Forest Ecology and Management 295 (2013) 162–172

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Storage and drivers of organic carbon in forest soils of southeast Germany (Bavaria) – Implications for carbon sequestration

Martin Wiesmeier [a,*], Jörg Prietzel [a], Frauke Barthold [b], Peter Spörlein [c], Uwe Geuß [c], Edzard Hangen [c], Arthur Reischl [c], Bernd Schilling [c], Margit von Lützow [a], Ingrid Kögel-Knabner [a,d]

[a] Lehrstuhl für Bodenkunde, Department für Ökologie und Ökosystemmanagement, Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt, Technische Universität München, 85350 Freising-Weihenstephan, Germany
[b] Institute of Earth and Environmental Sciences, University of Potsdam, Karl-Liebknecht-Str. 24–25, 14476 Golm, Germany
[c] Bavarian Environment Agency (LfU), 95030 Hof, Germany
[d] Institute for Advanced Study, Technische Universität München, Lichtenbergstr. 2a, D-85748 Garching, Germany

ARTICLE INFO

Article history:
Received 18 December 2012
Received in revised form 15 January 2013
Accepted 25 January 2013
Available online 24 February 2013

Keywords:
Tree species effect
Soil organic matter
Climate change
Forest management

ABSTRACT

Temperate forest soils of central Europe are regarded as important pools for soil organic carbon (SOC) and thought to have a high potential for carbon (C) sequestration. However, comprehensive data on total SOC storage, particularly under different forest types, and its drivers is limited. In this study, we analyzed a forest data set of 596 completely sampled soil profiles down to the parent material or to a depth of 1 m within Bavaria in southeast Germany in order to determine representative SOC stocks under different forest types in central Europe and the impact of different environmental parameters. We calculated a total median SOC stock of 9.8 kg m^{-2} which is considerably lower compared with many other inventories within central Europe that used modelled instead of measured soil properties. Statistical analyses revealed climate as controlling parameter for the storage of SOC with increasing stocks in cool, humid mountainous regions and a strong decrease in areas with higher temperatures. No significant differences of total SOC storage were found between broadleaf, coniferous and mixed forests. However, coniferous forests stored around 35% of total SOC in the labile organic layer that is prone to human disturbance, forest fires and rising temperatures. In contrast, mixed and broadleaf forests stored the major part of SOC in the mineral soil. Moreover, these two forest types showed unchanged or even slightly increased mineral SOC stocks with higher temperatures, whereas SOC stocks in mineral soils under coniferous forest were distinctly lower. We conclude that mixed and broadleaf forests are more advantageous for C sequestration than coniferous forests. An intensified incorporation of broadleaf species in extent coniferous forests of Bavaria would prevent substantial SOC losses as a result of rising temperatures in the course of climate change.

1. Introduction

Forest ecosystems store more than 50% of total terrestrial carbon (C) and are regarded to have a high potential for sequestration of atmospheric CO_2 (IPCC, 2000; Lorenz and Lal, 2010). In particular temperate forests that cover only 8% of the global land surface play a key role for C sequestration that was estimated to be around 40% of total terrestrial C uptake with a hotspot in Europe (Nabuurs et al., 1997; Martin et al., 2001; Goodale et al., 2002; Liski et al., 2002; Ciais et al., 2008; Lal, 2008; Wamelink et al., 2009; Tyrrell et al., 2012). Despite the importance of forests as major terrestrial C pool, there are large uncertainties regarding C storage in forest soils which accounts for 60–70% of total forest C (IPCC, 2000; Johnson and Curtis, 2001; Lorenz and Lal, 2010). Many authors criticize the lack of forest soil data, particularly for deeper parts of the mineral soil (e.g. Perruchoud et al., 1999; Baritz et al., 2010; Price et al., 2012; Tyrrell et al., 2012). Most studies that estimated the storage of soil organic carbon (SOC) focused on the organic layer and surface horizons in the upper 30 cm of the soil. However, tree roots and thus input of organic matter (OM) extend to deep subsoil horizons down to a depth of 3 m that may contain more than 50% of total SOC stocks (Jobbagy and Jackson, 2000; Lorenz and Lal, 2010; Rumpel and Kögel-Knabner, 2011). Further, there is a high spatial variability of forest SOC stocks and therefore, large numbers of samples are required to determine SOC stocks and assess differences accurately (Lal, 2005; Schöning et al., 2006; Mäkipää et al., 2008; Spielvogel et al., 2009). Moreover, many forest SOC studies are not based on measured soil properties but partly use modelled parameters for calculation of SOC stocks that could lead to a systematic bias (Karjalainen et al., 2003; Lindner and Karjalainen,

* Corresponding author. Tel.: +49 (0)8161 71 3679; fax: +49 (0)8161 71 4466.
E-mail address: wiesmeier@wzw.tum.de (M. Wiesmeier).

0378-1127/$ - see front matter
http://dx.doi.org/10.1016/j.foreco.2013.01.025

2007; Schrumpf et al., 2008). Also information about the main environmental drivers for the storage of SOC in forest soils is limited (Wamelink et al., 2009; Luyssaert et al., 2010).

In order to increase C stocks in forests, several management practices were discussed such as thinning, drainage, extending of rotation period, fertilization, liming, site preparation, fire, storm and insect management, afforestation and reforestation, harvest management and input of harvest residues (Burschel et al., 1993; Lal, 2005; Jandl et al., 2007; Nabuurs et al., 2008; Lorenz and Lal, 2010; Carroll et al., 2012). However, one of the most promising approaches to promote C sequestration in forests is a change in tree species composition. Several studies investigated the storage of SOC under different tree species and reported various effects (Augusto et al., 2002; De Vries et al., 2003; Hagen-Thorn et al., 2004; Ladegaard-Pedersen et al., 2005; Oostra et al., 2006; Schulp et al., 2008; Vesterdal et al., 2008). However, most of these studies were again restricted to the organic layer and uppermost mineral horizons and thus quantified only a certain proportion of total SOC stocks. Therefore, more knowledge about forest type-specific SOC storage is needed before future composition of tree species can be recommended (Jandl et al., 2007; Vesterdal et al., 2012).

In this study we used a comprehensive data set of 596 completely sampled forest soil profiles down to the parent material or at least to a depth of 1 m within Bavaria in southeast Germany to gain insight into the storage and driving factors of SOC. The data set consisted of 88 broadleaf, 331 coniferous and 177 mixed forest sites that were sampled for SOC, nitrogen (N), bulk density (BD), stone content (SC), pH and partly soil texture for each soil horizon. Our aims were to (1) determine total SOC stocks under different forest types, (2) reveal the main environmental parameters that control the storage of SOC in forest soils and (3) derive information about C sequestration in forest soils of Bavaria as affected by different forest types.

2. Materials and methods

2.1. Study area

Bavaria comprises an area of 70,550 km^2 and is located in the southeast of Germany. The northwestern part of Bavaria is dominated by the southern German escarpment landscape that adjoins in the east to low mountain ranges of the Bohemian Massif. Southwards a Molasse basin affiliates that ascends at the southern border of Bavaria to the mountain range of the Alps. Elevation ranges between 107 and 2962 m above sea level. Due to its location in central Europe, Bavaria has a sub-oceanic climate that is characterized by a transitional situation between a maritime climate in the northwest and sub-continental influences in the east. Mean annual temperature and precipitation range from the escarpment landscape in the northwest to the Alps in the south between 10 and 3 °C and 550 and 2500 mm, respectively. Around 35% of the area of Bavaria is covered by forest (Fig. 1). Coniferous forests cover around 35% of the total forest area (Schnell and Bauer, 2005) and are dominated by two species, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). About 25% of the forest area is covered by broadleaf forests which are dominated by European beech (*Fagus sylvatica*), pedunculate oak (*Quercus robur*) and sessile oak (*Quercus petraea*). In the remaining 40% of the forest area, mixed forests with coniferous and broadleaf species are found. Predominant forest soil classes are soils with well-developed B horizons (Cambisols) and soils with water stagnation (Stagnosols, Albeluvisols, Planosols) according to the German soil systematic (AD-HOC AG Boden, 2005) and the equivalent Reference Soil Groups of the WRB system (IUSS Working Group WRB, 2006).

2.2. Selection of forest soil data

Available data from different soil surveys and permanent soil observation sites in Bavaria provided by the Bavarian Environment Agency (LfU) were screened to compile a representative data set for forest soils. Only sampling locations were incorporated where soil profiles were sampled by horizon down to the parent material or at least to 1 m depth. All soil horizons were analyzed for SOC and N concentration, BD, SC and pH. Minimum requirement for SOC and N analysis was a determination by dry combustion using a CN elemental analyzer. Generally, only soil data was included which was collected after 1990.

Overall, the selected sampling locations that fulfilled all requirements amounted to 596 soil profiles (Fig. 1) with 88 locations under

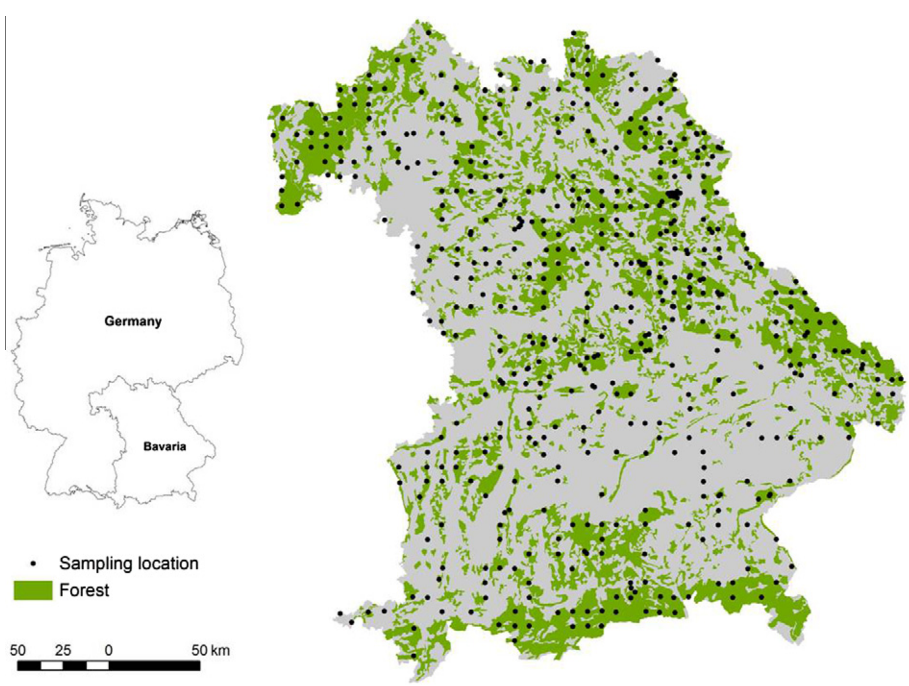

Fig. 1. Map of Bavaria with forest areas and sampling locations.