Warm Temp. Moist	839	76	58	77	61	25	3	646
W2 – Warm Temp. Dry	1275	26	30	118	17	9	1	511
C1 – Cool Temp. Moist	658	116	119	102	84	40	2	1108
C2 – Cool Temp. Dry	201	49	53	110	38	18	1	611
Bx – Boreal, undiff.[b]	68	149	159	106	75	43	14	551
Px – Polar, undiff.	62	118	150	127	50	45	1	582

[a] Abbreviations: sample size (n), mean (MEA), standard deviation (SD), coefficient of variation (CV), median (MED), median absolute deviation from the median (MAD), minimum (MIN), and maximum (MAX).

[b] For definition of climate zones, see IPCC (2006) and text. The $IPCC_{2006}$ Guidelines do not differentiate between the Boreal dry and Boreal moist zones, respectively the PolardDry and Polar moist zones, in the reference SOC framework; hence the undifferentiated (undiff.) classes.

defines this class as being comprised of "all mineral soils (regardless of taxonomic classification) having >70% sand and <8% clay (includes Arenosols)". As a result, it comprises coarse-textured profiles from 17 different FAO soil groups with widely varying values for SOC_{30}; see Batjes (2010a) for details.

Overall, minimum (mean) SOC_{30} values correspond with profiles from warm arid regions while maximum values are mainly for medium and fine textured profiles from humid and cold/temperate regions. The largest mean values for SOC_{30} are observed for poorly drained, organic soils (ORG, not shown here) followed by the POD, VOL and WET classes. Quite similarly, for mineral soils in the USA, Ogle et al. (2003) reported the highest SOC stocks for volcanic soils, followed by Podzols (Spodisols) and wetland soils. HAC and LAC soils have intermediate SOC_{30} stocks, with mean values reported for HAC soils being similar to those for LAC soils. Due to the fact that primary production is higher and SOM decomposition faster under tropical conditions, both processes may be balanced in natural ecosystems. As a result, overall, SOM levels in undisturbed temperate soils need not differ much from those in tropical soils (Theng et al., 1989; Lal and Sanchez, 1992; Woomer, 1993; Feller et al., 2001).

3.2.3. By IPCC climate–soil cluster

The simple assessment option of the CBP system is comparable, though not analogous, to the IPCC Tier 1 level approach (Milne et al., 2010a,b). It is good practice in the $IPCC_{2006}$ Guidelines to consider mean SOC_{30} stocks under native vegetation, per climate–soil class, when estimating changes in SOC_{30} subsequent to defined changes in land use and management. It should be noted, however, that for skewed distributions the median is considered more robust than the mean since it is more resistant to erratic observations (Snedecor and Cochran, 1980).

Detailed descriptive statistics for the various clusters are presented elsewhere (Batjes, 2010a). They include: the sample size before (n_0) and after outlier-rejection (n_1), the mean (MEA), standard deviation (SD), coefficient of variation (CV), minimum (MIN) and maximum (MAX), as well as the median (MED) and median absolute deviation from the median (MAD). For sake of brevity, however, results for n_1, MEA, SD, MED and MAD are summarized in Table 4.

CVs for mineral soils range from 38% for the "VOL-C1" class to 106% for "SAN-PX", with a mean of 59%. By comparison, the $IPCC_{2006}$ Guidelines assume a "relative error" (defined as 2xSD/MEA in said Guidelines) of ±90% for all climate–soil clusters, which corresponds to a mean, assumed, CV of 45%. Overall, the present variation in SOC_{30} stocks (SOC_{30_CBP}) by climate–soil cluster is greater than that assumed in the $IPCC_{2006}$ Guidelines (SOC_{30_IPCC}). Further, the estimates for SOC_{30_IPCC} are larger than those for SOC_{30_CBP} for 75% of the classes reported in Table 5. The relative difference (D_{rel} in %) can be assessed using

$$D_{rel} = 100 \times \mathrm{ROUND}((SOC_{30\_IPCC} - SOC_{30\_CBP})/(SOC_{30\_CBP}), 0) \quad (2)$$

As there is no absolute reference here, SOC_{30_CBP} was taken as the present best estimate for SOC_{30} being based on the largest, and probably most representative, selection of soil profiles available today. Further, when calculating D_{rel} only calculated values for SOC_{30_IPCC} were considered (i.e., comparison excludes values flagged as "*" and "**" in Table 4, see footnotes e and f).

D_{rel} ranges from −42% for the "W1-VOL" class to +244% for the "T4-SAN" class. However, absolute values for D_{rel} are ≤45% for some 75% of the cases shown in Table 5. As such, the differences reported here need not be statistically significant. This significance, however, cannot be assessed because the $IPCC_{2006}$ Guidelines do not provide any information on sample size nor SD.

Table 3
Descriptive statistics for SOC_{30} stocks under native vegetation by IPCC soil class.

IPCC soil class	SOC_{30} (Mg C ha^{-1})							
	n[a]	MEA	SD	CV (%)	MED	MAD	MIN	MAX
HAC – High activity clay class	3021	49	47	97	36	20	1	871
LAC – Low activity clay class	1098	46	32	70	38	17	3	250
POD – Spodic class	69	130	80	62	108	38	24	389
SAN – Sandy class	882	28	46	160	13	7	1	451
VOL – Volcanic class	118	127	84	66	112	44	10	646
WET – Wetland class	271	84	76	89	62	35	1	559
ORG – Organic class	101	353	191	54	314	123	88	1108

[a] Abbreviations: sample size (n), mean (MEA), standard deviation (SD), coefficient of variation (CV), median (MED), median absolute deviation from the median (MAD), minimum (MIN), and maximum (MAX). For definition of IPCC soil classes, see Section 2.1.

Table 4
SOC_{30} stocks for profiles under native vegetation clustered by default IPCC mineral soil types and climate zones (Mg C ha^{-1} to 30 cm)[a,b].

IPCC 2006 Climate zone	IPCC soil class																		
	Descr. statistics	HAC soils (HAC)			LAC soils (LAC)			Sandy soils (SAN)			Spodic soils (POD)			Volcanic (VOL)			Wetland soils (WET)		
T1 – Tropical	*n*, Mean, SD	114	51	28	84	44	22	11	52	30	–			10	96	48	12	82	73
Montane	*n*, Median, MAD	114	46	20	84	36	12	11	47	14	–			10	74	16	12	58	36
	IPCC 2006 default[c]	88*[e]			63*			34*			na[g]			80*			86		
T2 – Tropical	*n*, Mean, SD	137	60	30	271	52	25	43	46	31	–			14	77	40	33	49	27
Wet	*n*, Median, MAD	137	53	19	271	46	16	43	41	22	–			14	66	22	33	49	16
	IPCC 2006 default	44			60			66			na			130**[f]			86		
T3 – Tropical	*n*, Mean, SD	226	40	22	326	38	19	76	27	15	–			–			55	68	45
Moist	*n*, Median, MAD	226	35	14	326	33	12	76	23	11	–			–			55	53	24
	IPCC 2006 default	65			47			39			na			70**			86		
T4 – Tropical	*n*, Mean, SD	554	21	13	135	19	11	164	9	5	–			–			32	22	11
Dry	*n*, Median, MAD	554	17	7	135	17	7	164	8	3	–			–			32	20	7
	IPCC 2006 default	38			35			31			na			50**			86		
W1 – Warm	*n*, Mean, SD	489	64	33	183	55	29	39	36	26	9	143	65	42	138	56	28	135	101
Temp. Moist	*n*, Median, MAD	489	59	21	183	50	19	39	29	11	9	142	54	42	143	28	28	94	49
	IPCC 2006 default	88			63			34			na			80			88		
W2 – Warm	*n*, Mean, SD	781	24	16	41	19	10	338	10	5	–			10	84	88	49	74	45
Temp. Dry	*n*, Median, MAD	781	19	9	41	18	7	338	9	3	–			10	33	23	49	66	34
	IPCC 2006 default	38			24			19			na			70**			88		
C1 – Cool	*n*, Mean, SD	334	81	40	6	76	48	126	51	39	45	128	61	28	136	52	42	128	55
Temp. Moist	*n*, Median, MAD	334	74	28	6	66	18	126	42	22	45	115	41	28	137	28	42	113	36
	IPCC 2006 default	95			85			71			115			130			87		
C2 – Cool	*n*, Mean, SD	177	43	24	–			10	13	7	–			–			–		
Temp. Dry	*n*, Median, MAD	177	38	17	–			10	12	3	–			–			–		
	IPCC 2006 default	50			33			34			na			20**			87		
Bx – Boreal	*n*, Mean, SD	35	63	34	–			–			–			–			6	116	94
(undiff.)[d]	*n*, Median, MAD	35	58	22	–			–			–			–			6	110	76
	IPCC 2006 default	68			na			10**			117			20**			146		
Px – Polar	*n*, Mean, SD	24	59	61	–			18	27	29	–			–			–		
(undiff.)[d]	*n*, Median, MAD	24	30	27	–			18	14	12	–			–			–		
	IPCC 2006 default	–			–			–			–			–			–		

[a] Climate classes are according to IPCC (2006). Default soil classes are inferred from the FAO-1990/WRB-2006 classification in accordance with $IPCC_{2006}$ Guidelines, see Section 2.1.

[b] Results are only shown for categories with $n > 5$ observations per functional group, after rejection of possible outliers (see Section 2.4). The IPCC (2006) Tier 1 approach considers means in its SOC stock change inventories. Overall, confidence in results for mean SOC_{30} stocks presented here should increase with sample size (n), tentatively as follows: lowest ($5 < n \leq 15$), moderate ($15 < n \leq 30$), highest ($30 < n$).

[c] Mean the $IPCC_{2006}$ Guidelines assume a relative estimated error of ±90% (defined as 2 × standard deviation as percentage of the mean) for all climate–soil types; sample size (n) and SD are not given. This precludes analyses of statistical differences between $IPCC_{2006}$ estimates for SOC_{30} and present results.

[d] The $IPCC_{2006}$ Guidelines do not differentiate between the Boreal dry and Boreal moist zones, respectively the Polar dry and Polar moist zones, in the reference SOC framework. Present results for SOC_{30} stocks are for the undifferentiated (undiff.) Bx and Px classes.

[e] For Tropical Montane (flagged here as '*'), the IPCC Guidelines assume SOC stocks similar to those reported for the warm temperate moist region, which has similar mean annual temperature and precipitation.

[f] If no new data are available for the $IPCC_{2006}$ estimates, defaults (flagged as '**') from the $IPCC_{1996}$ Guidelines were retained (see IPCC, 2006, p. 2.31).

[g] NA denotes "not applicable" in the $IPCC_{2006}$ Guidelines because these soil categories do not normally occur in some climate zones; Table 1 provides an overview of main combinations of IPCC climate regions and soil types based on GIS overlay of the IPCC climate and soil classes map.

Table 5
Relative difference in SOC_{30} estimates reported in the $IPCC_{2006}$ Guidelines and the present study.

IPCC climate–soil class[a]	SOC_{30} IPCC ($Mg\,C\,ha^{-1}$)	SOC_{30} CBP ($Mg\,C\,ha^{-1}$)	Relative difference (D_{rel}, %)
W1-VOL	80	138	−42
W1-WET	88	135	−35
C1-WET	87	128	−32
T2-HAC	44	60	−27
C1-POD	115	128	−10
W1-SAN	34	36	−6
C1-VOL	130	136	−4
Bx-HAC	68	63	8
W1-LAC	63	57	11
C1-LAC	85	76	12
W2-LAC	24	21	14
T2-LAC	60	52	15
C2-HAC	50	43	16
C1-HAC	95	81	17
W2-WET	88	74	19
T3-LAC	47	38	24
Bx-WET	146	116	26
W1-HAC	88	64	38
C1-SAN	71	51	39
T2-SAN	66	46	43
T3-SAN	39	27	44
W2-HAC	38	24	58
T3-HAC	65	40	62
T4-HAC	38	21	81
T4-LAC	35	19	84
W2-SAN	19	10	90
C2-SAN	34	13	162
T4-SAN	31	9	244

[a]Excludes all climate–soil classes for which expert estimates are presented in the $IPCC_{2006}$ Guidelines (see footnotes of Table 4).

4. Discussion

4.1. Representativeness of selected soil profiles

The $IPCC_{2006}$ Guidelines and current study draw on legacy data (i.e., soil profiles derived from past surveys) and for both studies the soil profiles were selected based on purposive sampling. The methods for locating the soil profiles in the field depended on the purpose of the original investigations (often systematic soil surveys). In such surveys, sample sites are generally selected as typical of a soil-mapping unit (Soil Survey Staff, 1983; Landon, 1991; Rossiter, 2004). This purposive sampling can provide reasonable estimates when a population is very variable and resources allow few sites to be examined (McKenzie et al., 2000; Webster and Oliver, 2001). However, there is a risk of bias as purposive sampling relies heavily on personal (expert) judgement. As indicated by McKenzie et al. (2000) and others, there is no way of knowing just how good this judgement is. The only way to avoid bias inherent in purposive sampling is to follow probabilistic sampling (e.g., Snedecor and Cochran, 1980), as recommended for digital soil mapping (Lagacherie et al., 2006; Sanchez et al., 2009). For example, this is necessary to account objectively for short distance variation in vegetation (within defined strata), which can have marked effects on soil carbon levels. For many areas of the world, however, data derived from conventional soil survey will remain the only source of information for estimating pre-clearing SOC levels for defined climate–soil regions for IPCC Tier 1 inventories.

Default estimates for SOC_{30} presented in the $IPCC_{2006}$ Guidelines are based on analyses of soil profiles held in databases described by Jobbagy and Jackson (2000) and Bernoux et al. (2002). The former largely considered data extracted from two large national databases (USA, Canada) as well as an earlier version of WISE. Following data screening and clustering, Jobbagy and Jackson (2000) identified 1271 profiles as being under agricultural use and 802 under natural vegetation. Alternatively, for Brazil, Bernoux et al. (2002) identified 2694 profiles as being under natural vegetation out of 3969 profiles. Based on this information, it would appear that SOC_{30} stocks presented in the $IPCC_{2006}$ Guidelines are based on analyses of some 3500 profiles under natural vegetation, with a strong geographical bias (77%) with respect to profiles from Brazil.

The lowest SOC_{30} stocks are observed for the SAN class (Table 4), which is consistent with earlier findings (Ogle et al., 2003; IPCC, 2006; Maia et al., 2010). Values for the POD class, comprising WRB-Podzols having a texture finer than "<8% clay and >70% sand", for the cool temperate moist (C1; 128 $Mg\,C\,ha^{-1}$) and warm temperate moist (W1; 143 $Mg\,C\,ha^{-1}$) climates agree well with global mean values for Podzols of 175 $Mg\,C\,ha^{-1}$ to 50 cm depth presented by Kimble et al. (1990), respectively 136 $Mg\,C\,ha^{-1}$ to 30 cm reported by Batjes (1996). Worldwide, Podzols show a wide range in properties and hence SOC stocks (Mokma and Buurman, 1982; Thompson et al., 1996; Buurman et al., 2007; Olsson et al., 2009); they can comprise very shallow members in Arctic regions (Blume et al., 1996), poorly drained members (Thompson et al., 1996), as well as very deep members in the Tropics (Schwartz, 1988). The overall trend of mean SOC_{30} stocks for HAC soils being somewhat larger or similar to those for LAC soils, irrespective of climate region, is consistent with earlier results (Theng et al., 1989; Kimble et al., 1990; Lal and Sanchez, 1992; Sombroek et al., 1993; Woomer, 1993; Batjes, 1996; Feller et al., 2001).

For the south-western Amazon in Brazil, Maia et al. (2010, p. 2781) collected SOC_{30} data by ecoregion for a Tier 2 level inventory. On the basis thereof, the relative error for reference SOC_{30} stocks, *sensu* $IPCC_{2006}$, was calculated here (for ecoregions characterized by ≥10 profiles). Values ranged from ±98% for wetland soils from the Araguia depression to over 400% for Oxisols from northern Rondonia; the underlying study considered some 3484 profiles under native vegetation. Earlier, Tornquist et al. (2009) recommended validation of IPCC reference SOC stocks by comparison with results from field measurements, before their widespread adoption in a given project area. The current study supports that recommendation.

The large variation in SOC_{30} stocks, per IPCC climate–soil class reported here, reflects that other, often local, factors are also important (Spain et al., 1983; Eswaran et al., 1993; Sombroek et al., 1993; Batjes, 1996; Sombroek, 1996; Jobbagy and Jackson, 2000). These may include small-scale (i.e., local) differences in microclimate, topographic position, parent material, soil texture, soil drainage, soil nutrient status, salinity/sodicity or Al-toxicity, as well as vegetation type. Alternatively, changes in duration of the growing season, atmospheric CO_2 concentration, nitrogen deposition, or effects of climate change on natural enemies of pests may also alter SOC dynamics in so-called undisturbed natural systems (e.g., Bazzaz and Sombroek, 1996; Menzel and Fabian, 1999; Janssens et al., 2010; Thomson et al., 2010). The broad grouping of SOC_{30} data into the large, aggregated units that underlie the IPCC Tier 1 level approach may thus mask meaningful variation at the regional (*sensu* sub-national and project) level. For example, Cerri et al. (2000) reported regional differences in SOC content for three geographic clusters of Latossolos Vermelho Amarello (i.e., LAC class) under natural vegetation from the Brazilian Amazon; these were associated with regional differences in length of dry season and forest cover density. As indicated by Ravindranath and Ostwald (2008), developing a database on carbon stocks and stock change factors for various land-use categories (e.g., forest, cropland and grassland) and subclasses based on agroclimatic conditions, soil types and land use management systems at subnational level can reduce such uncertainty (see also Ogle et al., 2003, 2004; GOFC-GOLD, 2009; Tornquist et al., 2009; Maia et al., 2010).

4.2. Uncertainty

A large uncertainty remains in estimates for reference SOC_{30} stocks that underpin the $IPCC_{2006}$ Guidelines inventory approach, for data poor regions. For many climate–soil classes, estimates of SOC_{30} presented in this paper differ markedly – though not necessarily in a statistical sense – from earlier estimates in the $IPCC_{2006}$ Guidelines. Clearly, this will have direct implications when calculating changes in SOC stocks and GHG emissions subsequent to defined changes in land use and management, according to these Guidelines. In short, for mineral soils, the procedure considers: (a) default values for mean SOC stocks to 30 cm depth under native vegetation, for defined IPCC climate–soil classes (see Table 4); (b) stock change factors (dimensionless) for land-use system, management regime and input of organic matter; and, (c) the land area of stratum under consideration (e.g., IPCC, 2006; Ravindranath and Ostwald, 2008).

Maia et al. (2010) reported that the greatest source of uncertainty, when applying the $IPCC_{2006}$ Guidelines approach to soil ecoregions in south-western Brazil, is associated with the reference soil carbon stocks. Alternatively, for Rio Grande do Sul, Brazil, Tornquist et al. (2009) reported that, generally, $IPCC_{2006}$ default reference SOC stocks compared well with SOC stocks calculated from soil pedons. In this context, however, it should be observed that, apparently, the $IPCC_{2006}$ default values for reference SOC stocks were largely derived from Brazilian profile data. This could also partly explain why many estimates for SOC_{30} stocks presented in Table 4 are lower, though not necessarily in a statistical sense, than those presented in the $IPCC_{2006}$ Guidelines. Overall, the selection of soil profiles considered here originates from a wider and more diverse geographic area.

SOC data in Table 4 represent globally averaged values, per broad climate–soil region to 30 cm depth, of reference C stocks that may differ from country/region specific values. Bias can be reduced by deriving country/region-specific C reference values using a Tier 2, or Tier 3 level, system (e.g., Ravindranath and Ostwald, 2008; GOFC-GOLD, 2009; Maia et al., 2010). Main considerations with respect to uncertainty assessment, and reducing the current uncertainty, have been discussed by the IPCC (2006), Ravindranath and Ostwald (2008) and others. Similarly, procedures for reducing uncertainty in estimates of land use and management impacts on soil organic carbon storage (i.e., stock change factors), for a range of agricultural systems, have been discussed elsewhere (Ogle et al., 2003; Conant and Paustian, 2004; Ogle et al., 2004). In this context, it is also necessary to consider the *net* C gains of possible land use interventions, that is also take into account the GHG effect of added N-fertilizer, fuel use for tractors and pumping, etc. (e.g., Schlesinger, 2000; Powlson et al., 2011); these elements are also considered in the CBP system (Milne et al., 2010b).

Gains in accuracy for Tier 1 type assessments may also be achieved by improving the spatial resolution of the IPCC climate zones map. The same applies to the IPCC soil classes map which has been derived from the Harmonised World Soil Database (HWSD, see FAO/IIASA/ISRIC/ISSCAS/JRC, 2009), sections of which are still based on the old FAO-UNESCO Soil Map of the World (for details see Batjes, 2010b). Uncertainties are also associated with the procedures used to fill gaps in the measured data for bulk density and proportion of coarse fragments, needed to calculate SOC_{30} stocks, as well as with criteria used for flagging profiles under natural vegetation. The overall uncertainty, however, cannot be quantified as many of the underlying uncertainties are described in qualitative terms only.

Empirical Tier 2 methods that consider finer criteria for defining differences in climate zones and soil types, in combination with country/project-specific values for reference SOC stocks and stock change factors, may be used to reduce uncertainty at the national and project level. Alternatively, more data demanding process-based modelling (Tier 3) approaches may be applied, but such multi-compartment models of soil carbon dynamics will have their own large set of uncertainties and limitations (e.g., Wang et al., 2005; Larocque et al., 2008; Nol et al., 2010), which may limit application of such models for net carbon accounting. Consequently, sustainable land management projects, as well as carbon mitigation projects, should use the most accurate methods possible given the resources available and project objectives (e.g., Ravindranath and Ostwald, 2008; GOFC-GOLD, 2009; Milne et al., 2010a,b).

5. Conclusions

Uncertainty plays an important role in any net carbon accounting approach; it will determine the possible accuracy of estimates of carbon stocks and their changes, irrespective of scale. This uncertainty is inherently high in natural and land-use change systems mapped at global and national scales given the large variation in natural and human-driven factors that control carbon stocks and changes in terrestrial ecosystems.

This study provides a summary of SOC_{30} stocks under natural vegetation, based on the current selection of profile data in WISE ($n = 5560$). This set is 1.6 times the size of the one underpinning earlier estimates in the $IPCC_{2006}$ Guidelines. Further, profiles in the ISRIC-WISE database originate from a broader geographic area than has been considered for the $IPCC_{2006}$ Guidelines. The estimates for SOC_{30} derived from this study, with defined uncertainty ranges, may be used as new default values for the web-based CBP system (to be delivered in 2012), for application in data poor countries. They represent globally averaged values, per broad IPCC climate–soil region, of reference carbon stocks that may differ from country/region specific values.

Use of finer criteria for defining climate zones and soil types and the substitution of default reference stocks and stock change factors with country/project-specific values, initially using Tier 2 methods, will be necessary to reduce uncertainty in SOC stock changes. Overall, sustainable land management projects should be encouraged to use the most accurate methods possible, given the resources available and project objectives.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agee.2011.06.007.

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