Carbon sequestration under Miscanthus in sandy and loamy soils estimated by natural $^{13}C$ abundance

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Summary

Most studies of soil organic-carbon (SOC) dynamics using $^{13}C$ natural abundance have been conducted with maize. Here, we present data about the sequestration of $C$ derived from a perennial $C_4$ plant, Miscanthus $\times$ giganteus (Greef et Deu.) grown on loamy and sandy soils for 9 and 12 y, respectively. We expected a higher contribution of Miscanthus-derived $C$ to SOC formation compared to maize because of (1) higher net biomass production by Miscanthus, (2) lower shoot-to-root ratio, (3) deeper roots, and (4) the absence of plowing. In both soils, there was a significant contribution of Miscanthus-derived $C$ down to 1 m soil depth. The maximal contents of 3.0 g $C_4$-C (kg soil)$^{-1}$ and 2.4 g $C_3$-C (kg soil)$^{-1}$ for loamy and sandy soil, respectively, were observed for the upper 0–10 cm layer. The decline in the amount of Miscanthus-derived $C$ with soil depth was significant for both soils, but without significant differences between the differently textured soils except the depth of 0–10 cm. The total SOC was similar under Miscanthus and under reference grassland in the sandy soil (both 6.4 kg $C$ m$^{-2}$ down to 1 m soil depth). Amounts of SOC were slightly higher under grassland at the loamy site (12.1 kg $C$ m$^{-2}$) compared with 11.2 kg $C$ m$^{-2}$). So, $C$ accumulation under Miscanthus was similar to that under perennial grasses. After 9 and 12 y, respectively, the yearly incorporation of Miscanthus-$C$ in SOC of the upper 0–30 cm was 0.23 g $C_4$-C (kg soil)$^{-1}$ y$^{-1}$ in the loamy and 0.11 g $C_4$-C (kg soil)$^{-1}$ y$^{-1}$ in the sandy soil. This $C_4$-C incorporation in loamy soil under Miscanthus was 1.6–1.8 times higher than results reported for maize $C_4$-C incorporation in SOC grown under similar climatic conditions. In the sandy soil, the $C_4$-C incorporation under Miscanthus was nearly the same as under maize. The fraction of 22% of the Miscanthus residues remaining in SOC was similar to that one of maize residues in loamy soil. In sandy soil, only a small fraction of 9% of the Miscanthus residues was incorporated in SOC.

Key words: C sequestration / mean residence time / Miscanthus $\times$ giganteus / natural $^{13}C$ abundance / soil organic carbon / $C$ turnover

1 Introduction

In carbon ($C$)-sequestration studies, knowledge of the annual contribution of “new” organic carbon to soil organic carbon (SOC) is very important. Apart from methods using humification of artificially $^{14}C$- or $^{13}C$-labeled plants or plant residues, natural differences in the abundance of $^{13}C$ between $C_4$ and $C_3$ plants are frequently used to distinguish between old SOC and new plant-derived $C$ (e.g., Volkhoff and Cern, 1987; Balesdent and Mariotti, 1987; Kristiansen et al., 2005). The discrimination against $^{13}C$ is higher at $C_3$ photosynthesis, making the $\delta^{13}C$ values of $C_3$ plants smaller (ca. –27‰) than those of $C_4$ plants (ca. –12‰) (EHLENGER and CERLING, 2002). Therefore, by growing a $C_4$ plant on soils with former $C_3$ vegetation, the amount of $C_4$ plant-derived $C$ can be estimated on the basis of the changing $\delta^{13}C$ values of SOC. A reference location with similar soil properties and land-use history is required to represent a soil with unchanged vegetation as well as to consider isotopic effects during humification and microbial utilization of plant residues (Balesdent and Mariotti, 1996). Nearly all investigations using $^{13}C$ natural abundance have been conducted with maize (e.g., Balesdent and Balabane, 1996; Ludwig et al., 2003). Focussing solely on one of the various $C_4$ plants cultivated in temperate climates may yield biased information about $C$ dynamic in soils.

Nevertheless, a limited number of investigations with other $C_4$ crops is available. Garten and Wullschleger (2000) studied switchgrass (Panicum virgatum L.) and found extremely high portions of switchgrass-derived $C$ (19%–31%) in the upper 40 cm of soil after only 5 y of cultivation. As far as we know, only two investigations of $C$ dynamics using natural $^{13}C$ of Miscanthus cultivated under European conditions are available from a sandy soil in Denmark (Hansen et al., 2004; Foreid et al., 2004). Therefore, additional studies with other $C_4$ plants growing on various soils are necessary.

In Europe, Miscanthus $\times$ giganteus (Greef et Deu.) is used as bio-energy crop with high aboveground biomass–yield potential (e.g., Beuch, 2000). It can be cultivated for 15 up to 25 y without replanting and is harvested yearly, often in the following spring to reduce ash contents. Based on the results of Hansen et al. (2004) and Garten and Wullschleger (2000), but especially considering the physiological properties and growing methods of Miscanthus, the $C$ dynamics in soils under Miscanthus are expected to differ from those under maize. The following features of Miscanthus’ physiology and cultivation lead us to expect that the contribution of Miscanthus-$C$ to SOC could be higher than found for maize: (1) perennial plants such as Miscanthus displace high portions of the assimilated $C$ belowground as a $C$ reservoir for growth in spring (Kuzyakov and Domanski, 2000), (2) Miscanthus has a very deep and well-developed root system (Miridakw et al., 1975; Neukirchen, 1999), (3) the absence of soil tillage means less aeration, lower plant residues–de-
composition rates, and better C stabilization for longer periods, (4) a high input of aboveground harvest residues, because harvesting in late winter or early spring leads to an accumulation of stubbles and leaves on the soil surface as pre-harvest losses (e.g., Beuch, 1999), and (5) slower decomposition of plant residues (stubbles, leaves, and roots) because the absence or reduction of N fertilization lead to a larger C : N ratio. Thus, our hypothesis was a higher annual contribution of C₄-derived C in soils under Miscanthus and a different depth distribution of C₄-derived C compared to those observed in soils under maize.

Different stabilization of SOC as well as different aeration frequently results in different turnover rates in differently textured soils (Huggins et al., 1998; Wang and Hsieh, 2002). We expected higher turnover rates in a coarser soil and therefore compared a loamy and a sandy soil with similar cultivation periods of Miscanthus in Germany.

2 Material and methods

One of the two fields under Miscanthus was located in Stuttgart-Hohenheim, Baden-Württemberg, Germany (48°43’ N, 9°13’ E), on a loamy Gleyic Cambisol (WRB, 1998). Mean annual temperature is 8.7°C and average annual rainfall 679 mm (1961–1990, meteorological station Stuttgart-Hohenheim). Soil texture was silty loam without any significant textural change in soil profile. Miscanthus was planted in May 1994 on a former grassland plot, and aboveground standing biomass was harvested annually in February or March. Miscanthus yields at the loamy site were 0.95 kg C m⁻² y⁻¹ on average. Soil and plant samples for SOC and δ¹³C analysis were taken in April 2003. The cultivation period at the sampling time was around 9 y. The second site was in Großbeeren, 10 km S of Berlin (52°21’ N, 13°19’ E), on a sandy Gleyic Cambisol (WRB, 1998). Mean annual temperature is 8.7°C (1961–1990, meteorological station Potsdam), average annual rainfall 548 mm (1961–1990, meteorological station Großbeeren). Soil texture was loamy sand without any significant textural change in soil profile. Miscanthus was cultivated for 12 y at sampling in September 2003 and was established on a former fallow. Miscanthus yields at the sandy site were 0.64 kg C m⁻² y⁻¹ after 4 y of cultivation in 1995. The field was not harvested during the last 7 y. Grassland plots adjacent to the Miscanthus fields were used as references. Soil profiles both from the grassland and Miscanthus site were prepared to obtain volume samples in order to determine bulk densities and general soil characteristics. For δ¹³C analyses, soil samples were taken with a soil auger in steps of 10 cm to a depth of 100 cm. The distance between the replications was about 15 m. In Hohenheim, three field replicates were taken from Miscanthus soil, and two analytical replicates were measured from one sample of every depth layer for soil under grassland. In Großbeeren, five replicates were available from the Miscanthus plot and two from the reference plot. The soil samples were air-dried at room temperature and sieved (2 mm mesh size). Afterwards, in a subsample, all visible root and plant remains were removed with tweezers, and the soil was ball-milled. Plant samples (shoots, roots, and rhizomes) were dried at 60°C and ground. Amounts of 25–30 mg of ground soil samples and 4–6 mg of ground plant material were weighed into tin capsules for δ¹³C analyses. δ¹³C was measured on an isotope-ratio mass spectrometer (IRMS 20–20, PDZ Europe) coupled with a C/N-Analyser (Carlo Erba) (0.1% precision). The portion of Miscanthus-derived C in SOC was calculated according to Balesdent and Mariotti (1996):

\[
\%C_{Miscanthus} = \frac{\delta^{13}C_t - \delta^{13}C_3}{\delta^{13}C_4 - \delta^{13}C_3} \times 100,
\]

where \(\delta^{13}C_t\) is the δ¹³C value of the soil with Miscanthus, \(\delta^{13}C_3\) is the δ¹³C value of the corresponding layer of reference soil with continuous C₃ vegetation, \(\delta^{13}C_4\) is the δ¹³C value of a poor C₄ soil under Miscanthus. It was calculated based on the δ¹³C value of the Miscanthus (mean of root, shoot, and leaves) and corrected for isotopic fractionation during humification by subtraction of the differences between δ¹³C of C₃ vegetation and δ¹³C of SOC of the corresponding soil layer of the C₃ soil. This approach assumes equal isotopic fractionation for humification of C₃ plants and C₄ plants and considers different fractionation in different soil depths.

Total input of Miscanthus-derived residues during cultivation period was calculated under the assumption that (1) pre-harvest losses were 30% of total aboveground-biomass production (Boelcke et al., 1998), (2) direct harvest losses (e.g., stubbles) were 10% (Beuch, 1995), and (3) belowground biomass was 50% of aboveground biomass (Neukirchen, 1999) and 4% of the belowground root C were mineralized yearly (Boelcke et al., 1998). During the 3 y establishment phase of Miscanthus, yield was fixed to 50% of the average biomass yield of the established Miscanthus stock (Clifton-Brown et al., 2001). Total aboveground-biomass production was first calculated based on the Miscanthus yield and the information about pre-harvest and direct harvest losses. Afterwards, yearly Miscanthus-C input as pre-harvest losses, direct harvest losses, and dying root biomass was calculated and added up for the whole vegetation time.

Turnover rate of C₃-derived SOC was calculated by using an exponential approach according to the difference in the amount of C₃-derived C in Miscanthus soil and the amount of C₃-derived C in grassland soil (Gregorich et al., 1995). The mean residence times (MRTs) were calculated as reciprocal to turnover rates. Standard deviation of Miscanthus-derived C was calculated according to John et al. (2003). The significance of differences between sandy and loamy soils were examined using one-way analysis of variance (ANOVA, \(\alpha = 0.05\)). Standard errors of means are presented on the figures as variability parameter.

3 Results and discussion

3.1 Total organic-C content

In the upper 30 cm of the loamy soil, the SOC content under Miscanthus (11–14 g C kg⁻¹) was lower than under grassland (13–16 g C kg⁻¹). Soil organic-C content declined clearly with soil depth (Fig. 1). The absolute SOC amounts in the loamy soil were slightly lower under Miscanthus compared to grassland, both in the upper 30 cm (5.4 vs. 7.0 kg C m⁻²) and at
0–100 cm (11.2 vs. 12.1 kg C m⁻²). For the sandy soil, absolute SOC amounts at 0–100 cm were slightly higher under grassland than under Miscanthus (7.0 kg SOC m⁻² vs. 6.4 kg SOC m⁻²). More SOC was found under Miscanthus for the upper 30 cm (4.6 kg C m⁻² vs. 4 kg C m⁻²). Soil organic-C amounts were higher in both loamy plots than in both sandy plots (Fig. 1, Fig. 2). This is explained by slower decomposition of plant residues in loamy soil due to less aeration, as well as by higher protection of SOC by clay particles. In opposition to Boelcke et al. (1998) who found a SOC content increase by 0.12% (silty loam) and 0.3% (sand) after 6–9 y of Miscanthus cultivation, we found no significant differences to the SOC between Miscanthus and grassland plots. These results suggested that C accumulation under Miscanthus is similar to that under perennial C₃ grasses.

3.2 Contribution of Miscanthus-derived C to SOC

The δ¹³C values slightly increased with depth in both grassland soils (Fig. 3). Similar trends were observed in several other studies (e.g., Veldkamp, 1994; Gregorich et al., 1995). In addition to δ¹³C discrimination during decomposition (Ågren et al., 1996), the decrease in δ¹³C in of atmospheric CO₂ during the last century contributes to decrease of d¹³C values in the upper soil horizon (Gregorich et al., 1995). The input of Miscanthus-derived C resulted in significantly greater δ¹³C values of the SOC on the sandy and loamy sites compared to the soils under grassland. In the loamy topsoil, 3.8 g C₄-C (0–10 cm) to 0.8 g C₄-C kg⁻¹ (20–30 cm) (kg soil)⁻¹ were Miscanthus-derived (Fig. 1). The content of Miscanthus-derived C in the sandy topsoil was lower than that in loamy soil (Fig. 1–2). However, the differences between the sandy and the loamy soils were significant only for 10–20 cm (p < 0.05).

Total amounts of Miscanthus-derived C at 0–100 cm depth accounted for 1.1 kg C₄-C m⁻² and were nearly twice as high as in the sandy soil (0.6 kg C m⁻²). In a sandy soil in Denmark under Miscanthus, Hansen et al. (2004) found 0.7 kg C₄-C m⁻² (0–100 cm) after 9 y. About 85% of the total Miscanthus-derived C at 0–100 cm were concentrated in the upper 30 cm of the sandy soil and 76% in the upper 30 cm of the loamy soil. This corresponds to results of Gregorich et al. (1995), who found 88% of total maize-derived C in the Ap horizon (0–27 cm). Depth had a strong effect on the contribution of Miscanthus-derived C to SOC (Fig. 1–2). In contrast to our study and the study of Hansen et al. (2004) with Miscanthus, Gregorich et al. (1995) detected no maize-derived C below 60 cm. This supports our hypothesis of a higher C sequestration under Miscanthus especially in deeper soil layers compared to maize.

The annual incorporation of Miscanthus-derived C in the upper 30 cm was 0.23 g C kg⁻¹ y⁻¹ in the loamy and 0.11 g C kg⁻¹ y⁻¹ in the sandy soil. The average annual incorporation of maize-derived C into SOC of Ap horizons of selected soils with different textures was 0.13 g C kg⁻¹ y⁻¹ (Kuzyakov and Schneckenberger, 2004) with high variations (0.03–2.6 g C kg⁻¹ y⁻¹, STD 0.053) caused by tillage, fertilization level, aboveground-biomass production, climatic conditions, and soil texture. The comparison of the annual incorporation of Miscanthus- and maize-derived C into SOC showed a higher incorporation of Miscanthus-C only for the loamy soil. For sandy soil exclusively, we could observe a slightly higher or similar incorporation of Miscanthus-derived C compared to maize-derived C. Flessa et al. (2000) found an incorporation...
SOC of the sandy soil. This is lower than the accumulation of 26\% of the Miscanthus residues in the SOC of the sandy soil reported by Hansen et al. (2004) where aboveground biomass was harvested. On our sandy site, the aboveground Miscanthus biomass was harvested only during the first 5 y. Therefore, most of the Miscanthus-shoot residues were decomposed aboveground. According to Flessa et al. (2000) and Balesdent and Balabané (1996), the accumulation of root residues in soil is higher than the accumulation of aboveground plant residues. Therefore, Flessa et al. (2000) found a much higher portion of silage-maize residues remained in the SOC compared to our loamy soil (31\% at 0–70 cm vs. 22\% at 0–100 cm). There should remain only direct harvest losses of 10\% of the aboveground-biomass production on field (Angers et al., 1995) compared to 40\% of the aboveground-biomass production of Miscanthus even on loamy site.

We calculated the MRT of the C\(_3\)-C in the upper soil horizon of the loamy soil using an exponential approach on the basis of the amount of C\(_3\)-C (kg C\(_3\)-C m\(^{-2}\)) in the Miscanthus field after 9 y of Miscanthus cultivation and the amount of C\(_3\)-C in the reference soil. We assumed that the C\(_3\)-C amount in the reference soil reflects the amount of C\(_3\)-C in the Miscanthus field prior to Miscanthus cultivation. In the loamy soil, the MRT of the C\(_3\)-C was 11 y for 0–10 cm, 34 y for 10–20 cm, and 39 y for 20–30 cm. Collins et al. (1999) found MRTs of 40–96 y for the top layers (0–20 cm) of variously textured soils. An MRT of 55 y was estimated for the C\(_3\)-C by Gregorich et al. (2001). While the MRTs of Collins et al. (1999) and Gregorich et al. (2001) are longer than the MRT of the C\(_3\)-C in our loamy soil, Gregorich et al. (1995) and Angers et al. (1995) found similar MRTs under maize in Canada and USA.

4 Conclusions

Continuous Miscanthus cropping on a loamy and a sandy soil during 9 and 12 y, respectively, led to C sequestration similar to that of perennial grassland. The C amount of Miscanthus-derived C\(_3\)-C incorporated annually into SOC of loamy soil was higher than that found in other investigations on maize. This is evident both in the total amounts of Miscanthus residues remaining in the soil after the cultivation and in the annually increase of the Miscanthus-derived C content. However, our expectation of a higher contribution of perennial Miscanthus compared to annual maize was supported only for the loamy soil. A higher contribution of Miscanthus-derived C to SOC in deeper soil layers compared to maize points to the possibility of belowground C sequestration by planting perennial C\(_4\) grasses.

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The part of the total input of Miscanthus residues retained in SOC was calculated by estimating the total C input to the soil during the cultivation period in comparison with the total amount of C\(_3\)-C remained in the SOC. Within 9 y, 22\% of the C derived from the Miscanthus residues (5 kg C m\(^{-2}\)) were retained as SOC in the loamy soil (100 cm depth). Only 9\% of Miscanthus residues (6.8 kg C m\(^{-2}\)) were incorporated in

Figure 3: \(\delta^{13}\)C values (± SE) of the SOC of the loamy and sandy soils after 9–12 y of Miscanthus cultivation and under reference C\(_3\) grassland.

- \(\delta^{13}\)C value (%)
  - sandy grassland
  - sandy Miscanthus
  - loamy grassland
  - loamy Miscanthus

Depth (cm)
- 0
- 20
- 40
- 60
- 80
- 100

- \(\delta^{13}\)C value (%)
  - sandy grassland
  - sandy Miscanthus
  - loamy grassland
  - loamy Miscanthus

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