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Long-term monitoring of soil quality changes in Northern Germany

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ABSTRACT

The German regional long-term soil monitoring network (SMN) BDF-SH (Boden-Dauerbeobachtung Schleswig-Holstein) was assessed focusing on the quality of this soil monitoring network to detect and evaluate impacts of land-use change (LUC) from pasture to arable land on soil organic carbon (SOC) and biological soil properties. This included a review and evaluation of the monitoring methods to detect long-term SOC changes over time. Two loamy LUC study sites were selected from the monitoring program. The BDF-SH is not only focusing on monitoring of soil organic carbon but also on a wide range of data of soil chemistry, physics, biology and management at field scale. The quality of the SMN as a SOC monitoring was assessed using a catalogue of essential soil monitoring requirements which resulted in a classification of monitoring levels for each parameter. A SMN-specific method is given how to calculate SOC stock changes over time. Within seven and one year(s) respectively the conversion from pasture to arable land resulted in significant SOC losses of 19.4 Mg ha^{-1} (19.8%) at the sandy loam site 11 and 27.2 Mg ha^{-1} (20.2%) at the clay loam site 13. SOC measurements and microbiological parameters of the soil microbiological program confirmed and defined the results of the main program more precisely. Soil faunistic results underlined the impact of LUC on the soil ecosystem. Using evaluation schemes of the literature the quality of the SMN was evaluated as highly suitable to detect and evaluate SOC stock changes over time and further LUC impacts on the soil. Most of the assessed monitoring parameters of the SMN were evaluated as fulfilling the highest level. However, a SOC fractionation method could be included in the SMN to enable an even more thorough evaluation of SOC stock changes using SOC fraction measurements in process-based SOC modeling.

1. Introduction

1.1. Introduction to long-term soil and soil organic carbon (SOC) monitoring types

Changes of soil properties over time, e.g. SOC loss, as a consequence of soil degradation are focal points in recent literature (FAO & ITPS, 2015; Lal, 2014; BIO Intelligence Service, 2014; Louwagie et al., 2009). Soil degradation can develop through land-use change (LUC), erosion, compaction or contamination and may have impact on soil properties. Therefore, soil properties have to be monitored (Jandl et al., 2014). As soil properties change slowly, a long-term monitoring is essential for the assessment of changes in soil and the development of sustainable management strategies against soil degradation.

Long-term soil monitoring systems are well known in literature. Morvan et al. (2008) showed the concept of soil monitoring networks (SMNs). The authors defined them as “a set of sites/areas where changes in soil characteristics are documented through periodic assessment of an extended set of soil parameters”. The term SMN is used as well by Arrouays et al. (2012) and van Wesemael et al. (2011) who described general requirements of soil monitoring systems. Jandl et al. (2014) and Richter et al. (2007) use the term LTSE (long-term soil experiments) for a set of single long-term sites. They define LTSEs as “field experiments with permanent plots that are periodically sampled to quantify soil change across decadal time scales” (Jandl et al., 2014). Both authors see LTSEs as highly relevant for a SOC monitoring.

1.2. Introduction to the SMN “Boden-Dauerbeobachtung”

The German long-term soil monitoring program “Boden-Dauerbeobachtung” (BDF) (Prechtel et al., 2009; Schröder et al., 2003, 2004; Kaufmann-Boll et al., 2012; Nerger, 2010; Barth et al., 2001; Huschek and Krengel, 2004) is a SMN existing since 1985. The

Abbreviations: BDF, long-term soil monitoring (Boden-Dauerbeobachtung); BDF-SH, long-term soil monitoring of Schleswig-Holstein (Boden-Dauerbeobachtung Schleswig-Holstein); BDF site, long-term soil monitoring site (Boden-Dauerbeobachtungsfläche); CFE, chloroform-fumigation extraction; C_{mic}, microbial biomass; C_{org}, organic carbon concentration; DIN, German Industry Standard (Deutsches Institut für Normung); LTSE, long-term soil experiments; LUC, land-use change; qCO_2, metabolic ratio; $RESP_{Basal}$, basal respiration; SIR, substrate-induced respiration; SMN, soil monitoring network; SOC, soil organic carbon.

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monitored sites are called "Boden-Dauerbeobachtungsflächen" (long-term soil monitoring sites; BDF sites), which are 0.1 ha sized squares inside a field. Agriculturally used BDF sites are managed by farmers with contractual obligation to report all management actions to the responsible regional authorities (Huschek and Krengel, 2004). The top soil material of the BDF sites is sampled at regular time intervals (6 to 10 years) using standard soil monitoring techniques. Additionally at currently five sites, there is an intensive monitoring, which includes an annual soil sampling, a biweekly atmospheric deposition sampling and a weekly leachate sampling.

The focus of this study is the long-term soil monitoring program in Schleswig-Holstein (BDF-SH) (Nerger, 2010; Cordsen, 1993). Within the BDF-SH program there are currently 37 BDF sites monitored, which were selected representatively based on landscape units, soil types and land use management (Nerger, 2010; Schröder et al., 2003, 2004). The recent literature for SOC and soil monitoring mainly describes monitoring aims for accomplishing information on the regional scale (e.g. Morvan et al., 2008; Jandl et al., 2014; Arrouays et al., 2012; van Wesemael et al., 2011; Prechtel et al., 2009). Opposite to that the main focus of the BDF-SH program lies on the observation of site-specific soil properties and processes which shall be representative for the related landscape unit, soil type and land use management.

In addition to the BDF-SH program there are further regional BDF programs in Germany (e.g. Bavaria, Lower Saxony). They follow the same main guideline (Barth et al., 2001) which includes site installation and maintenance, major sampling strategies, etc., but specific rules (e.g. amount of composite samples, sampling intervals) can be implemented flexibly. Furthermore the BDF-SH program can be compared to other SMNs, such as the national long-term soil monitoring of Switzerland (Nationale Bodenbeobachtung der Schweiz (NABO); Desaules et al., 2010; Nerger, 2010).

1.3. Focal points of a soil/SOC monitoring

Jandl et al. (2014) state that for the assessment of SOC pool changes and even ecosystem processes soil monitoring programs or repeated soil inventories are necessary. Thereby, the benefit of SMNs/LTSEs increases with their age (Richter et al., 2007). Therefore, a reliable database for quantifications of SOC and other soil chemical, physical and biological properties is essential to assess soil degradations and long-term changes of soil properties. Especially in the context of climate change long-term observations become indispensable. A long-term soil monitoring features several focal elements (Jandl et al., 2014; Arrouays et al., 2012; van Wesemael et al., 2011; Morvan et al., 2008). Among them are the specific sampling design (sampling depth, amount of composite samples, etc.), aspects of SOC change detection (measurement method, SOC stock calculation method, uncertainty determination, sampling interval, trend, etc.) and other topics (e.g. sampling archives and change of staff for field survey and laboratory).

Specifically focusing on a long-term soil carbon monitoring system the most important requirement is its capability to detect changes in SOC stocks. Ellert and Bettany (1995) proposed a basic method for the calculation of SOC stocks. They found that when comparing temporal changes of SOC stocks the soil mass needs to remain equivalent, if there is no erosion influence. Ellert et al. (2002) confirmed this finding with the measurement of coal dust addition to soils of microsites. The subsequently measured effective SOC recovery did not result from the fixed volume (fixed depth without considering soil thickness or mass) method, but from using the equivalent soil mass method described in Ellert and Bettany (1995). Mikha et al. (2012) focused on the differences in fixed-depth and equivalent soil mass sampling as well and concluded that the equivalent soil mass approach is more exact. The sample depth was also a central point in the study of VandenBygaart et al. (2011), the authors found that land management induced changes (tillage, forage, crop types) of SOC stocks of 5 Mg ha^{-1} can be assessed correctly only with samples of >15 cm depth.

1.4. Land-use change – Grassland to cropland

Land-use change (LUC; conversion) in general is closely connected to SOC balances (Poeplau et al., 2011). Whereas LUC from cropland to pasture or forest serves positive SOC balances through SOC sequestration, LUC to cropland usually results in SOC loss (Guo & Gifford, 2002). Therefore, LUC to cropland can be a cause of soil degradation and SOC loss its effect. LUC from grassland to cropland can result in a loss of up to ~50% (Guo & Gifford, 2002) for sites of >35 years of pasture prior to LUC and >500 mm precipitation. Other authors found average SOC losses of 36.1 ± 4.6% within 17 years to equilibrium (Poeplau et al., 2011) and 24 ± 5 Mg C ha^{-1} for a depth of 0–30 cm (Poeplau & Don, 2013). Soussana et al. (2004) collated results of SOC loss by LUC in France from the INRA database and showed an average loss of 19 Mg C ha^{-1} (32% of the initial average SOC stock) for a period of 20 years. A recent study for a poorly drained clay loam in Ireland (Necpalova et al., 2014) resulted in a SOC loss of ~22% (32 Mg C ha^{-1}) during 2.5 years. For Northern Germany Strebel et al. (1988) studied a sandy soil in Lower Saxony and found a SOC loss of 58% (100 Mg C ha^{-1}) after 2–4 years of LUC. The soil properties affected by land-use change have been observed on the long-term monitoring BDF sites in Schleswig-Holstein (Germany) since two decades (LLUR, 2010).

1.5. Research gap and aims

To date there is neither an international publication presenting a specific regional long-term soil monitoring network in Germany and evaluating its quality, nor a peer-reviewed result of long-term SOC loss through LUC from such a SMN. This study aims to evaluate the specific design and structure of the BDF-SH program regarding its suitability to assess effects of soil degradation - exemplarily SOC loss and further impacts on soil water parameters and microbiologic and faunistic soil properties - through LUC considering different sampling and analytical methods at two study sites. Additionally, other impacts on SOC stocks shall be determined. Furthermore, the quality of the monitoring program will be assessed using scientific characteristics suggested in the relevant literature (Arrouays et al. (2012), Jandl et al. (2014), van Wesemael et al. (2011) and Morvan et al. (2008). The analysis of these focal points shall elaborate how the BDF-SH program may be used to assess long-term changes of soil properties and monitor land-use change impacts on soil. An associated topic is the optimization of the program. Which measures should be undertaken to make the program more adequate to answer these questions?

2. Material and methods

2.1. Evaluation of the monitoring network

As a first step essential requirements and sampling effort parameters of soil and soil carbon monitoring networks which were realized in the BDF-SH SMN or described in the literature (Jandl et al., 2014; Arrouays et al., 2012; van Wesemael et al., 2011; Morvan et al., 2008) were evaluated for the BDF-SH program. Among them were the specific sampling design (samples per plot, sampling depth, bulk density, soil biology, stoniness, etc.), aspects of SOC change detection (measurement method, SOC stock calculation method, uncertainty determination, sampling interval, trend, fractionation, etc.) and other topics (e.g. management database, sampling archives and change of field survey and laboratory staff).

The second step was to rank the sampling effort parameters of the BDF-SH program using the proposed hierarchy of sample effort levels of SMNs/LTSEs of Jandl et al. (2014). The authors pointed out four different effort levels, ranging from Level 1 with no statistical design to Level 2 (random sampling), to Level 3 (stratified random sampling) and Level 4 (nested sampling design). The further monitoring parameters were