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Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey

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ABSTRACT

Soil organic carbon (SOC) stocks in forest floors and in mineral and peat forest soils were estimated at the European scale. The assessment was based on measured C concentration, bulk density, coarse fragments and effective soil depth data originating from 4914 plots in 22 EU countries belonging to the UN/ECE ICP Forests 16 × 16 km Level I network. Plots were sampled and analysed according to harmonized methods during the 2nd European Forest Soil Condition Survey. Using continuous carbon density depth functions, we estimated SOC stocks to 30-cm and 1-m depth, and stratified these stocks according to 22 WRB Reference Soil Groups (RSGs) and 8 humus forms to provide European scale benchmark values. Average SOC stocks amounted to 22.1 t C ha^{-1} in forest floors, 108 t C ha^{-1} in mineral soils and 578 t C ha^{-1} in peat soils, to 1 m depth. Relative to 1-m stocks, the vertical SOC distribution confirmed global patterns reported for forest soils: ~50% of SOC was stored in the upper 20 cm, and ~55–65% in the upper 30 cm of soil. Assuming 163 Mha of European forest cover and by using various scaling up procedures, we estimated total stocks at 3.50–3.94 Gt C in forest floors and 21.4–22.7 Gt C in mineral and peat soils down to 1-m, which is ~40% more than commonly published. The most useful predictors and stratifiers for C stocks were humus form and tree species for the forest floor, RSG for mineral soils and parent material for peat soils.
This dataset will be further explored, predominantly for validation of soil C models, resampling and comparison with legacy and future forest SOC inventories.

1. Introduction

Approximately one third of the European land area is covered by forests (FOREST EUROPE UNECE FAO, 2011). Their soils, including the forest floors, are considered a major store for terrestrial soil carbon (C), with an equivalent (Smith et al., 2006) or a much larger (Dixon et al., 1994; Eswaran et al., 1993; Lal, 2005) amount of C than found in the aboveground biomass. When considering similar soil types, forest soils usually contain more C than soils under arable land, while soils under grasslands were reported to have similar or lower SOC stocks (Guo and Gifford, 2002; Poeplau et al., 2011; Smith et al., 2005b).

Forest soils in a steady-state are expected to be neither sinks nor sources for atmospheric C (Ågren et al., 2008). Climate change together with direct (forest management) or indirect anthropogenic factors (e.g. air pollution) affect the ecosystem C balance by changes in C and N inputs (litter production) and outputs (respiration, leaching). Even small changes in the SOC pool, which contains more than twice the atmospheric C, could have dramatic impacts on the CO_2 concentration in the atmosphere (Schils et al., 2008; Smith, 2008). Hence, the response of SOC stocks to global warming and land-use management is critical and accurate data of past and current SOC stocks are essential to quantify these dynamics.

While national forest SOC inventories based on systematic grids become more available due to C accounting and reporting requirements, SOC accounting at the European level is scarce. Current EU estimates

Abbreviations: BD_{fe}, fine earth bulk density; BRT, boosted regression tree model; CD, carbon density; CDDF, carbon density depth function; CF, coarse fragments; $CI_{95\%}$, 95% confidence interval; Cs, carbon stock; Cs30, carbon stock to 30 cm depth; ETRS, European Terrestrial Reference System; EU, European union; FF, forest floor; FFCs, forest floor carbon stock; FSCC, forest soil coordinating centre; FSCDB, forest soil condition database; LOQ, limit of quantification; MAP, mean annual precipitation; MAT, mean annual temperature; OLM, organic layer mass; RFA, reference forest area; $P_{97.5}$, 97.5% percentile; RSG, reference soil group; SMU, soil mapping unit; SOC, soil organic carbon; SOCs, carbon stock till 1 m depth; VPcf, volume proportion of CF; WRB, world reference base.

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of SOC stocks in forest soils are mostly model-based (Liski et al., 2002; Smith et al., 2006) and often not externally validated by field measured data.

The first attempt to estimate EU-wide baseline forest soil C concentrations and stocks from measured data (ICP Forests Level I, 16 × 16 km grid, 5269 plots) was performed and reported by Baritz et al. (2010). This study was exclusively based on the 1985–1996 soil survey data gathered by 31 countries during the first ICP Forests soil condition inventory (Vanmechelen et al., 1997). At that time the sampling and analysis methods were not fully harmonized, nor adequate for proper SOC stock assessments (i.e. various analytical C determination methods, often missing bulk density and coarse fragments data, limited depth of assessment). Since this first attempt, the Forest Soil Coordinating Centre (FSCC) of ICP Forests further improved and harmonized sampling and analysis methodologies (Cools and De Vos, 2013; Cools et al., 2004; FSCC, 2006) among countries which were fully implemented in the second forest soil condition inventory (De Vos and Cools, 2011), conducted between 2004 and 2009 during the EU Forest Focus BioSoil demonstration project (Hiederer et al., 2011).

Based on the new contemporary, comprehensive and harmonized dataset, gathered through the BioSoil survey, the aim of this study was to determine the SOC stocks in (i) the forest floors, (ii) the mineral and (iii) the organic (peat) soil profiles down to 1 m of depth.

SOC stocks were stratified according to internationally referenced humus forms and soil types providing European benchmark values. By scaling up plot-based SOC stocks to the European level using various approaches we addressed the questions: (i) how much SOC is stored in the forest soils of Europe and (ii) which are the dominant controls/explanatory factors of these SOC stocks.

2. Materials and methods

2.1. Study area and sampling design

The survey area covers most of the European forests west of 31°34′ longitude, comprising twenty-two European countries, including Cyprus and the Canary Islands. Fig. 1 shows the geographical distribution of 4914 Level I plots belonging to the ICP-Forests network (www.ICP-Forests.net). About half of these plots were also assessed during the first European Forest soil survey (1985–1996) reported by Vanmechelen et al. (1997) and Baritz et al. (2010).

2.2. Forest soil description, classification and sampling

Soil profiles were described according to FAO (FAO, 2006) and classified following the World Reference Base for Soil Resources (IUSS Working group WRB, 2007). International training courses were organized for cross-calibration among soil surveyors. Soil organic layers were stratified into hydromorphic peat (H) and aeromorphic forest floor (O) layers according to FAO (2006).

They were distinguished from mineral layers by minimum organic carbon (OC) concentrations of 20% by mass for O horizons and of 12 to 18%, according to clay content, for H horizons (FAO, 1998; FSCC, 2006). Forest floor (FF) O horizons were divided in sub-horizons: litter (OL), fragmentation (OF) and humus (OH), or if OH < 1 cm thick a combination of the latter two (OFH) (Fig. 2). For hydromorphic or semi-terrestrial humus forms, equivalent Hf, Hfs or Hs sub-horizons were distinguished. However, when total thickness of these sub-horizons exceeded 40 cm, they were classified and sampled as Histosols.

All FF subhorizons were sampled separately by removing all dead organic material less than 2 cm thick from a sampled area of minimum 25 × 25 cm. Fresh mass and thickness were recorded for each layer and a subsample was taken to determine the moisture content.

Humus form description was based on the proposed European classification (Zanella et al., 2006, 2011), under development during the survey. Nine main humus forms were recognized: Mull, Moder, Mor, Amphihumus, Anmoor, Histomull, Histomoder, Histomor and Histoamphi (FSCC, 2006).

For each plot, composite samples were taken, mostly made from 5 subsamples (range: 1–25) per FF or soil layer, sampled >1 m away from trees and avoiding disturbed areas (trails, ditches, wind throws; FSCC, 2006).

Incremental depth sampling was applied to mineral and organic soil profiles as schematically shown in Fig. 2, fixed-depth samples being designated, M01 and H01 (0–10 cm), M/H12 (10–20 cm), M/H24 (20–40 cm) and M/H48 (40–80 cm). The sampling protocol allowed splitting M/H01 into two 5-cm intervals (M/H05 and M/H51).

2.3. Analytical methods

Physical and chemical analyses were performed by national laboratories following the reference methods outlined in the ICP Forests Manual IIIa on sampling and analysis of soil (FSCC, 2006; ICP Forests, 2010). The proficiency of the participating laboratories in conducting these analyses was controlled through inter-laboratory ring tests (Cools et al., 2007).

Coarse fragments (CF) content was assessed by field estimation and/or in the laboratory (FSCC, 2006). Field estimation was performed during soil profile description; abundance of rock fragments was estimated as a percentage class (0-5-15-40-80) of total soil volume (FAO, 2006). Alternatively, the rod penetration or Finnish method (Viro, 1952) was applied to estimate the volumetric percentage of CF (CFVOL, vol%) in the upper 30 cm of soil. In the laboratory, CF of mineral layers were separated from the fine earth fraction (ISO, 1994). The content of CF (CFMASS, mass%) was determined by weighing the residue left on a 2 mm sieve, compliant with the ISO 11277 method (ISO, 1998) for determination of particle size distribution in mineral soil material.

The volume proportion of coarse fragments (*VPcf*) was then calculated from either CFVOL, as VPcf = CFVOL/100 (60% of all layers), or from CFMASS (27% of all layers) by a layer-specific empirical formula, calibrated on $n = 2174$ (19%) samples where both volume and mass were reported. For the M05, M51 and M01 layers, this predictive equation was: $VP_{cf} = 0.5233 * CFMASS/100$. Coefficients of determination (R^2) ranged from 0.80 to 0.95.

Bulk density (BD, kg m^{-3}) was assessed on the fine earth (<2 mm), by means of 100 to 400 cm^3 steel cores taken from non-gravelly layers according to ISO 11272 (ISO, 1993). In the case of gravelly or very stony soils, a combined approach was used for estimating the BD of both fine earth and CF (FSCC, 2006).

Prior to C analysis, soils were air-dried, macroscopic roots were removed and all mineral and organic soil materials passing a 2 mm sieve were analysed. OC concentration (g kg^{-1}) was determined by dry combustion after correction for inorganic C, according to ISO 10694 (ISO, 1995). The average limit of quantification (LOQ) of OC analysis for all labs was 1.2 g kg^{-1}.

In addition to the mandatory ring-test participation of the labs, a 10% subset of all samples was analysed for OC by a single, central laboratory (Laboratoire d'analyses des sols, INRA, Arras, France), in order to assess the uncertainty by multi-laboratory analysis. Hiederer et al. (2011) compared OC results of central and national labs and found a very good agreement ($r^2 = 0.98$), with a mean bias ($OC_{national\ lab} - OC_{central\ lab}$) of -0.23 g kg^{-1} and -1.1 g kg^{-1} for mineral and organic layers respectively.

2.4. Forest soil condition database version 2.0

Relevant data for stock calculation were extracted from the Level I ICP Forests Soil Condition Database (FSCDB.LI.2.1) described by De Vos and Cools (2011). This database is the successor of the FSCDB.LI.1, compiled after the first European forest soil condition survey (Vanmechelen