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Soil carbon stocks in different bioenergy cropping systems including subsoil

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ABSTRACT

Despite the growing importance of energy cropping systems, little is known about their soil organic carbon (SOC) stocks in topsoils and subsoils. Furthermore, information regarding the impact of N-fertilization on C-sequestration for perennial compared with annual energy cropping systems is scarce. In order to study SOC changes in the soils of different energy cropping systems, a long-term study was established in southwestern Germany with the following cropping systems: energy maize (*Zea mays*) with reduced tillage, Miscanthus (*M. x giganteus*), switchgrass (*Panicum virgatum*) and willow (*Salix schwerinii x viminalis*), as well as a crop rotation with conventional tillage (CT) and no-till (NT) consisting of oilseed rape (*Brassica napus* ssp. *oleifera*), winter triticale (*Triticale triticosecale*) and winter wheat (*Triticum aestivum*). The soil is a Haplic Luvisol (Siltic). For each cropping system three N-fertilization regimes adapted to the needs of each crop were applied. With the main hypothesis that perennial energy cropping systems increase SOC stocks compared with conventional annual cropping systems, the SOC stocks were analyzed to a depth of 90 cm after 11 years of continuous cropping (2002–2012). Compared with the control (CT) with 76 Mg SOC ha^{-1}, the perennial crops had significantly higher SOC stocks in all N-fertilization regimes, which amounted to 92–95 Mg SOC ha^{-1} in the N1-fertilization regime. The crop rotation with NT also had higher SOC stocks with 93 Mg SOC ha^{-1} in the N1-fertilization regime. N-fertilization generally led to higher SOC stocks in all cropping systems, although SOC stocks did not increase any further from reduced to highest crop-specific N-fertilization, with the exception of energy maize. The current findings also stress the importance of subsoil carbon analyses: SOC stocks at a depth from 30 to 90 cm made up 44–55% of the total stocks and differed significantly between cropping systems.

1. Introduction

Soil organic carbon (SOC) concentration and stock are considered significant soil parameters since their alterations affect not only the agricultural properties of the site itself, but also the global carbon cycle (Smith et al., 1993; Zeng et al., 2004). The potential capacity for all managed ecosystems as soil sinks is estimated to be 55–78 Gt CO_2 which equals the cumulative historic C loss from soils (Lal, 2004). Whether soils under human management serve as a source or sink for CO_2 depends strongly on the overall land management (forest, grassland, arable land and all intermediate management systems) as well as the implemented farming methods, such as reduced tillage or fertilization strategies using organic inputs (Smith, et al., 2008). Energy crops, designated to different pathways of conversion have widened the spectrum of cropping systems in the past decades (Wright, 2006). Whether such cropping systems have a negative carbon balance depends, among other aspects, on their ability to sequester carbon (Brandão et al., 2011).

Long-term studies on the changes in soil parameters of different bioenergy cropping systems below the topsoil (>30 cm depth) have rarely been conducted. There are indications that perennial crops increase SOC stocks as the extensive root system of perennial crops enmesh particles to aggregates and stimulate the formation of microbial polysaccharids that join particles together (Six et al., 2006). In addition, root exudates form organo-mineral complexes (Bolan et al., 2011) and promote microbial activity, which also promotes SOC sequestration (Miltner et al., 2012). Some authors

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(e.g. Shi et al., 2013; Syswerda et al., 2011) state that changes of SOC stocks due to management changes or the change from annual to perennial crops are more distinct in the topsoil (0–30 cm) than in deeper soil and tend to fade with increasing depth. However, the current debate on the role of subsoils for C-sequestration shows that the disregard of changes in subsoil SOC stocks can distort overall carbon sequestration rates (Liebig et al., 2005; Olson et al., 2005; Rasse et al., 2006). However, sampling of deeper soil is often avoided as it is more expensive and SOC changes are harder to detect as carbon concentrations are lower and more variable than in the topsoil due to pedogenic factors (Syswerda et al., 2011).

The availability of nitrogen (N) is an important factor affecting carbon dynamics in agricultural systems as N is often the limiting nutrient and determines biomass production, which therefore influences carbon flows. Moreover, the availability and form of N influences the composition and decomposition and eventually the stability of soil organic matter (Ludwig et al., 2011). Generally, an increased input of N leads to increased carbon accumulation until a new equilibrium is reached depending on pedogenic and climatic factors (Hellebrand et al., 2010; Jung and Lal, 2011; Mazzoncini et al., 2011).

To bring light to this knowledge gap, the aim of the current study is to evaluate the potential of perennial energy crops to sequester carbon in top- and subsoils, compared with annual energy crops, based on the rate of N-fertilization. In addition, for an annual energy crop rotation, different tillage systems (no-till vs conventional inversion tillage by moldboard plough) which affect C dynamics are analyzed.

Based on these research aims, the following hypotheses were set up:

a Perennial crops grown without tillage sequester more SOC than conventional tilled annual crops, which leads to significantly different overall SOC-stocks in the long term.
b No-till in annual cropping systems does not lead to an increase in SOC stocks compared to conventional tillage when the whole soil profile is considered.
c SOC stocks in subsoils do not differ significantly between energy cropping systems.
d Increased N-fertilization significantly increases the SOC stock in the topsoil in perennial and annual bioenergy cropping systems.

2. Material and methods

2.1. Site description and experimental design

This study was part of a long-term field trial located at the research station Ihinger Hof (48.75°N and 8.92°E, 480 m asl) of the University of Hohenheim, in southwestern Germany. Located in a fertile area where plane fields and gently sloping hills alternate, this site was agriculturally used for several centuries. The location is characterized by a mean annual temperature of 9.1 °C (ten-year average for 2002–2012) and a mean annual precipitation of 714 mm. The soil is a Haplic Luvisol (Siltic) (IUSS, 2007), (Table 1). Overall, the soil has an udic moisture regime and a mesic temperature regime. The slope on this site is below 1%. Before the trial was established in 2002, the soil was conventionally tilled with moldboard plough and showed a mean bulk density of 1.35 g cm^{-3} in the topsoil (0–30 cm) and 1.48 g cm^{-3} at 30–60 cm depth (Table 1).

The trial began in 2002 and the same management continued until 2012, when soil samples for the current study were taken. Six cropping systems for annual and perennial energy crops adapted to the environment in Central Europe were tested in four replications. Different rates of N-fertilization were included in a split plot design (Table 2). The selection of cropping systems reflects different plant-based energy production systems prevalent in Central Europe: (1) Combustion of the plant material, (2) fuel production and (3) biogas production. The 1st and 2nd cropping systems (Table 2) were comprised of one crop rotation including the annual crops winter oilseed rape, winter wheat and winter triticale with the application of two different tillage systems: conventional inversion tillage using a moldboard plough (CT, 20–30 cm) versus no-till (NT). The annual crop maize ('Mikado') in a maize monocropping system was selected as a 3rd system. Three perennial energy crops, Miscanthus, *switchgrass* and willow, (harvested every third year) were used to study both trees and grasses. Each cropping system was divided into three N-fertilization regimes (split-plot design). Each subplot had a size of 160 m^2 and was replicated four times. Spaces between blocks were 18 m, while split-plots had 4 m buffer between each other. Within each subplot, sampling was done with at least a 2 m buffer to the border. N-fertilizer regimes were adapted to the N-demand of the different crops and included a control with no N-fertilization (N0), a reduced fertilization regime (N1) and a fertilization regime based on the current agricultural practice (N2) (Table 2). The ammonium-stabilized N-fertilizer Entec 26 (K+S Nitrogen GmbH, Mannheim, Germany), containing 75 g kg^{-1} nitrate-N, 185 g kg^{-1} ammonium-N and 130 g kg^{-1} sulphur was used throughout the study. Phosphorus (P), magnesium (Mg), potassium (K) and sulphur (S) were applied to maintain a sufficient supply of plant available nutrients based on soil tests and in accordance with good agricultural practice.

2.2. Soil analyses

Soil samples were taken to a depth of 90 cm at the beginning of the study in March 2002 after the soil was ploughed 5 months before and again, 11 years later, in March 2013. Soil sampling was done with a soil probe three times in every subplot to a depth of 90 cm. The sample was divided into 0–30 cm depth, 30–60 cm depth and 60–90 cm depth. All three samples within each subplot were merged to one composite sample. In 2013, a second sampling was conducted for the topsoil (0–10 cm, 10–20 cm and 20–30 cm) in the described manner to gain a higher resolution of soil characteristics in the topsoil. All soil samples were air-dried and sieved to 2 mm. Total C (C_t) and total N were determined by combustion (Vario Max CNTS, Elementar). In 2013, the samples from 0 to 90 cm depth with 30 cm increments were treated with

Table 1
Soil characteristics of a Haplic Luvisol (Siltic) at the trial site (Particle-size classes according to FAO (2006)).

Horizon	Depth [cm]	Sand 2–0,063 mm [g kg^{-1}]	Silt <0,063–0002 mm [g kg^{-1}]	Clay <0,002 mm [g kg^{-1}]	Bulk density [g cm^{-3}]	Effective porosity [cm^3 cm^{-3}]	Field capacity [cm^3 cm^{-3}]	Effective field capacity [cm^3 cm^{-3}]	pH
Ap	−30	24	748	228	1.55	0.047	0.369	0.206	7.38
Bt1	−50	22	743	235	1.50	0.042	0.391	0.148	7.15
Bt2	−73	25	764	211	1.50	0.043	0.390	0.187	7.05
BCg	−112	15	846	139	1.54	0.048	0.368	0.206	7.34