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Carbon concentrations and stocks in forest soils of Europe

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ABSTRACT

This study presents the results of a series of evaluations of a continent-wide soil database (EU/UN-ECE Level I) with the aim to estimate baseline soil carbon concentrations and stocks. The methodology included the biogeographic stratification of soil carbon measurements throughout Europe using climatic zones derived from the Soil Regions Map of Europe. The presented stock estimates range from 1.3 to 70.8 t C/ha for the O-layer, and from 11.3 to 126.3 t C/ha for the mineral soil 0–20 cm (Germany: 0–30 cm) (5 and 95 percentiles). Histosols were excluded because of methodological differences and data gaps. When looking at the median values of the strata investigated, relationships were found. For example, carbon stocks in the O-layer of sandy soils are distinctly higher than those of fine-textured soils. However, the variability is so high that some of these relationships disappear. For example in western and central Europe, the level of carbon stocks in the mineral soil between shallow soils (Leptosols) and more deeply developed soils (Podzols and Cambisols) do not differ very much. It was also found that just the investigation of topsoils is not sufficient to understand the regional pattern of organic matter in forest soils – unless the subsoil becomes included as well. It is hypothesized that for Europe, the impact of site factors such as climate, texture and relief are difficult to extract from such a database if the data are only stratified according to macro-climatic areas. It has to be considered that the effect of systematic error in the database is quite large (but cannot be identified on the level of the current data availability). In order to receive a first impression of the landscape-level distribution of carbon, a map of carbon concentrations in the topsoil was generated. The results support the relationships found between carbon stocks and site factors, such as climatic zones and soil type. Compared to the much lower carbon concentrations of agricultural soils, the results demonstrate clearly the importance of forest soils for the terrestrial carbon cycling in Europe.

1. Introduction

Forest soils in the Northern hemisphere undoubtedly play an important role in the terrestrial greenhouse gas balance (Janssens et al., 2003; IPCC, 2003, 2006). For example, forest soils in Europe store roughly 1.5 times more carbon than trees (EC/UN-ECE, 2003). It is expected, that the importance of forest soils for the European carbon cycle increases even more in the future (Liski et al., 2002; Smith et al., 2006). However, an accurate continent-wide assessment of the role of soils to store carbon is still difficult considering the great range of available model and inventory results. For example, Cannell et al. (1992) have presented a first rough estimate of 3–4 Gt carbon stored in European forest soils. Liski et al. (2002) gave a model-based estimate of 5 Gt C. Goodale et al. (2002) have estimated a forest soil C stock of 13.7 Gt including the O-layer. Jones et al. (2004, 2005; continued evaluations for Schils et al., 2008) estimated a pool size of 79 Gt C for all European soils including peat. Of course, each estimate refers to a different area extent, soil depth, and methodology, and deviations to country-specific results can be quite substantial. Schils et al. (2008) conclude that existing regional data are difficult to integrate into a single harmonized continent-wide assessment.

These frame conditions also affect the estimation of current and future carbon sinks and sources. Such trend estimates are still mostly model-based because data from repeated soil inventories or monitoring are still the exception (Bellamy et al., 2005). According to Liski et al. (2002), the carbon content of forest soils in western Europe has been increasing at the rate of 26 Mt C a^{-1} in 1990. De Vries et al. (2000) estimated a sequestration of 76 Mt a^{-1} in forest soils (EU 15; see also Table 1). Janssens et al. (2003) have pub-

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lished an estimate of 110 g C m^{-2} a^{-1} (which equals 151 Mt C a^{-1} after applying the same size of forested area calculated by Liski et al. (2002)). Schils et al. (2008) cite various national studies mostly based on modelling, and mostly indicating sink rather than source behaviour of forest soils: values differ from study to study, ranging from 0.01 to 0.8 t ha^{-1} a^{-1} for managed forest land, and from 0.02 to 0.45 t ha^{-1} a^{-1} after conversion of cropland to forest. The reliability of these model results depends on reliable baseline and/or calibration data (Chertov et al., 2002; Faubert et al., 2006). According to Lal et al. (2003), the development of reliable baselines is still a knowledge gap in the search for reliable information about carbon sequestration in forest soils.

It has been demonstrated that the role of soils cannot be accurately determined without comparable and harmonized inventory data. Such an inventory exists with the EU/ICP Forests Level I soil condition inventory 1990–1995 (UN-ECE ICP Forests, 1998). Because its design has not initially focussed on soil carbon monitoring, some improvements were recently made (UN-ECE ICP Forests, 2006). Meanwhile the inventory was repeated (2006–2008; http://biosoil.jrc.ec.europa.eu/). Until now, baseline values for the carbon content of forest soils were not derived from this database. The general difficulties involved in applying large databases for such a purpose were commented by Amichev and Galbraith (2004). In the case of the Level I inventory, national design modifications and data gaps cause difficulties to develop a harmonized soil carbon baseline. An additional challenge for evaluations of plot-level inventories in Europe is the variability of its soils (Montanarella, 2005).

This study attempts for the first time to produce a harmonized assessment of the carbon content of forest soils in Europe, using data from the EU/ICP Forests Level I inventory. The quantification of soil carbon stocks requires that carbon concentration measurements are further recaclulated to a volume to area basis. For that, additional data are needed which are often not measured in extensive surveys, such as the bulk density and stoniness of soils. This study will develop reliable estimates at the continental level. In order to assess the effects of regional variability, a map of soil carbon concentrations is to be developed. At the same time, effects of climate must be additionally considered because the study area covers a large geographic gradient, and because climate strongly affects the properties of otherwise pedogenetically similar soils (Finke et al., 1998). Methodically, the results of this study are expected to support the further use of the Level I forest soil condition database, for example in combination with the results of repeated samplings, both nationally and across Europe. This study will produce harmonized baseline soil carbon stocks which help to assess the plausibility of diverse published inventory data. They can be directly applied to soil carbon models, and thus contribute to support the comparability of model results. Therefore, these results will indirectly also improve the reporting of soils in IPCC greenhouse gas inventories.

2. Materials and methods

2.1. ICP Forests Level I forest soil inventory in Europe

The International Co-operative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) has established a forest health monitoring programme using an extensive 16 km × 16 km survey grid (Level I) and a network of stratified intensive monitoring plots (Level II) (www.ICP-Forests.org). In 1990–1995, 31 countries participated in a Level I soil condition inventory (Vanmechelen et al., 1997; UN-ECE ICP Forests, 1998). The data are stored in the ICP Forests Soil Condition Database at the Forest Soil Coordinating Centre of the ICP Forests and at the EU Joint Research Centre. The data extract for this study includes the original SOC concentrations of the mineral soil and of the O-Layer (see Table 1 for definitions), bulk density and stone content, and the dry weight of the O-layer. The reference depth for the mineral soil in this study is 0–20 cm, which is also the mandatory sampling depth of the ICP Forests. For Germany, the mineral soil SOC stocks refer to 0–30 cm because of the country-specific sampling scheme. Sampling of the O-layer has usually included the OF and OH horizons, in many countries also the OL horizon. The pre-treatment of the O-layer samples has included the removal of all material >2 cm, drying at 40 °C, and crushing or milling to <2 mm. Despite the availability of a common manual for sampling and analysis (UN-ECE ICP Forests, 1998), various national modifications of the sampling scheme were implemented (Table 1). This has introduced systematic errors which increase uncertainties involved with the evaluations of this data. Despite significant differences between countries, the ICP Forests Level I soil inventory represents the only comprehensive national and European continent-wide soil survey of the condition of forest soils.

2.2. European soil map

The Soil Geographical Database of Europe (SGDBE) with a scale of 1:1,000,000 is used to upscale the Level I measurements (CEC, 1985; King et al., 1994; ESBN, 1999). That version has not yet contained the recently updated national soil map of Sweden, which was kindly provided by the Swedish University of Agriculture, Uppsala. The modified SGDBE contains $N = 1650$ Soil Map Units (SMU). Each SMU consists of one to several soil typological units (STU, $N = 5306$) for which the area proportions are known. The SGDBE was also used to assign a soil type to those Level I plots where such names were not reported ($N = 276$; Italy, and partly Sweden). This work has been done by Wiedemann et al. (2001), who identified the soil type for each Level I plot at the level of the STU for the main land use 'forest'.

2.3. Climatic zones

The European soils are distributed along large environmental gradients. It is therefore necessary to stratify the Level I soil data set as well as map units which extend across different eco-regions. For example, an Eutric Cambisol in Lithuania is ecologically different from the same soil type in Catalonia because of the different climatic conditions and vegetation, such that the conditions for the accumulation of soil organic matter also differ. The stratification requires information about climate or biogeographic areas. Several eco-geographic and climatic classifications for Europe were reviewed (EEA/ETC BD, 2000; EEA 1995–2002, cited in Roekerts, 2002; Metzger et al., 2003; Mücher et al., 2003; Hartwich et al., 2006). For several of these classifications, soil maps were used as auxiliary data sets. For the purpose of stratification here, a classification of rather broadly defined macro-climatic areas is needed, which is independent from the distribution of soils in maps. It was then decided to use Hartwich et al. (2006), which was developed for the map of Soil Regions in Europe (BGR, 2005). The classification of climatic zones is primarily based on Köppen (1936), Walter and Lieth (1960–1969) and Bohn et al. (2000). It distinguishes 34 climate areas, which are composed of combinations of so-called climate zones (subpolar to boreal, boreal, boreal to temperate (cool-temperate), temperate, Mediterranean) and climatic types (oceanic, suboceanic, subcontinental, continental). The climate areas were aggregated to 7 main climatic zones for this study here in order to assure that sufficient Level I sampling size is maintained within strata.

Table 1
Level I sampling and analytical scheme.

Country	16 km × 16 km grid (Level I)	O-layer	Mineral soil	Carbon	BD	Stone content
AT	*N* = 131, 1987–1989	OL + OF + OH	1 soil pit, 130 cm wide	DC	PTF from SOC	Visual assessment
BE_{Fl}	*N* = 16; 1993	OL + OF + OH, 36 subsamples	Auger sampling in each of the 4 Level I quadrants	DC	Measured	Visual assessment
BE_{Wa}	*N* = 21, 1994–1995	OL + OF + OH, 10 subsamples		DC	Measured	Visual assessment
BU	*N* = 286 (10 regions, 2 per year)	OF + OH (OH sampled separately if >1 cm); 3 subsamples	1 soil pit, 3 subsamples	Tyurin	Measured	Measured: 2–5 mm; >5 mm: visual assessment
CH	*N* = 48, 1993	Sampled occasionally: independent inventory	1 soil pit	DC	Measured (80% of the sites)	Visual assessment
CZ	*N* = 100, 1995–1996	No OL, OF and OH are mixed, 5 subsamples	1 soil pit, 3 subsamples (from all pit sides)	Tyurin	n.d.	Visual assessment
EE	*N* = 91, 1990–1994	No OL, OF and OH separate, 3 subsamples	1 soil pit, 3 samples	Tyurin	Estimated	Visual assessment
DE	*N* = 416, 1987–1993	OL (depends on Federal land; if yes, then with OF); OF, OH mostly separately; 8 subsamples	1 soil pit in the plot centre; 8 satellite borings	DC, WB	Measured, estimated	Visual assessment
DK	*N* = 25; 1994	OL, OF + OH, 4 repetitions per horizon	Along diagonal line of a 50 m × 50 m plot; 16 borings to one composite each 4.7 m	DC	Measured	Visual assessment
EL	*N* = 15, 1993/1994	No OL; OF + OH	2 soil pits (high stone content: sampling in an adjacent area)	WB	Not determined	Visual assessment
ES	*N* = 464, 1993–1995	OF and OH separate; 4 subsamples (1 per quadrant of the ICP plot)	3 pits	WB	Measured	Visual assessment
F	*N* = 517, 1993–1994	OL, OF + OH, 2 subsamples	2 soil pits	DC	Measured	Visual assessment
FI	*N* = 384 plots, 1986–1989, 1995 (104 plots) (Histosols were excluded)	No OL, OF + OH mixed, 10–30 subsamples (10 locations around the soil pit (composite from 1 to 3 subsamples)	*N* = 5 soil pits (50 cm deep) 1 pit: horizons, 4 pits: depth classes	DC (and LoI)	Measured, estimated	Soil pit: visual estimate; plot: Viro's stoniness index
HU	*N* = 67, 1994	OL + OF + OH, 9 subsamples	9 small pits	Tyurin	Estimated	Visual assessment
IE	*N* = 22, 1995	OL + OF + OH, 3 subsamples	1 soil pit	WB, LOI	Measured	Not recorded
IT	*N* = 20, 1994	OL + OF + OH	3 borings	n.d.	n.d.	n.d.
LT	*N* = 67, 1992	OL + OF + OH, Subsamples: *N* = 10	Soil pit 8 no samples from the pit; 12 subsamples from cores	DC	Not determined	Visual assessment (stones present/absent)
LV	*N* = 75, 1991	H and O layers sampled	No samples	Not analysed	n.d.	n.d.
NL	*N* = 11, 1995	OL + OF + OH	20 subsamples	n.d.	Estimated	Visual assessment
PO	*N* = 148, 1995 (Level II)	OF + OH (no L), 9 samples (cylinders)	Soil pit (soil textural analyis, pH) (spade) 0–10, 10–20, 20–40, 40–80 cm: 9 cores	DC	BD measured in 2003 (0–10 cm)	1–20 mm: analysed; >20 mm: visual assessm.
PT	*N* = 157, 1995	OL + OF + OH	16 subsamples	n.d.	n.d.	n.d.
RO	*N* = 242, 1992	OL + OF + OH (composite sample)	1 soil pit	Tyurin	n.d.	n.d.
SE	*N* = 1249 as part of the NFI 5 km × 5 km–15 km × 15 km (1985–1988, *N* = 75 in 1995)	O-layer > 2 cm: OF + OH (composite, no L) O-layer < 2 cm (Mull, Mullmoder): L + OF + A 1–5 samples per plot (core sampler)	1 soil pit; horizons in depth layers 0–10, 10–20, 50–60 cm; Podzols: additionally 0–5 cm of the upper part of the Bs horizon	DC	PTF based on SOC	Viro method
SI	*N* = 43, 1994–1995	OL, OF, OH separately, 3 subsamples	Composite sample from borings *N* = 9 (0–5, 5–10 cm) and *N* = 6 (10–20 cm)	DC	Measured	n.d.
SK	*N* = 112, 1993	OL + OF + OH, 20 (10) subsamples	20 soil pits ("shallow pit method")	Tyurin	Measured, estimated	Visual assessment
UK	*N* = 67, stratified, 1993–1996	OL + OF mixed, OH separate, 4 subsamples (1 for each direction as composite from 7 subplots	*N* = 28 small soil pits (spade)	LOI	No	No

n.d.: no data reported to the Level I Forest Soil Condition Database; no metadata available.
Country: AT (Austria), BE (Belgium; Flanders and Wallonia), BU (Bulgaria), CH (Switzerland), CZ (Czech Republic), EE (Estonia), DE (Germany), DK (Denmark), EL (Greece), ES (Spain), F (France), FI (Finland), HU (Hungary), IE (Ireland), IT (Italy), LT (Lithuania), LV (Latvia), NL (The Netherlands), PO (Poland), PT (Portugal), RO (Romania), SE (Sweden), SI (Slovenia), SK (Slovakia), United Kingdom (UK). EU countries not listed in this table: LU (Luxembourg), MT (Malta), CY (Cyprus). Abbreviations acc. to EUROSTAT. BE_{Fl}: Flanders; BE_{Wa}: Wallonia.
O-layer: aerated organic layer of the forest floor, comprising of undecomposed or partially decomposed litter (UN-ECE ICP Forests, 1998, 2006); *OL horizon* (litter, förna): leaves/needles, twigs and woody materials (including bark), fruits, etc. *OF horizon* (fragmented and/or altered): partly decomposed (i.e. fragmented, bleached, spotted) organic matter. *OH horizon* (humus, humification): well-decomposed amorphous organic matter.
Carbon: WB (wet oxidation by Walkley and Black (1934)), DC (dry combustion), LOI (loss on ignition), Tyurin (1931; modification of WB).
BD: bulk density; PTF (pedo-transfer function).
Stones: Sweden and Finland: Viro (1952).
Sources: Vanmechelen et al. (1997); UN/ECE (1998); Baert et al. (1999); COST E21 Expert meeting on "Monitoring of Forest Soils and Soil Carbon Assessment in Eastern European Countries", Brasov, Romania, 06-07-08 June, 2002; FAO/GTOS Workshop on "Harmonisation of terrestrial carbon measurements in CEE countries", Prague, Czech Republic, 22–25 June, 2004.

Table 2
Level I statistics for available data.

Parameter	# inventory plots
Total Level I plots processed[a]	5269
Weight organic layer[b]	3930 (79%)
C concentration (0–5/0–10 cm)	4279 (91%)
Bulk density[c]	2186 (42%)
Stones[d]	3873 (73%)
Parent material	2120 (40%)
Soil type (FAO, 1988)	4993 (95%)
Texture class	3418 (65%)

[a] Excluding the Azores and Kanares.
[b] $N = 313$ plots with H horizon; $N = 4113$ plots with identified O-layers: the weight of the O-layer was not always determined.
[c] BD based on PTF: $N = 580$; BD from expert judgement during field work: $N = 474$; BD analysed: $N = 1132$.
[d] Mostly visual assessment.

2.4. Forest area

The spatial presentation of carbon concentrations in forest soils requires an overlay between the SGDBE and a forest map. The most recent and accurate forest layer is the Forest/Non-Forest Map 2000 – Version 1.4 (Pekkarinen et al., 2009), a Landsat ETM+ based 30 m raster map, which we have re-sampled to 250 m for better portrayal.

2.5. Content of organic carbon in forest soils

The carbon content of the O-layer is calculated differently from that of the mineral soil:

O-layer:

$$\text{C-stock}_{\text{O-lay}} = \text{C-conc}_{\text{O-lay}} \times \text{weight} \quad (1)$$

$\text{C-stock}_{\text{O-lay}}$ = carbon stocks in the organic layer ($g/m^2/100 = t/ha$).
$\text{C-conc}_{\text{O-lay}}$ = concentration of organic carbon in the organic layer (g/kg).
weight = dry weight of the organic layer (kg/m^2).

The organic material has been sampled by using either a metal frame (e.g. 25 cm × 25 cm) or a core sampler (e.g. Ø10 mm). This procedure provides the *weight* of all the organic material sampled per unit area, independently of its depth. The stock of carbon is received after multiplying *weight* with the carbon concentration which has been determined for a homogenized mixture of the sample material.

Mineral soil:

$$\text{C-stock}_{\text{min}} = \text{C-conc}_{\text{min}} \times \text{BD} \times d \times \text{CF}_{\text{st}} \quad (2)$$

$\text{C-stock}_{\text{min}}$ = C stock in the mineral soil ($kg/m^2 \times 10 = t/ha$).
d = depth class/horizon thickness (m).
$\text{C-conc}_{\text{min}}$ = concentration of organic carbon (g/kg).
BD = bulk density (kg/dm^3).
CF_{st} = correction factor for stoniness, 100 − (% stones)/100.

First, the carbon content per volume of soil is calculated as the carbon concentration ($\text{C-conc}_{\text{min}}$) times the bulk density (BD) of the fine soil. In order to calculate the amount of carbon per area, the carbon content is multiplied with the soil volume down to a depth of 20 cm. This is the reference depth of the ICP Forests soil sampling. For soils containing coarse material (>2 mm), the soil volume has to be reduced corresponding to the volume of the stones.

Methodical differences exist between countries regarding the assessment of the parameters for Eqs. (1) and (2) (Table 1). Especially bulk density and stoniness are fundamental input parameters which introduce high uncertainties (Rosell et al., 2001). Missing values for these parameters in the Level I database (Table 2) have required some pre-processing of the database which introduces additional error. Because these conditions are important to know for the interpretations of the results, further methodical details are given below.

2.5.1. Bulk density

For 2570 plots with upland soils, no values for *bulk density* (*BD*) were available from the database. Therefore, an estimation procedure was applied based on the *pedo-transfer function* (*PTF*) by Honeysett and Ratkowsky (1989). This function requires that $\text{C-conc}_{\text{min}}$ was converted to the amount of *soil organic matter* (*SOM*) by multiplication with 1.724 (assuming that SOM consists of 58.14% C) (Honeysett and Ratkowsky, 1989).

$$\text{BD} = \frac{1}{0.564 + 0.0556 \times \text{SOM}} \quad (3)$$

Before Eq. (3) was selected, various other PTF were investigated (Baritz et al., 2006). That comparison included the PTF by Adams (1973), which was recommended for application to European forest soils by UN-ECE ICP Forests (2006). This recommendation is based on De Vos et al. (2005) who compared 12 published PTFs. They found that Adams (1973) and Honeysett and Ratkowsky (1989) were among the three PTFs with the highest accuracy and precision. However, re-calibration of any used PTF to regionally typical soils was still recommended. This was attempted by Baritz et al. (2006) for a regional data set in central Germany, with Adams (1973) showing unacceptable deviations from the measured BD.

Fig. 1 presents the bulk densities as delivered by the national data centres ($\text{BD}_{\text{measured}}$). It can be seen that there is an enormous range of values ($\text{BD}_{\text{measured}}$ vs. $\text{C-conc}_{\text{min}}$), which prevents to develop an own PTF. Tested regression models with this data remain below 35% explanation of the measured values, while published PTFs perform 50–60% (De Vos et al., 2005). The PTF by Honeysett and Ratkowsky (1989) becomes less accurate with increasing depth, so that the estimated topsoil C stocks (0–20 cm), as determined for this study, seem to be quite acceptable (see also Fig. 1, $\text{C-stock}_{\text{min}}$ based on $\text{BD}_{\text{measured}}$ and BD_{PTF}). A very extensive analysis of the variability and uncertainties of bulk density in a large data set was conducted by Wirth et al. (2004). Even though BD in that study was not derived from PTF, but estimated in the field (e.g. using the penetration method), it gives an estimate of the direction of error if using inaccurate BD. They found great overestimations of the BD (thus overestimations of the SOC stock).

2.5.2. Stone content

For 73% of the Level I plots, estimates the stone content were available. Mostly, these estimates were derived from visual assessment (estimated from a soil profile; see also Table 1). Such estimates are known to be highly uncertain because its quality strongly depends on the routine and experience of the mapping/sampling personnel. Despite the high uncertainty involved, exclusion of the stone content from the carbon stock calculation would certainly cause substantial overestimations of the carbon content (5 calibration sites; see also Baritz et al., 2006). In Finland and Sweden, a stone index method has been applied (Viro, 1952; Eriksson and Holmgren, 1996). In order to use as many Level I plots as possible for the evaluations here, a gap filing procedure was needed for those sites which lack estimates of the stone content. For that, a high correlation to soil type (sub unit-level) was assumed. Cluster analysis was applied to the available data on

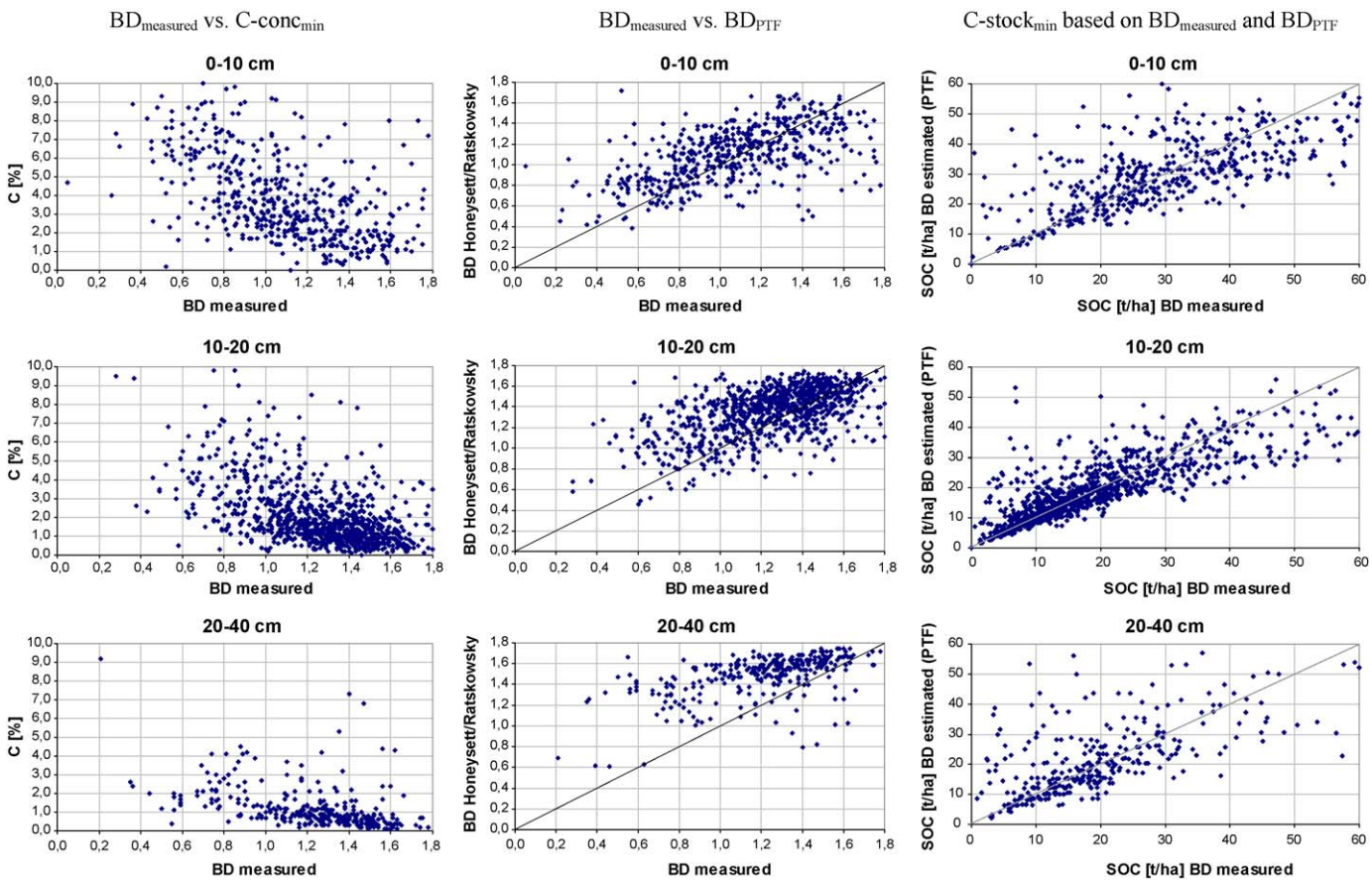

Fig. 1. Variability of carbon concentrations, bulk density (measured vs. estimated from PTF), carbon stocks, for different soil depths.

stoniness in the various depth classes (WARD cluster; SPSS Inc., 2007). Table 3 presents the aggregated results at the level of 10 clusters. It can be seen, that most of the top soils investigated contain <30% stones. The cluster results were then sorted by FAO soil name (with one qualifier; FAO, 1988) and region (based on information about country and climatic zone). A cluster value for each soil type and depth class was then assigned to all sites, including those for which data were originally provided. This conservative approach has the advantage that all plots are treated the same way, and the disadvantage that for quite a large number of plots the new estimates are lower compared to the reported visual assessments. This is justified because strong overestimations of the visual assessment are reported. For example, Wirth et al. (2004) could demonstrate that the field assessment during a Level I inventory in central Germany has overestimated the measured stone content by up to 40%.

2.5.3. Soil carbon concentration

Interpretations of results from the Level I inventory need to consider that a large proportion of variability is introduced by different analytical methods (Table 1). Dry combustion (DC) refers to the determination of total organic carbon after sample combus-

Table 3
Default values for the content of stones (%) according to clustered depth-profiles of stoniness (U = lower end of each depth class in cm).

Cluster	U5	U10	U20	U30[a]	Dominant soil types[b]	*N*
1	9	12	14	19	Dystric Gleysols, Calcaric Regosols, Cambic Arenosols, Eutric Cambisols, Haplic and Chromic Luvisols, Haplic and Ferric Alisols	843
2	40	16	26		Eutric Fluvisols	9
3	3	3	5	12	Calcaric Fluvisols, Eutric and Calcic Gleysols, Haplic Arenosols, Gleyic Cambisols, Haplic Calcisols, Stagnic and Gleyic Luvisols, Dystric Planosol	579
4	4	20	25	20	Gleyic Arenosols, Calcaric Cambisols, Podzols (Haplic, Cambic and Carbic)	829
5	19	22	24	36	Eutric and Dystric Leptosols, Cambisols (Dystric, Humic and Chromic), Gleyic Podzols	1220
6	22	31	34	57	Dystric Regosols, Rendzic Leptosols Ferric Podzols	615
7	36	34	36		Lithic Leptosols	56
8	25	14	17		Vertic Cambisols, Vertic Luvisols	6
9	6	27	33		Haplic Chernozems	12
10	1	1	3		Albic Luvisols, Podzoluvisols (Dystric, Gleyic and Stagnic)	135

[a] Only plots in Germany.
[b] Nomenclature acc. to FAO (2006b).

Table 4
Calculatory schemes to calculate soil C stocks for Level I plots.

Code	*N*	Mineral soil (min)	O-layer (O)	H horizon (H)	Pre-processing
0	173	n.d.	n.d.	n.d.	No data available
1	1851	Measured	X	(X)	min: BD provided; default values for stoniness O: calculated acc. to Eq. (1) (includes 104 plots with H)
2	1707	Estimated	X	(X)	min: BD not provided; pedo-transfer function was used; default for stoniness O calculated acc. to Eq. (1) (includes 73 plots with H)
3	389	Estimated	n.d.	n.d.	min: as with code = 2 O: no gap filling; many Eutric and Calcaric soil types with humus type = Mull (no O-layer sampled)
4	259	Measured	n.d.	n.d.	min: as with code = 1 O: as with code = 3
5	634	n.d.	X	n.d.	min: no gap filling: (a) shallow or hydromorphic soils and peat; (b) missing data for one depth class O: thick O-layers; calculated acc. to Eq. (1)
6	113	n.d.	n.d.	*Weight* is missing	min: no gap filling; peat soils H: BD based on PTF; standard depth = 20 cm
7	7	n.d.	X	X	min: no gap filling O/H: calculated acc. to Eq. (1)
8	129	Estimated	*Weight* is missing	n.d.	min: as with code = 2 and 3 O: *weight* was estimated based on averages per soil type
9	6	Measured	*Weight* is missing	n.d.	min: as with code = 1 and 4 O: as with code = 8

n.d.: no data; BD: bulk density; *weight*: dry weight of the O-layer.

tion at high temperatures (>800 °C) with subsequent collection and determination of the evolved CO_2 (elementary analysis) (ISO 10694, 1995). In the case of calcareous soils, the samples need to be either pre-treated with a non-oxidising mineral acid, or the inorganic carbon needs to be determined with a different method. The other very common analysis is wet oxidation (WO): organic carbon is received after oxidation with a dichromate–sulfuric acid mixture, heated at 120 °C (Walkley and Black, 1934; WB). A correction factor ("oxidation factor") is needed because oxidation with this temperature is incomplete. 76% of the carbon is typically assumed to be oxidized, but factors can range from 1.19 to 1.40 depending on soil and even soil horizon (Nelson and Sommers, 1996). WO in most eastern European countries is based on Tyurin (1931; see also Kononova, 1966). There, organic C is oxidized with a dichromate solution in the presence of concentrated H_2SO_4. The excess of dichromate ($-Cr_2O_7$) is titrated against $FeSO_4$. Variability between laboratories certainly depends on the routine and experience developed, but also on sample preparation and pre-treatment and very specific analytical conditions such as cooking temperature and length of cooking, titration volume, and the CO_2 determination method (titrimetric (less accurate) or photometric) (Spiegel et al., 2007; Hegymegi et al., 2007).

In order to facilitate comparability of the ICP Forests soil analyses, regular inter-laboratory ring tests are performed. Despite methodical differences between laboratories, the mean coefficients of variability (CV) for SOC were fairly low compared to other soil chemical parameters (11.1%, 33.1%, and 9.7%, for the top mineral soil, the subsoil, and the organic layer, respectively) (2002–2003 3rd ring test; Cools et al., 2003). DC has now been selected as the default method in the revised manual for soil sampling and analysis (UN-ECE ICP Forests, 2006). However, only 20% of the laboratories involved in the ICP Forests Level I inventory have stated that they have good experience with the reference method (DC). This explains why the most commonly used methods during the 1990–1995 inventory were WB and Tjurin.

2.5.4. Calculation of soil organic carbon (SOC) stocks

Depending on the availability of data for Eqs. (1) and (2) and the required pre-processing, 9 different calculatory schemes were applied to the database (Table 4 and Fig. 2).

For $N = 3558$ plots, a combined assessment of carbon stocks in the O-layer and in the mineral soil based on Eqs. (1) and (2) was possible (code = 1 and 2). For quite a large number of additional plots, data were either incomplete or missing. This has required some pre-processing, which is explained below in detail.

While working with the database, it became obvious that organic horizons of wetland soils (e.g. Histosols, Gleysols) and semi-hydromorphic soils (e.g. *gleyic* Podzols) were classified and sampled quite differently, especially in the Nordic countries. Because *weight* was not reported for most of the H horizons of Histosols in Sweden, the amount of organic carbon had to be estimated using Eq. (2). The BD of peat was received after applying the PTF by Honeysett and Ratkowsky (1989), but using a SOC/SOM ratio of 2.0 for material rich in organic matter (code = 6). A standard depth of 20 cm is assumed. In Sweden, large carbon stocks for H horizons[1] were received for some non-hydromorphic (well-aerated) upland soils (Podzols and Arenosols). Carbon stocks for H horizons of Histosols in Norway are quite low (in the range of values between Mullmoder and Mor (I) according to Table 5). There, values for O-layers are similar to those of H horizons (codes 1 and 5; Table 4). Apparently, thin O-layers and H horizons have formed on bare rock or on till soils rich in stones and boulders. These soils were classi-

[1] H horizons of wet soils are similar to the "ecto-organic" OF and OH horizons of upland soils, but are saturated with water for prolonged periods (FAO, 2006a). H horizons ≥40 cm qualify as Histosols (see also FAO, 2006b).

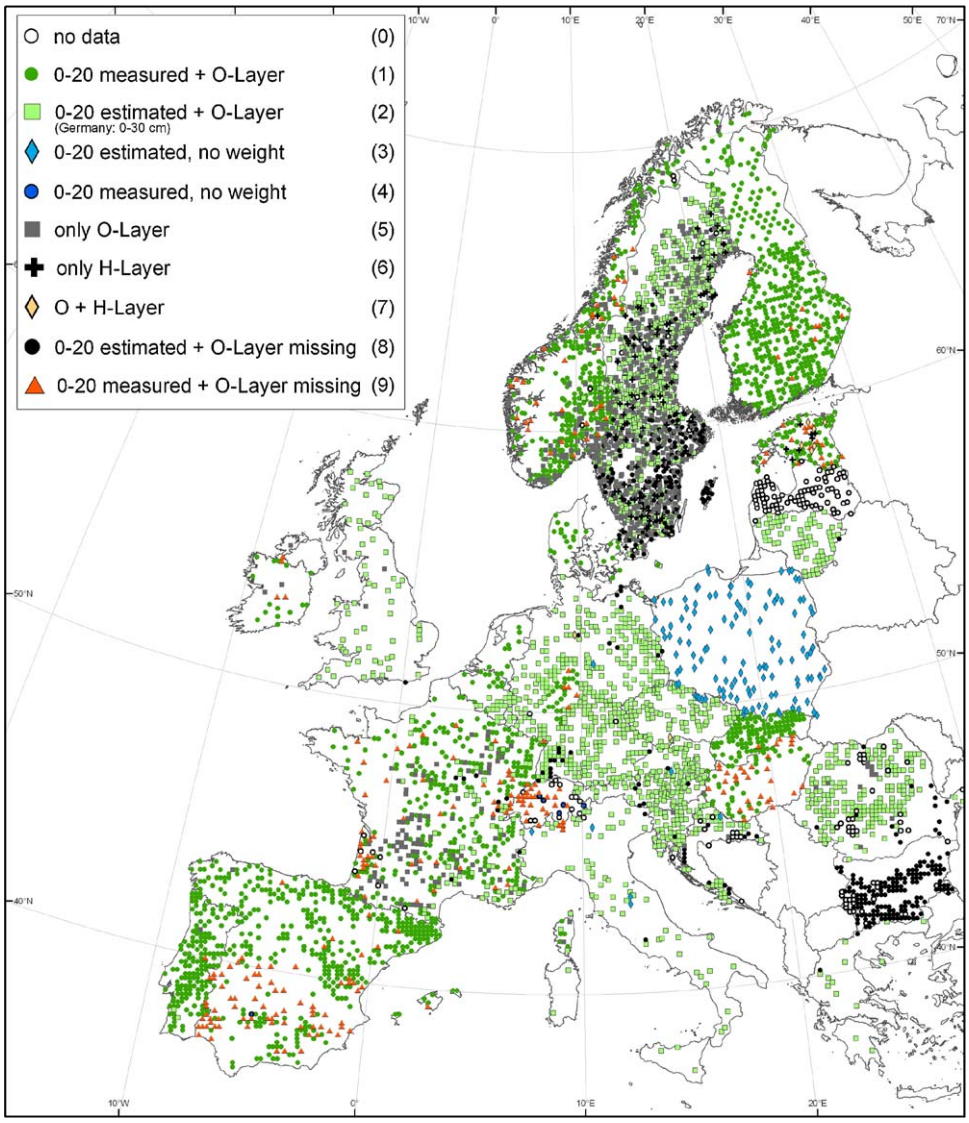

Fig. 2. Map of the EU/ICP Forests. Level I plots according to calculatory scheme for assessing soil carbon stocks (the codes 0–9 are further explained in Table 4).

fied as Histosols. Therefore, in Sweden, the values for O-layers and H horizons of Histosols are clearly higher than in Norway. Because soil profile descriptions were not made available to the ICP Forests Soil Condition Database, plausibility checks of the data for Histosols could not be made.

For 648 Level I plots, Eq. (1) could not be applied due to a lack of carbon concentration measurements and *weight* (codes 3 and 4). Because mostly *eutric* and *calcaric* soils are concerned, it is assumed that the O-layer of these comparatively nutrient-rich soils is very thin and, thus, could not be sampled (examples for *eutric* Cambisols and Gleysols are provided in Fig. 6). In the case of Bulgaria, data for the O-layer exist but were delivered only after the ICP Forests reporting period. The O-layer for rich soils in Sweden (Cambisols with humus form Mull and Mullmoder, and thickness

Table 5
Carbon stocks in the O-layer of northern European forest soils.

Humus forms[a]	Northern German lowlands[b]		Sweden[c]		*N*
	C stock ± STD (t C/ha)	Thickness ± STD (cm)	C stock ± STD (t C/ha)	Thickness ± STD (cm)	
Mull	4.7 ± 6.1	2.3 ± 1.9			719
Mullmoder	10.9 ± 7.4	3.2 ± 1.3			213
Moder	25.2 ± 14.9	7.4 ± 2.8	39.7 ± 89.3	8.3 ± 8.7	665
Mormoder	38.8 ± 15.6	8.6 ± 2.4			
Mor (I)	49.1 ± 32.4	9.8 ± 3.8	24.4 ± 19.8	7.3 ± 4.8	3219
Mor (II)			34.4 ± 25.4	8.5 ± 4.9	1302
Peaty Mor			69.2 ± 43.3	17.1 ± 6.4	870

[a] Definitions see Baritz (2003). Mor types defined according to the Swedish Forest Soil Inventory (MI): Mor type I: >50% of the O-layer thickness is OF, <50% is OH; Mor type II: 25–50% of the O-layer is OF, 50–75% is OH; Peaty Mor: H < 30.5 cm.
[b] Baritz (2003) based on the German Forest Soil Condition Inventory (BZE, 8 km × 8 km).
[c] Data provided by Swedish University of Agricultural Sciences, Uppsala; evaluations and documentation in Baritz et al. (2006).

of the O-layer <2 cm) was sampled in mixture with the top mineral soil.

For some soils, carbon concentration measurements below 10 cm soil depth were not reported. This includes some Podzols and Arenosols in Sweden, Leptosols and Arenosols in Norway and France, and Lithosols and Regosols in Spain. These soils were kept in the database assuming that organic matter could not accumulate below a depth of ca. 10 cm due to rocks.

For $N = 385$ plots, data are missing for the uppermost depth class while values for the lower, subsequent depth were reported. In the case of Sweden, this can be explained with the sampling scheme, which deviates from the one proposed by the ICP Forests manual. In Sweden, the mineral soil was sampled according to genetic horizons combined with depth layers 0–10 cm, 10–20 cm and 50–60 cm. For Podzols, additional bulk samples were taken from the top 5 cm of the B horizon. Apparently, this sampling scheme has caused some data gaps for topsoils, especially for Podzols.

Each of the above-mentioned solutions was separately coded in the database (Table 4 and Fig. 2), so that future re-calculations are always possible (e.g. if improved national data become available, e.g. from the repetitions of the Level I soil inventory).

2.6. Upscaling methodology and representativity

In order to develop a carbon concentration map, each Level I plot was assigned to the respective soil map unit (SMU) of the European Soil Database (SGDBE) using point-polygon analysis. The mean carbon concentration was then calculated and mapped for each SMU. Before that, the soil map was stratified according to climatic zones. In order to assess the reliability of the soil carbon concentrations map, the frequencies of plot occurrences per climate-SMU were separately mapped. This very simple approach to representativity combines the distribution of Level I plots with the heterogeneity of the SGDBE. It has to be considered that the polygons of SMUs are very refined in some countries (e.g. France with many SMUs), while only fairly large, quite coarsely delineated SMUs are found in others (e.g. Sweden).

Point-polygon analysis could lead to wrong assignments of Level I plots to SMUs if the georeferencing of the Level I plots is inaccurate. Such limited accuracy of the Level I plot data was reported by Wiedemann et al. (2001) and Baritz et al. (2006). However, because the SGDBE has a known error of one to few kilometres, this limitation could be ignored here.

3. Results

3.1. Carbon stocks for typical soils under forest cover

Fig. 3 presents the descriptive statistics of soil carbon stocks, stratified according to climatic zone and main soil type (median and frequency distributions: quartiles (25, 75), min/max, extremes and outliers; SPSS Inc., 2007). It has to be noted that very few plots occur in the temperate continental climatic zone, so that it is mostly absent from representation in Fig. 3. Histosols were excluded because of the systematic differences in sampling and nomenclature between some countries.

Soil carbon stocks in the O-layer are highest for Gleysols, Podzols, and Arenosols, which mostly store more than 15 C t/ha. Relative to the total soil carbon content ($C\text{-}stock_{O\text{-}lay} + C\text{-}stock_{min}$), these soils store clearly more than 30% carbon in the O-layer (up to 50% for Gleysols). For many climatic zones, these soils have also the highest variability in the O-layer (highest for Gleysols). Fluvisols and Luvisols have the lowest relative C stocks in the O-layer, with clearly less than 15% of the total carbon content. However, there are not many occurrences of Fluvisols. The effect of climate on carbon storage in the O-layer is difficult to elaborate with this database. For Arenosols, Leptosols and Cambisols, the median carbon stock increases from the northern European subboreal (climate zone 1) towards the central and southern Scandinavian boreal temperate areas (climate zone 2). However, the variability especially in climatic zone 2 is quite large. This trend is not found for Podzols and Regosols. A clear increase of carbon in the O-layer is found between northern Europe and the temperate-oceanic-suboceanic climate zone in the case of Podzols, Arenosols, and Regosols, but this trend is reversed for Luvisols and Leptosols, and less strongly for Cambisols. The carbon content in the O-layer is the lowest for the Mediterranean plots. Among the soils abundant in mountainous areas (climate zone 6), no distinct pattern of carbon in the O-layer is observed (Cambisols, Luvisols, Podzols, Leptosols).

As for carbon stored in the top mineral soil, values increase from northern towards southern Scandinavia for most of the upland soils (Podzols, Arenosols and Regosols, slightly indicated by Cambisols as well). Similar to the observations for the O-layer, the variability of carbon stocks in climatic zone 2 is especially high. The trend for water-logged soils (Gleysols and Fluvisols) is less dependent on climate because decomposition and organic matter accumulation are mainly controlled by the groundwater regime. Only Leptosols indicate a reverse trend, but they are not very abundant in the most northern climate zone 1. All soils except Luvisols and Cambisols show a distinct increase towards central and western Europe (climate zone 3), and also in the mountainous areas (climate zone 6). Especially the carbon stocks of Cambisols show very little response to the climatic zones. The highest mineral soil carbon stocks for all soils except Luvisols are found in the mountainous climatic zone. The highest mineral soil carbon stocks under Mediterranean climate are found for Luvisols.

Leptosols are shallow soils, probably most abundant in the mountainous areas throughout nearly all climatic zones. It would be expected that such soils tend to have thicker O-layers because of the unfavourable climatic conditions at higher elevations. Because these soils are typically younger of age, carbon stocks in the mineral soil would be expected to be lower than for deeply developed soils with a long history of productive vegetation development and site stability. These assumptions are not reflected in the data found here. Carbon stocks in the O-layer are quite low, and in the top mineral soil, no substantial differences are found compared to Cambisols and Luvisols.

3.2. Map of forest SOC concentrations

Fig. 4 shows the carbon concentrations (%) of the topsoils (0–5/0–10 cm). The values found under forest are clearly higher than under agriculture (compared to Jones et al., 2004). Concentrations below 2% are mostly found in northern Sweden and Finland (Podzols dominate, with typical eluviated humus-poor top soils). Other areas with such low C concentrations are found in sub-continental Eastern Europe (e.g. Poland). The map shows a distinct border in central Scandinavia, which separates the subboreal from the subboreal-temperate climatic zone. In reality, this macro-climatic border is very gradual.

Similar to the trend observed for the carbon stocks, the average regional carbon concentration increases from the northern Scandinavian subboreal climatic zone towards southern Sweden and Norway. This also correlates well with observations made by Liski et al. (2002), Olsson (2002), and Callesen et al. (2003). The authors hypothesize that the increasing litter input with increasing forest productivity towards the south is responsible for this observation.

For most lowland sites and mid-mountain ranges throughout Europe, the typical carbon concentrations range between 2 and 5%. Concentrations between 5 and 8% are found in the higher elevations (e.g. Tatra Mountains, Carpathians, Black Forest, Ore Mountains),

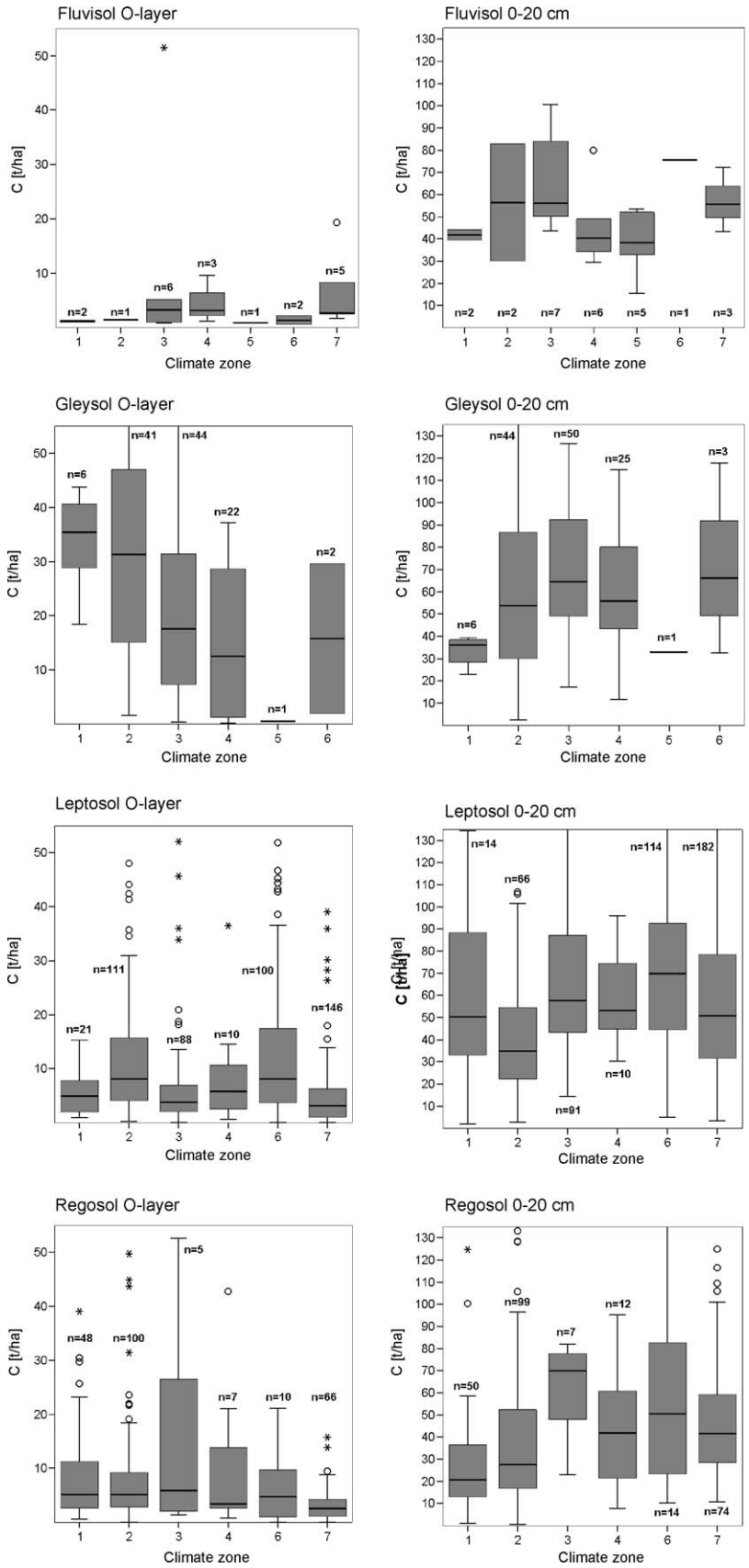

Fig. 3. Default values for carbon in forest soils according to climate areas (O-layer (left), mineral soil 0–20 cm (right); 0–30 cm in the case for Germany). Climatic groups: 1, subboreal-boreal; 2, boreal to temperate; 3, temperateoceanic to suboceanic; 4, temperate-suboceanic to subcontinental; 5, temperatecontinental; 6, temperate-mountainous; 7, Mediterranean. (○) Outliers and (*) extremes.

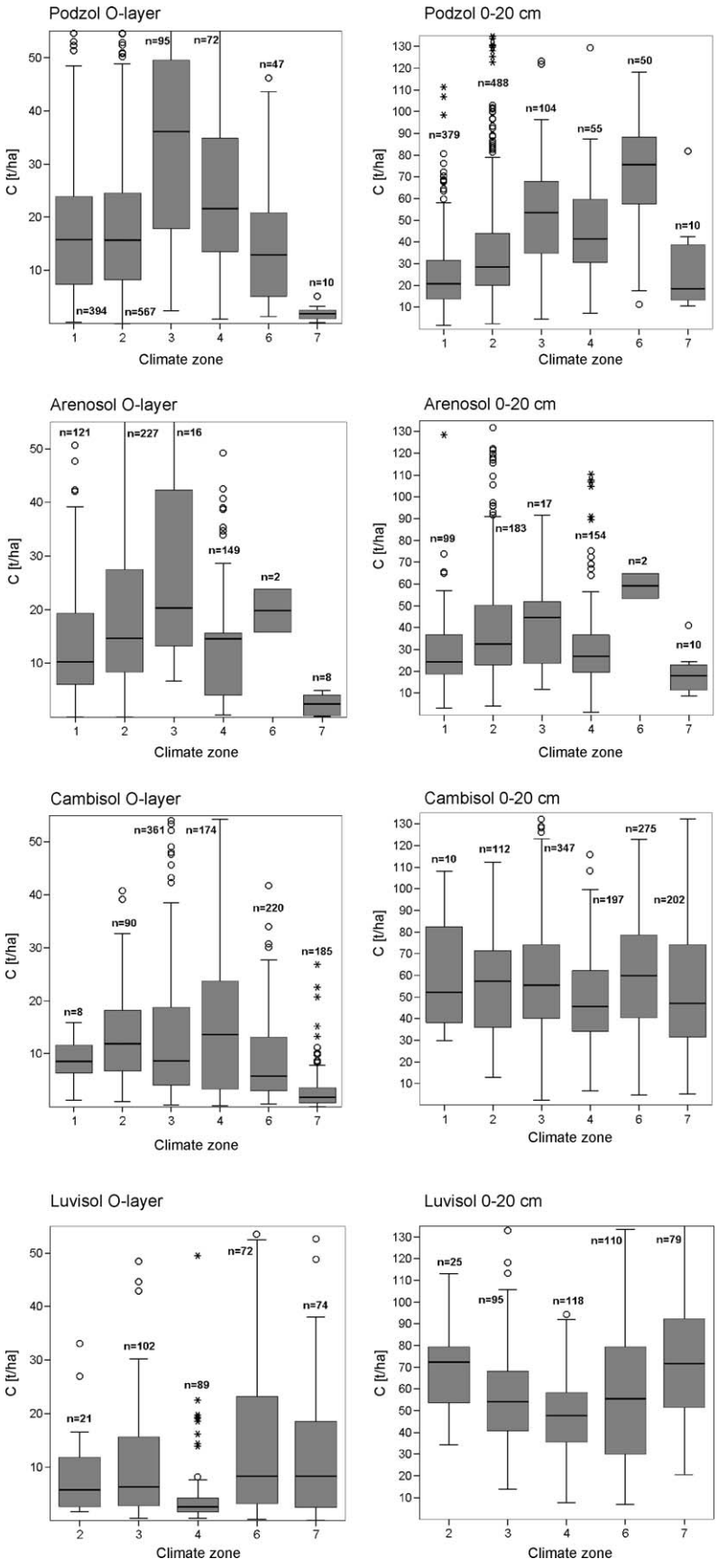

Fig. 3. (*Continued*).

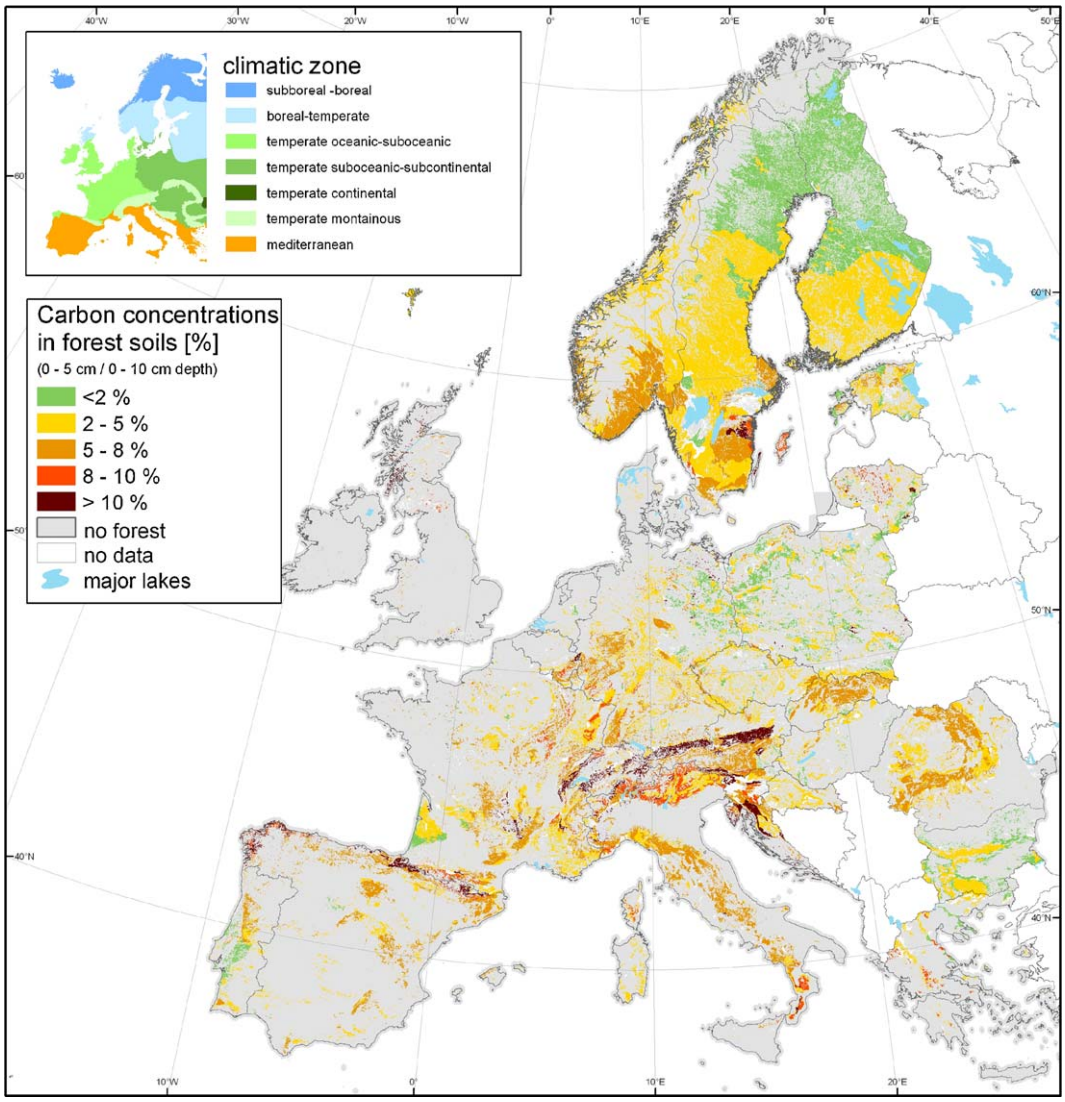

Fig. 4. Map of the carbon concentration in forest soils (0–5/0–10 cm) (%).

and in areas where groundwater influences the soils, such as in the central-northern European Pleistocenic lowlands (Baltic states, northern Germany). The highest C concentrations are found in the Alps, in some parts of the Pyrenees, and along the western border of the Atlantic coast. A large proportion of soils in climatic zone 7 (southern Europe, mostly Mediterranean soils) shows fairly high SOC concentrations as well (5–8%, partly even higher). This is especially found in Cantabria and throughout central Italy. Presumably, SOC is accumulated strongly in calcareous (mountainous) soils. Correlations between parent material and soil carbon were thoroughly elaborated by Romanyà et al. (2006).

3.3. Representativity

Fig. 5 shows the density of plots overlaid with the European soil map (SGDBE), and stratified by climatic zone. Because the SGDBE is used as the main data basis to upscale the Level I plot data, the map indicates areas with very weak predictions of the topsoil carbon concentration. Lowest representativity is found in landscapes with highly fragmented and low forest cover (UK, Ireland, France, parts of Hungary and northern Germany, The Netherlands). In Greece and Italy, only a subset of the main Level I 16 km × 16 km grid has been sampled (15 out of 95 plots, and 20 out of 207 plots, respectively). In Latvia, no carbon measurements were provided. In Poland, only the Level II intensive monitoring plots were sampled for the soil condition inventory (see also Table 1).

The representativity for the Scandinavian countries seems quite high, but it is not clear whether the available dataset represents the real proportions of the distribution of soils, especially of the hydromorphic soils (Gleysols and Histosols). In the case of Finland, forested mires were completely excluded from the Level I inventory. In addition, soils were classified differently by the national systems in Sweden and Norway. For example, in Norway, the soils were originally classified according to the Canadian System of Soil Classification (organic soils: Fibrosol, Humisol, Folisol, mineral soils: Podzol, Gleysol, Brunisol, Regosol) and were then re-classified for reporting under the ICP Forests. Soils in Finland and Sweden were classified according to FAO (1988). However, Sweden has used a simplified version, which does not fully correspond to FAO (Iron Podzol, Iron-humus Podzol, Humus Podzol). In addition, the Swedish inventory cannot be compared to the Level I inventories in other countries because it has connected its soil inventory to the National Forest Inventory (NFI) as a stratified random sample, which results in a much higher number of plots ($N = 1249$) than otherwise to be expected under the Level I 16 km × 16 km systematic reference grid. In addition, the resolution of the SGDBE for northern Europe is quite low. For example, only two mapping units represent 60% of the Swedish land area. Therefore, the number of Level

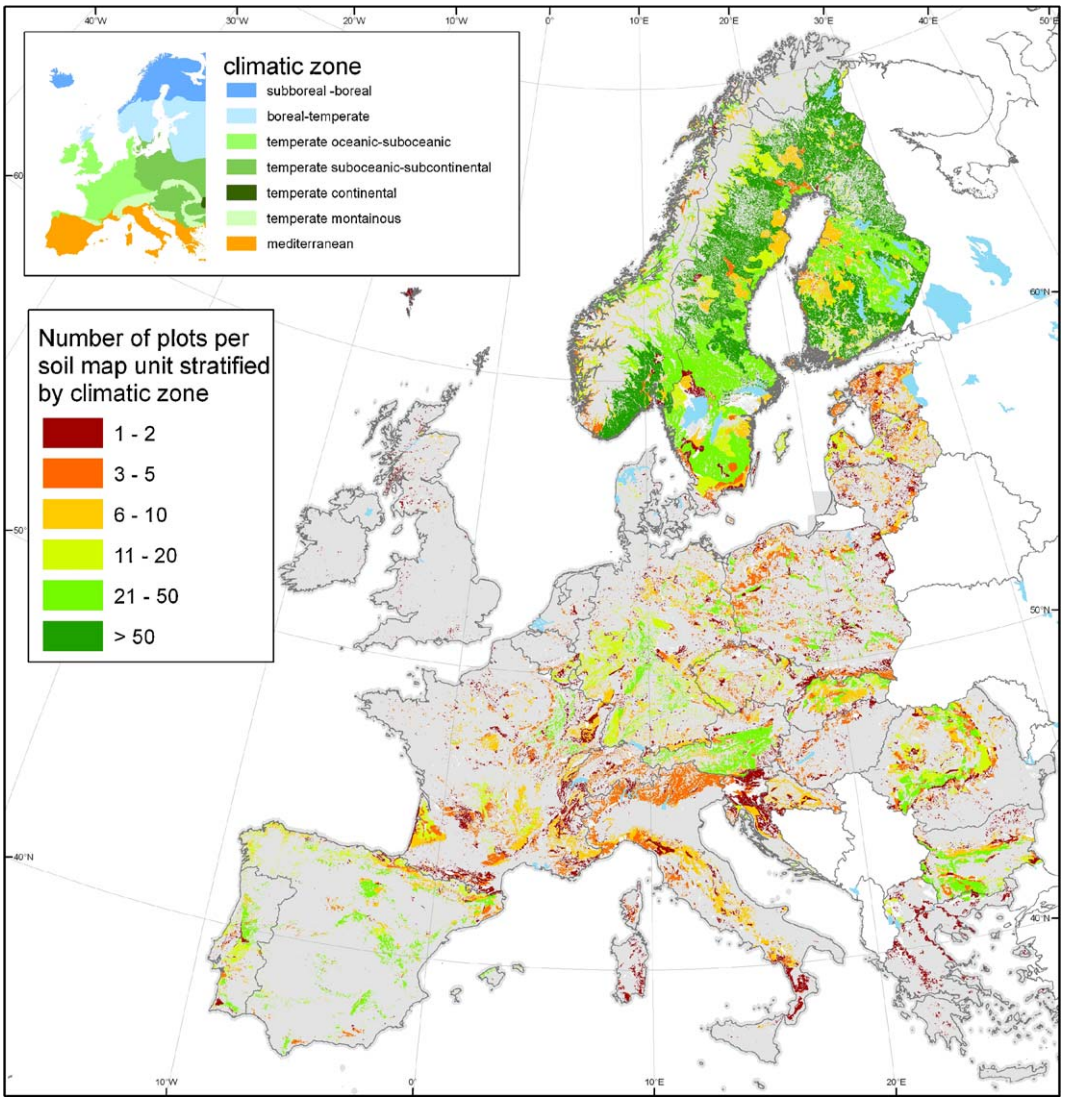

Fig. 5. Map of the representativity of ICP Forest Level I plots with regard to soil mapping units.

I plots per mapping unit appears to be high (see Fig. 5), while the number of plots per unit area is much lower. It was also found that in the Level I dataset, the less-forested Cambisol-dominated map units (acc. to the SGDBE map legend) have as many Podzols as Cambisols, and that Histosol-dominated map units are actually dominated by Podzols in the Level I soil inventory.

3.4. Validation of SOC stocks derived from the Level I database

Various plausibility checks have been made for different countries. For each country, the national carbon stocks from this study were presented to the national soil inventory experts in the frame of the EU-COST E21 activity (Laitat et al., 2000). The results from this study were additionally compared to published national data for various countries: Austria: FBVA (1992) and Weiss et al. (2000); Belgium: Lettens et al. (2004, 2005); Bulgaria: Filcheva et al. (2002); Denmark: Vejre et al. (2003) and Krogh et al. (2003); Finland: Ilvesniemi et al. (2002); France: Arrouays et al. (1999); Hungary: Nemeth et al. (2002); Ireland: Tomlinson (2005); Northern Ireland: Cruickshank et al. (1998); Norway: De Wit and Kvindesland (1999); UK: Milne and Brown (1997). The results found here are in good agreement to these national studies. Because of the methodical deviations from the ICP forests manual, an extra effort was made to investigate the plausibility of estimates from the Swedish Level I. Table 5 shows results for carbon stocks in the O-layer.

4. Discussion

For the first time, a Europe-wide evaluation of SOC stocks has been conducted using measured carbon data from the EU-ICP Forests Level I soil inventory. Until now, the methodical differences between countries and data gaps have prevented such an evaluation at the European level. Therefore, the methodical framework of this study can be used as a reference for further applications of this database.

The behaviour of soils to store carbon seems to support known observations that coarse-textured soils behave differently from more fine-textured soils (see also Callesen et al., 2003), and that the processes which lead to the accumulation of carbon in the O-layer differ from those in the mineral soil (Baritz et al., 1999). Podzols, Arensosols and some Regosols are typically coarse-textured sandy soils with a low nutrient regime. Cambisols and Luvisols are more fertile soils, with higher productivity of the vegetation and a highly active soil biological system. The litter of nutrient-poor, sandy soils is usually conifer-dominated, and its decomposition is reduced. Therefore, organic matter typically accumulates so that

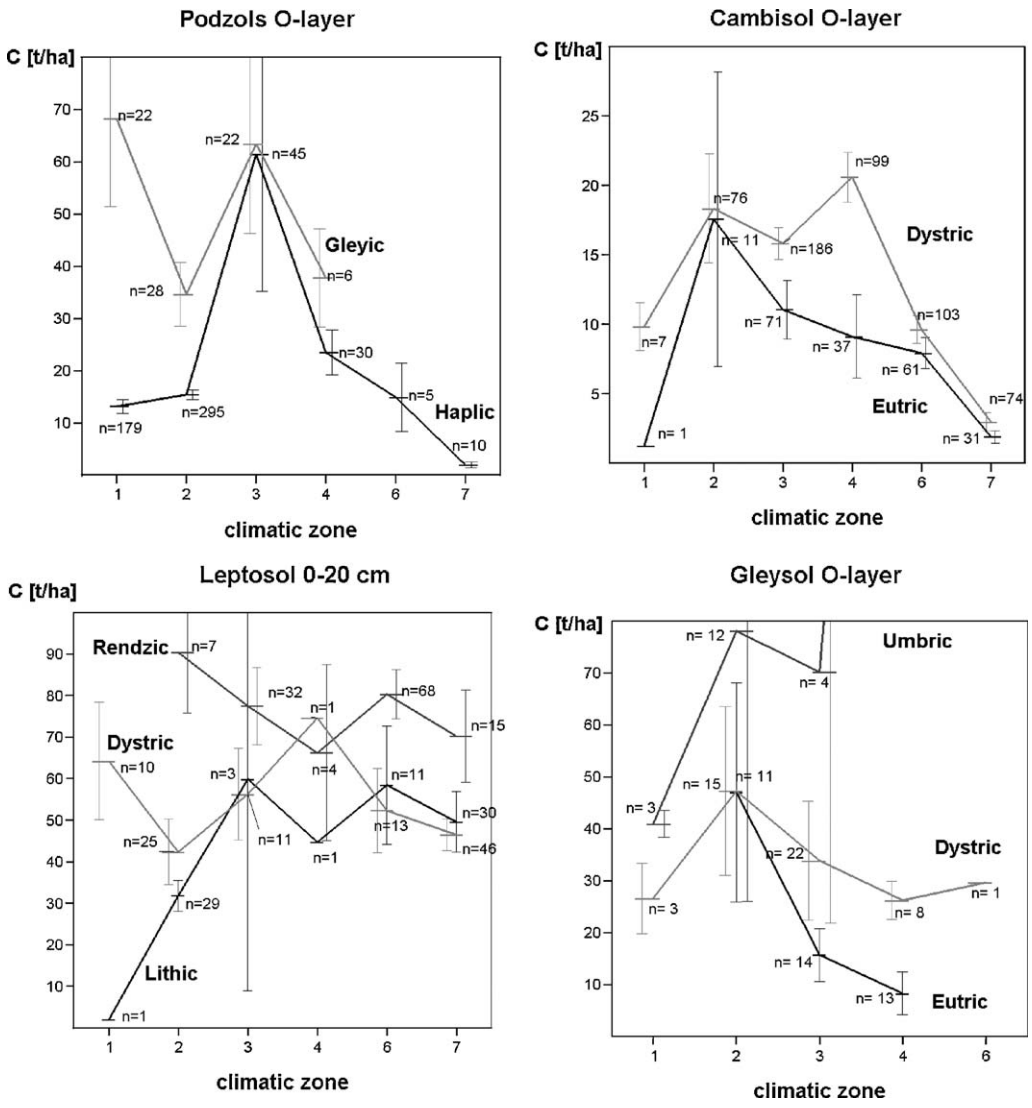

Fig. 6. Variability of carbon stocks at the level of soil subunits (nomenclature acc. to FAO, 2006b; diagram contains mean values and 75% confidence intervals).

carbon stocks in the O-layer of Podzols and Arenosols are clearly higher than for Cambisols and Luvisols. Reduced decomposition is also caused by prolonged water-saturation of the top soils as found for Gleysols, or Gleyic Podzols (see also Fig. 6). Very often, the O-layer of Gleysols is of peaty nature which becomes evident given the high number of H horizons found with Gleysols (25% of all plots with Gleysols compared to 8% for Podzols). However, in western and central Europe (climatic zone 3), carbon stocks in the O-layer are highest for Arenosols and Podzols. This is difficult to explain if only natural site factors are considered. Sandy soils are usually managed for conifers although this is not the natural vegetation except at the extremely poor and high-elevation sites. Needle litter is known to acidify top soils, especially if coupled with low buffer capacity, typical for nutrient-poor sandy soils. These soils have often also suffered from other anthropogenic influences, such as historic cultivation and secondary uses such as litter raking (Feger, 1992), and in some areas a lowering of the water table. These degradative effects have caused thick O-layers to develop, which is indicated by the presence of Mor and Mor-like humus forms (Brethes et al., 1995, Baritz, 2003 based on the evaluation of 443 Level I plots in the northern German lowlands).

The O-layer of forests is known to respond rapidly to environmental changes, for example after tree species change, or atmospheric pollutant input. These factors probably add to the high natural variability of forest soils, so that O-layers in managed forests are especially variable regarding thickness and carbon storage (Riha et al., 1986; Belotti and Babel, 1993). Effects of climate were then not clearly visible for the O-layer in the Level I dataset, except for the soils in the Mediterranean climatic zone, which have the lowest carbon stocks. Fig. 6 shows that distinct O-layers are found depending on the soil nutrient status, indicated as Dystric (base saturation BS < 50%; FAO, 2006b) and Eutric (BS > 50%) top soils. These conditions seem to affect carbon storage more than climate and soil type.

Carbon stocks in the mineral soil seem to be more influenced by less-variable site factors such as climatic zone, elevation and texture. The effects of climate and elevation are most clearly visible with coarse-textured soils (Arenosols, Podzols, Regosols). It is very likely that the lack of data for the subsoil has prevented clearer relationships to appear. However, fine-textured soils in northern Europe have higher carbon stocks in the top mineral soil than coarse-textured soils (climatic zones 1 and 2). This trend is not continued in central and western Europe. There, both groups of soils perform similarly. Carbon stocks of fine-textured soils are expected to be high because they are generally more fertile (high litter and root production, highly active decomposer system).

Different mechanisms must then be responsible for the carbon storage of Regosols, Leptosols and Podzols, which is as high as for fine-textured soils in some climatic zones. In the Pleistocenic lowlands, such as in the Netherlands, northern Germany, Denmark and Poland, high carbon stocks could be the result of reduced decomposition from the influence of ground water, for example found with semi-hydromomorphic soils such as Gleyic Podzols. Less favourable climate at higher elevation is probably responsible for the relatively high carbon stocks even in the top section of shallow soils. Unexpectedly, Leptosols, typically eroded or young soils, have among the highest carbon stocks in the climatic zones 3 and 4, but also the highest variability (see Fig. 5). The variability for Leptosols could be significantly reduced if the data were further stratified according to parent material: Leptosols with a Rendzic qualifier (humus-rich dark topsoil and calcareous material) have clearly higher carbon stocks in 0–20 cm than other subunits of Leptosols (Fig. 6).

These results for the mineral soil show that the pattern of carbon storage cannot sufficiently be explained, if only the top 20 cm of soils are considered. Loamy, deeply developed soils have substantial amounts of carbon stored in the subsoil (Rumpel et al., 2004). Approximately 25% of the total soil organic C stock occurs in the O or A horizon, 50% in the mineral soil to 1 m and the remaining 25% from 1 to 2 m depth (Olsson, 2002).

The difficulties to elaborate the pattern of carbon storage for different soils and climate with the Level I dataset are probably also affected by the uncertainties related to sampling methodology, data gaps, and pre-processing solutions applied. De Vos et al. (2005) have already concluded that the use of pedotransfer functions (PTF) from the literature is problematic, unless they become regionally validated and improved (e.g. Tamminen and Starr, 1994). Wirth et al. (2004) have demonstrated the magnitude of error coming from estimation methods for bulk density (BD) and stoniness. On the one hand, stoniness from visual assessment in the field is often overestimated, which results in an underestimation of the soil carbon stock. On the other hand, estimates of BD are often too high, so that the carbon stock is overestimated. Both effects partly compensate each other, but the effect of overestimated BD dominates. The objective of the pre-processing applied to the Level I dataset was to keep as many plots with available measurements as possible in the database, and to introduce some basic harmonization, for example in the case of stoniness. Obviously, site factors such as texture, slope position, climate and management (for example: liming) must be investigated further once more accurate data become available, such as soil profile descriptions, and more detailed descriptions of the humus and vegetation types.

The regional pattern of C concentrations correlates with assumptions about important driving factors for carbon storage in soils. Reduced decomposition from unfavourable climate probably explains the increase of carbon in the mineral soil with increasing elevation (see mountainous areas in Fig. 4; carbon stocks in climatic zone 6) despite the fact that forest productivity thus litter input to the soil is also reduced. Another site factor, which has been clearly identified with the results produced here, is the influence of parent material. Calcareous soils seem to store a significantly higher amount of carbon than soils developed on non-calcareous parent material (see also Fig. 6: Rendzic vs. Dystric Leptosols). This is especially true for forest soils in southern Europe and the Alps, where calcareous parent material is mostly abundant, and where carbon concentrations are among the highest.

The results further develop the findings by Jones et al. (2004). While Jones et al. (2004) have estimated soil carbon concentrations using pedo-transfer rules applied to the European soil map (SGDBE), measured data were used in this study here. The new results presented here support these earlier estimates quite well with the exception for Nordic soils. The results from our study reveal that Nordic topsoils have quite low carbon concentrations. This is because Podzols dominate vast land areas, and low topsoil C concentrations are typical (Ilvesniemi et al., 2002; Olsson, 2002). Even mapping units which would be dominated by Cambisols according to the SGDBE, have as many Podzols as Cambisols in the Level I database. The same holds for mapping units with Histosols. At the same time, the area of Histosols is underrepresented in the SGDBE. Carbon in peat is additionally underestimated because of the exclusion of peat soils from the 1990 to 1995 Level I inventory in Finland. In Sweden, the soil inventory is part of the national forest inventory, which only deals with peat that is covered by productive forestry and hence drained (groundwater below 1 m; Olsson, oral communication). National data support the result, that with decreasing temperature towards southern Scandinavia, carbon concentrations increase (Liski and Westmann, 1997). According to Liski et al. (2002), high carbon concentrations (and stocks) in the soil correlate with litter production (litter represents 70–80% of the SOC source). It has to be considered, that vegetation productivity depends on a combination of different key soil properties such as texture and water table together with climate.

The study has elaborated the frame conditions for analysing carbon storage in forest soils at the continental scale. Despite availability of a representative network of inventory plots, the restrictions to come to comparable and harmonized SOC stock estimates are still quite high. Some of these restrictions, such as uncertainties related to bulk densities and stone estimates, are expected to be solved with the results of the repeated sampling programme, the BioSoil project (http://biosoil.jrc.ec.europa.eu/). For each plot, the stock estimates can soon be re-calculated using the original soil concentration measurements from the 1990 to 1995 survey together with the newly measured soil physical data. In addition, a large number of new site descriptive data (relief, soil profile descriptions, vegetation data, humus form) will also become available, so that baseline assessments and model applications using the 1990–1995 dataset can be substantially improved.

5. Conclusions

Carbon stocks in forest soils have been estimated based on the EU/ICP Forests Level I soil inventory in Europe. The results have led to hypotheses about the effects of site factors on soil carbon storage, for example climatic zone and soil type. In order to support these hypotheses, a map of typical carbon concentrations in forest soils was produced which represents the regional pattern of carbon in the very top part of the mineral soil of forests. The reliability of the map is best where a sufficient number of plots is found (for example, at least 10–15 plots should be available to derive valid statistical averages; Baert et al., 1999).

In general, macro-climate appears to be less important than expected, especially for the O-layer. Apparently, the effect of natural site factors such as climate becomes distorted in managed ecosystems, for example after artificial tree species change. The distribution of carbon stocks in the mineral soil shows a clearer relationship with climate, especially the nutrient-poor coarse-textured soils. There, SOC is highest in the temperate-oceanic climatic zone of western and parts of central Europe, where the productivity of the vegetation is high, but also in the mountainous areas of the Alps and southern Europe, where unfavourable decomposition conditions cause high carbon values. In northern Europe, that gradient does not seem to be confirmed. The carbon concentration decreases with decreasing latitude. Despite the high number of available plots especially in Sweden, this trend could not be elaborated in greater spatial detail because of the relatively coarse soil map in northern Europe. This study also concludes that the methodical limitation of the inventory to 0–20 cm is not sufficient to clearly differentiate relationships between soil carbon stocks and its drivers. For

example, Podzols and fine-textured soils such as Luvisols typically accumulate carbon in the subsoil. When just looking at the first 20 cm of the soil, Podzols appear to be extremely low in carbon, while shallow soils such as Leptosols have similar carbon stocks compared to Luvisols and Cambisols. We also expect that the different levels of carbon accumulation between sandy and clayey soils would become clearer if the subsoils were included.

A large proportion of the variability of estimated SOC stocks of different soils in this study is probably influenced by uncertainties coming from the database. However, the magnitude of systematic errors can only be quantified on the basis of systematic plausibility checks, for example on the basis of detailed soil profile descriptions, and comparative analysis and post-sampling calibration exercises (provided that the sampling methods were exactly documented). Despite these drawbacks, this study has developed a systematic and harmonized framework to derive continent-wide comparable SOC stock estimates on the basis of the EU/ICP Forests Level I inventory. The methodical framework which has been developed here can be used later to develop an extensive uncertainty assessment once improved plot and mapping data become available.

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References

Adams, W.A., 1973. The effect of organic matter on the bulk and true densities of some uncultivated podzolic soils. J. Soil Sci. 24, 10–17.

Amichev, B.Y., Galbraith, J.M., 2004. A revised methodology for estimation of forest soil carbon from spatial soils and forest inventory data sets. Environmental Management 33 (1), S74–S86.

Arrouays, D., Delais, W., Badeau, V., 1999. The carbon content of topsoils and its geographical distribution in France. Soil Use and Management 17, 7–11.

Baert, G., Vanmechelen, L., Van Ranst, E., 1999. Critical Review of Soil Sampling Methods in the ICP Forests Programme, Background document for the 8th meeting of the ICP Forests "Forest Soil Expert panel" (FSEP), Soil Forest Soil Coordinating Centre (FSCC), Gent, Belgium (unpublished report).

Baritz, R., Adler, G., Wolff, B., Wilke, B.-M., 1999. Carbon in German forest soils and its relation to climate change. Zeitschrift für Angewandte Geologie 45 (4), 218–227.

Baritz, R., 2003. Humus forms in forests of the northern German lowlands. Technical University Berlin, Institute of Ecology. Dissertation. Geologisches Jahrbuch, Reihe SF, vol. 3. Federal Institute for Geosciences and Natural Resources (BGR). Schweizerbart Verlag, Stuttgart.

Baritz, R., Zirlewagen, D., Van Ranst, E., 2006. Methodical standards to detect forest soil carbon stocks and stock changes related to land use change and forestry – landscape scale effects. Final report Deliverable 3.5-II. Multi-source inventory methods for quantifying carbon stocks and stock changes in European forests (CarboInvent), contract no. EU EVK2-2001-00287.

BGR (Bundesanstalt fuer Geowissenschaften und Rohstoffe), 2005. Soil Regions Map of the European Union and Adjacent Countries 1:5,000,000 (Version 2.0). Special Publication, Ispra. EU catalogue number S.P.I.05.134.

Belotti, E., Babel, U., 1993. Variability in space and time and redundancy as stabilizing principles of forest humus profiles. European Journal of Soil Biology 29 (1), 17–27.

Bellamy, P.H., Loveland, P.J., Bradley, R.I., lark, R.M., Kirk, G.J.D., 2005. Carbon losses from all soils across England and Wales 1978–2003. Nature 437, 245–248.

Bohn, U., Gollub, G., Hettwer, C. (Eds.), 2000. Map of the Natural Vegetation of Europe, Scale 1:2,500,000 – 10 Maps and Legend, 153 p. – Federal Agency for Nature Conservation, Bonn-Bad Godesberg.

Brethes, A., Brun, J.J., Jabiol, B., Ponge, J., Foutain, F., 1995. Classification of forest humus forms: a French proposal. Ann. Sci. For. 52, 535–546.

Callesen, I., Liski, J., Raulund-Rasmussen, K., Olsson, M.T., Tau-Strand, L., Vesterdal, L., Westman, C.J., 2003. Soil carbon stores in Nordic well-drained forest soils – relationships with climate and texture class. Global Change Biology 9, 358–370.

Cannell, M.G.R., Dewar, R.C., Thornley, J.H.M., 1992. Carbon flux and storage in European forest. In: Teller, A., Mathy, P., Jeffers, J.N.R. (Eds.), Responses of Forest Ecosystems to Environmental Changes. Elsevier, London, pp. 256–271.

CEC, 1985. Soil Map of the European Communities 1:1,000,000. – Directorate-General for Agriculture, Coordination of Agricultural Research, Office for Official Publications of the EC (EUR 8982, ISBN 92-825-5427-9), Luxembourg.

Chertov, O.G., Komarov, A.S., Bykhovets, S.S., Kobak, K.I., 2002. Simulated soil organic matter dynamics in forests of the Leningrad administrative area, northwestern Russia. Forest Ecology and Management 169, 29–44.

Cools, N., Delanote, V., De Vos, B., Quataert, P., Roskams, P., Scheldmann, X., 2003. 3rd interlaboratory ring test 2002–2003. In: UN/ECE ICP Forests and EC (2003). 11th Forest Soil Expert Panel Meeting. Meeting documents. Item 5: Quality assurance and quality control. Gent, 24–26 March 2003.

Cruickshank, M.M., Tomlinson, R.W., Devine, P.M., Milne, R., 1998. Carbon in the vegetation and soils of Northern Ireland. Proceedings of the Royal Irish Academy 98B, 9–21.

De Vos, B., Van Meirvenne, M., Quataert, P., Deckers, J., Muys, B., 2005. Predictive quality of pedotransfer functions for estimating bulk density of forest soils. Soil Sci. Soc. Am. J. 69, 500–510.

De Vries, W., Reinds, G.J., Gunderson, P., Klap, J.M., 2000. Assessment of the current carbon sequestration in European forest soils. In: Fischer, R., De Vries, W., Seidling, W., Kennedy, P., Lorenz, M. (Eds.), Forest Condition in Europe. Executive Report 2000. UN-ECE and EC, Geneva, Brussels, pp. 32–34.

De Wit, H.A., Kvindesland, S., 1999. Carbon stocks in Norwegian forest soils and effects of forest management on carbon storage. Rapport fra Skogforskningen – Supplement 14. Norsk Institutt for Skogforskning (NISK), As, Norway. 52 pp.

EC/UN-ECE, de Vries, W., Reinds, G.J., Posch, M., Sanz, M.J., Krause, G.H.M., Calatayud, V., Renaud, J.P., Dupouey, J.L., Sterba, H., Vel, E.M., Dobbertin, M., Gundersen, P., Voogd, J.C.H., 2003. Intensive Monitoring of Forest Ecosystems in Europe, 2003 Technical Report. EC/UN-ECE 2003, Brussels, Geneva, 163 pp.

EEA/ETC BD, 2000. Digital Map of European Ecological Regions (DMEER), Version 2000/05 – European Environment Agency/European Topic Centre for Biological Diversity, Kopenhagen.

Eriksson, C.P., Holmgren, P., 1996. Estimating stone and boulder content in forest soilsevaluating the potential of surface penetration methods. Catena 28, 121–134.

ESBN (European Soil Bureau Network) (1999), Soil Geographical Database of Europe, version 3.21, Ispra, Italy.

FAO, 1988. Soil Map of the World. Revised Legend. World Soil Resources Report 60. FAO, Rome.

FAO, 2006a. Guidelines for Soil Profile Description and Classification, 4th ed. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2006b. 2006. World Reference Base for Soil Resources 2006 – A Framework for International Classification, Correlation and Communication. World Soil Resources Reports 103. Food and Agriculture Organization of the United Nations, Rome.

Faubert, P., Lindner, M., Thürig, E., Peltoniemi, M., Palosuo, T., Chertov, O., Komarov, A., Mikhailov, A., Suckow, F., Lasch, P., Wattenbach, M., Smith, P., Gottschalk, P., 2006. Comparison of soil carbon stocks and stock changes simulated with four soil models. In: Meyer, J., Vilén, T., Peltoniemi, M., Faubert, P., Thürig, E., Lindner, M. (Eds.), Uncertainty Estimate of the National Level Biomass and Soil Carbon Stock and Stock Change. Final report Deliverable 6.3. Multi-source inventory methods for quantifying carbon stocks and stock changes in European forests (CarboInvent) EU EVK2-2001-00287. European Forest Institute, Joensuu, Finland.

FBVA, 1992. Österreichische Waldbodenzustandsinventur. Austrian Forest Soil Condition Inventory, Federal Forest Research Centre, Vienna, Mitteilungen der Forstlichen Bundesversuchsanstalt, Bd. 168/I, Bd. 168/II.

Feger, K.H., 1992. Importance of land-use history for nutrient cycling in Central European forests. In: Teller, A., Mathy, P., Jeffers, J.N.R. (Eds.), Responses of Forest Ecosystems to Environmental Changes. Elsevier Applied Science, pp. 473–480.

Filcheva, E., Rousseva, Sv., Kulikov, A., Nedyalkov, S., Chernogorova, Tz., 2002. Organic carbon stocks in soils of Bulgaria. In: Kimble, J.M., Lal, R., Follett, R.F. (Eds.), Agricultural Practices and Policies for Carbon Sequestration in Soil. CRC Press, pp. 471–476.

Finke, P.A., Hartwich, R., Dudal, R., Ibàñez, J.J., Jamagne, M., King, D., Montanarella, L., Yassoglou, N., 1998. Georeferenced Soil Database for Europe, Manual of Procedures, Version 1.0. – European Soil Bureau Research report No. 5, Office for Official Publications of the EC (EUR 18092 EN), Luxembourg. 184 pp.

Goodale, C.L., Apps, M.J., Birdsey, R.A., Field, C.B., Heath, L.S., Houghton, R.A., Jenkins, J.C., Kohlemeier, G.H., Kurz, W., Liu, S., Nabuurs, G.-J., Nilsson, S., Shvidenko, A.Z., 2002. Forest carbon sinks in the northern hemisphere. Ecological Applications 12 (3), 891–899.

Hartwich, R., Thiele, S., Baritz, R., Fuchs, M., Krug, D., 2006. Erläuterungen zur Bodenregionenkarte der Europäischen Union und ihrer Nachbarstaaten im Maßstab 1:5,000,000 (Version 2.0) [The report additionally contains the Map of Climate Areas in Europe 1:10,000,000, and the Parent Material Associations Map 1:5,000,000. These products were developed for Finke et al. (1998) which is currently under revision]. BGR, Hannover, www.bgr.bund.de.

Hegymegi, P., Spiegel, H., Filcheva, E., Gal, A., Verheijen, F.G.A., 2007. Review and comparison of methods used for soil organic carbon determination. Part 2: Laboratory Study. Soil Science Agrochemistry and Ecology XLI (4), 19–25.

Honeysett, J.L., Ratkowsky, D.A., 1989. The use of ignition loss to estimate bulk density of forest soils. J. Soil Sci. 40, 299–308.

Ilvesniemi, H., Forsius, M., Finer, L., Holmberg, M., Kareinen, T., Lepistö, A., Piirainen, S., Pumpanen, J., Rankinen, K., Starr, M., Tamminen, P., Ukonmaanaho, L., Vanhala, P., 2002. Carbon and nitrogen storages and fluxes in Finnish forest ecosystems. In: Käyhkö, J., Talve, L. (Eds.), Understanding the Global System – The Finnish Perspective. Finnish Global Change Research Programme FIGARE, pp. 69–82.

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Institute for Global Environmental Strategies (IGES), http://www.ipcc-nggip.iges.or.jp.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.). IGES, Japan, http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

Janssens, I.A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G.-J., Folberth, G., Schlamadinger, B., Hutjes, R.W.A., Ceulemans, R., Schulze, E.-D., Valentini, R., Dolman, A.J., 2003. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emissions. Science 300, 1538–1542.

Jones, R.J.A., Hiederer, R., Rusco, E., Loveland, P.J., Montanarella, L., 2004. The map of organic carbon in topsoils in Europe, Version 1.2 September 2003: Explanation of Special Publication Ispra 2004 No.72 (S.P.I.04.72). European Soil Bureau Research Report No.17, EUR 21209 EN, 26 pp, 1 map. Office for Official Publications of the European Communities, Luxembourg.

Jones, R.J.A., Hiederer, R., Rusco, E., Loveland, P.J., Montanarella, L., 2005. Estimating organic carbon in the soils of Europe for policy support. European Journal of Soil Science 56, 655–671.

King, D., Daroussin, J., Tavernier, R., 1994. Development of a soil geographical database from the soil map of the European Communities. Catena 21,37–56.

Köppen, W., 1936. Das geographische System der Klimate. In: Köppen, W., Geiger, R. (Eds.), Handbuch der Klimatologie, vol.5 (part C). Gebrüder Bornträger, Berlin, 44 pp.

Kononova, M.M., 1966. Soil Organic Matter, 2nd ed. Pergammon Press, Inc., Oxford, 544 pp.

Krogh, L., Noergaard, A., Hermansen, M., Greve, M.H., Balstroem, T., Breunig-Madsen, H., 2003. Preliminary analysis of contemporary soil organic carbon stocks in Denmark using multiple datasets and four scaling-up methods. Agriculture, Ecosystems and Environment 96, 19–28.

Laitat, E., Karjalainen, T., Loustau, D., Lindner, M., 2000. COST E21: contribution of forests and forestry to mitigate greenhouse gas effects. Towards an integrated scientific approach for carbon accounting in forestry. Biotechnol. Agron. Soc. Environ. 4 (4), 241–251.

Lal, R., Kimble, J.M., Birdsey, R.A., Heath, L.S., 2003. Research and development priorities for carbo sequestration in forest soils. In: Kimble, J.M., Heath, L.S., Birdsey, R.A., Lal, R. (Eds.), The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press LLC/Lewis Publishers, London/New York.

Lettens, S., Van Orshoven, J., Van Wesemael, B., Muys, B., 2004. Soil organic and inorganic carbon content of landscape units in Belgium for 1950–1970. Soil Use and Management 20, 40–47.

Lettens, S., Van Orshoven, J., Van Wesemael, B., De Vos, B., Muys, B., 2005. Stocks and fluxes of soil organic carbon for landscape units in Belgium derived from heterogeneous data sets for 1990 and 2000. Geoderma 127, 11–23.

Liski, J., Westmann, C.J., 1997. Carbon storage in forest soil of Finland. 2. Size and regional patterns. Biogeochemistry 36, 261–274.

Liski, J., Perruchoud, D., Karjalainen, T., 2002. Increasing carbon stocks in the forest soils of western Europe. Forest Ecology and Management 169, 159–175.

Metzger, M., Bunce, B., Jongman, R., Mateus, V., Mücher, S., 2003. The environmental classification of Europe, a new tool for European landscape ecologists. Landscape 20 (5), 50–54.

Milne, R., Brown, T.A., 1997. Carbon in the vegetation and soils of Great Britain. Journal of Environmental Management 49, 413–433.

Montanarella, L., 2005. The state of European soils. In: Proceedings of Strategies, Science and Law for the Conservation of the World Soil Resources, vol. 4, SCAPE - Landbunaoarhaskoli Islands, pp. 9–19.

Mücher, C.A., Bunce, R.G.H., Jongman, R., Klijn, J.A., Metzger, M., Wascher, D.M., 2003. Identification and characterization of Environments and Landscapes in Europe. ALTERRA Report 832, ALTERRA, Wageningen, 119 pp.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon and organic matter. In: Sparks, D.L., et al. (Eds.), Methods of Soil Analysis Part 3 – Chemical Methods. Chapter 34. Soil Science Society of America and American Society of Agronomy, Madison, WI, pp. 961–1010.

Nemeth, T., Micheli, E., Pasztor, L., 2002. Carbon balances in Hungarian soils. In: Kimble, J.M., Lal, R., Follett, R.F. (Eds.), Agricultural Practices and Policies for Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 449–457.

Olsson, M., 2002. Monitoring soil organic carbon stock changes for forest land in Sweden – methods and constraints. MISTRA Programme. Swedish University of Agricultural Sciences, Uppsala (unpublished report).

Pekkarinen, A., Reithmaier, L., Strobl, P., 2009. Pan-European Forest/Non-Forest mapping with Landsat ETM+ and CORINE Land Cover 2000 data. ISPRS Journal of Photogrammetry and Remote Sensing 64, 171–183.

Riha, S.J., Senesac, G., Pallant, E., 1986. Effects of forest vegetation on spatial variability of surface mineral soil pH, soluble aluminium and carbon. Water, Air and Soil Pollution 31, 929–940.

Roekerts, M., 2002. The biogeographical regions map of Europe. EEA/ETC BD [European Environment Agency/European Topic Centre for Biological Biodiversity], Kopenhagen, 17 pp.

Romanyà, J., Vayreda, J., Tarrasón, D., Rovira, P., 2006. Application of the Roth-C model in the CarboInvent test area Catalonia. In: Baritz, R., et al. (Eds.), Methodology that Links Forest Ecosystem with the Regional Carbon Inventories. Final report Deliverable 3.4. Multi-source inventory methods for quantifying carbon stocks and stock changes in European forests (CarboInvent) EU EVK2-2001-00287 (unpublished report).

Rosell, R.A., Gasparoni, J.C., Galantini, J.A., 2001. Soil organic matter evaluation. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Assessment Methods for Soil Carbon. CRC Press LLC P. Lewis Publishers, Boca Raton, USA, pp. 311–322.

Rumpel, C., Eusterhues, K., Kögel-Knabner, I., 2004. Location and chemical composition of stabilized organic carbon in topsoil and subsoil horizons of two acid forest soils. Soil Biology and Biochemistry 36, 177–190.

Schils, R., Kuikman, P., Liski, J., Van Oijen, M., Smith, P., Webb, J., Alm, J., Somogyi, Z., Van den Akker, J., Billett, M., Emmett, B., Evans, C., Lindner, M., Palosuo, T., Bellamy, P., Jandl, R., Hiederer, R., 2008. Review of existing information on the interrelations between soil and climate change. (CLIMSOIL). Final report. Brussels, European Commission, 208 pp. http://ec.europa.eu/environment/soil/pdf/climsoil_report_dec_2008.pdf.

Smith, P., Smith, J., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M., Reginster, I., Kankaanpaa, S., 2006. Projected changes in mineral soil carbon of European forests, 1990–2100. Canadian Journal of Soil Science 86, 159–169.

Spiegel, H., Filcheva, E., Hegymegi, P., Gal, A., Verheijen, F.G.A., 2007. Review and comparison of methods used for soil organic carbon determination. Part 1: Review of the methods. Soil Science Agrochemistry and Ecology XLI (4), 3–18.

SPSS Inc., 2007. SPSS for Windows, Rel. 16.0. Chicago.

Tamminen, P., Starr, M., 1994. Bulk density of forested mineral soils. Silva Fennica 28 (1), 53–60.

Tomlinson, R.W., 2005. Soil carbon stocks and changes in the Republic of Ireland. Journal of Environmental Management 76 (1), 77–93.

Tyurin, I.V., 1931. A modification of the volumetric method of determining soil organic matter by means of chromic acid. Pochovovodenye 26, 36–47 (cited in Thiessen and Moir 1993).

UN-ECE ICP Forests, 1998. International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests. Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Federal Research Centre for Forestry and Forest Products (BFH), 4th edition, Hamburg. (http://www.icpforests.org).

UN-ECE ICP Forests, 2006. Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Part IIIa – Sampling and Analysis of Soil. Updated 06/2006. http://www.icp-forests.org/Manual.htm.

Vanmechelen, L., Groenemans, R., van Ranst, E. (Eds.), 1997. Forest Soil Conditions in Europe – Results of a Large-Scale Soil Survey. Forest Soil Co-ordinating Centre, University of Gent, EC/UN-ECE, Brussels, Geneva, 261 pp.

Vejre, H., Callesen, I., Vesterdal, L., Raulund-Rasmussen, K., 2003. Carbon and nitrogen in Danish forest soils – contents and distribution determined by soil order. Soil Science Society of America Journal 67, 335–343.

Viro, P.J., 1952. Kivisyyden Määrittämisestä, on the determination of stoniness. Communicationes Instituti Forestalis Fenniae 40, 1–23.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37, 29–38.

Walter, H., Lieth, H., 1960–1969. Klimadiagramm Weltatlas. Gustav Fischer Verlag, Jena.

Weiss, P., Schieler, K., Schadauer, K., Radunsky, K., Englisch, M., 2000. Die Kohlenstoffbilanz des österreichischen Waldes und Betrachtungen zum Kyoto-Protokoll. Federal Environment Agency, Monographie 106, Vienna, 94 pp.

Wiedemann, T., Klap, J., Langouche, D., Van Ranst, E., 2001. Confrontation of the Forest Soil Condition Level I Database with the Soil Geographical Database of Europe. Forest Soil Co-ordinating Centre, Ghent, May 2001 (unpublished report).

Wirth, C., Schwalbe, G., Tomczyk, S., Schulze, E.-D., Schumacher, J., Vetter, M., Böttcher, H., Weber, G., Weller, G., 2004. Dynamik der Kohlenstoffvorräte und -flüsse in den Wäldern Thüringens. Thüringer Landesanstalt für Wald, Jagd und Fischerei (Hrsg.). Mitteilungen 23/2004, Gotha, 308 pp.