Short Communication

Soil aggregation and aggregate-associated organic carbon concentrations for the perennial energy crop cup plant in comparison to maize

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Abstract

The objectives of this study were to analyze soil aggregation and associated soil organic carbon (SOC) under cup plant and maize in a field trial (sandy loam) and two farmers’ fields (both silty loams) during the 2018 growing period. On the sandy loam, aggregation under the two crops did not differ despite higher bulk SOC under cup plant. At the silty loam sites, cup plant exhibited a 64% higher aggregate mean weight diameter than maize in spring and higher aggregate-associated SOC in autumn.

Key words: biogas crops / carbon sequestration / soil structure / water-stable aggregates

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1 Introduction

Soil aggregation is a crucial parameter for soil structure and soil organic carbon (SOC) stabilization and thus for various soil functions such as water infiltration, aeration and root permeability. Soil aggregates protect occluded organic matter (OM) from decomposition (Six et al., 2004). The stability of soil aggregates depends on their size, with microaggregates (53–250 μm) being more stable than macroaggregates (> 250 μm) (e.g., John et al., 2005).

Compared to annual crops, perennial crops can increase aggregation because of their larger root biomass (Ontl et al., 2015; Schoo et al., 2017; McGowan et al., 2019), higher earthworm abundances (Schorpp and Schrader, 2016) and larger fungal biomass (McGowan et al., 2019). The absence of tillage operations in perennial crops in itself promotes macroaggregate formation and stability (Six et al., 2000). Perennial crops were also found to increase SOC levels (Harris et al., 2015; McGowan et al., 2019). However, previous studies gave contradictory results with regard to the effect of perennial crops on soil aggregation and associated SOC, which could be due to the use of different crops and soil textures (Ontl et al., 2015; Tiemann and Grandy, 2015; Schrama et al., 2016).

Because of its high methane yield potential, perennial cup plant (Silphium perfoliatum L.) is an alternative energy crop to maize (Haag et al., 2015). Cup plant was found to significantly increase water infiltration rates and to reduce soil erosion compared to maize (Grunwald et al., 2020), suggesting an improved soil structure. In the present study, soil aggregation and SOC associated with aggregates under cup plant and maize were analyzed over the course of a growing period at three sites with different soil texture and OM content in Northern Germany.

2 Material and methods

2.1 Study sites

The study consisted of an experimental field in Braunschweig (52.296° N, 10.438° E) and two farmers’ fields at Giesen (52.195° N, 9.850° E) and Hedeper (52.052° N, 10.691° E), all sites in Lower Saxony, Germany.

The soil of the experimental field in Braunschweig is classified as Haplic Luvisol with 60% sand, 34% silt and 6% clay in the top 25 cm. A trial with a completely randomized block design with four replicates comparing permanent cup plant and maize was established in 2012. The maize plots were ploughed each year to a depth of 25 cm. Maize received 180 kg N ha⁻¹ and cup plant 170 kg N ha⁻¹ as mineral fertilizer. In 2018, the experiment was irrigated with a total of 270 mm.

In Giesen (Gleyic Chernozem, 4% sand, 75% silt, 21% clay) cup plant was grown continuously since 2013 without fertilization next to continuous maize (since 2015), which in 2018 was fertilized with 25 m³ biogas slurry ha⁻¹, incorporated by ploughing in May 2018.
In Hedeper (Calcic Histosol, 4% sand, 77% silt, 19% clay, as well as 1.1% inorganic carbon), cup plant was grown continuously since 2013 next to a maize–spring wheat rotation with different catch crops. Maize was fertilized with 20 m³ biogas slurry ha⁻¹, incorporated with a compact disc harrow, while cup plant received the same fertilization as maize every other year, but not in 2018.

2.2 Soil sampling

Soil samples were taken with an Edelman auger (Eijkelkamp, Giesbeek, The Netherlands) to 25 cm depth. The sampling dates were at the beginning of the growing season in April, at full flowering of cup plant in July, and after crop harvest in September. In Braunschweig, samples were taken in each cup plant and maize plot in the four blocks. At the farmers’ fields, four samples were taken randomly across the cup plant and maize fields. In Braunschweig, additional soil samples in 0–30 cm soil depth were taken half-yearly from October 2016 until March 2019 to analyze the bulk SOC concentrations.

2.3 Laboratory analyses

Water-stable aggregates were isolated with the wet-sieving fractionation method described by Cambardella and Elliott (1993). Four sieves were used to isolate the aggregate size-classes: large macroaggregates (> 2 mm), medium macroaggregates (1–2 mm), small macroaggregates (0.25–1 mm), microaggregates (0.053–0.25 mm), and silt and clay (< 0.053 mm). From all aggregate fractions a mean weight diameter (MWD) was calculated following John et al. (2005).

All samples were analyzed for total carbon concentrations according to the Dumas combustion method (vario MAX cube C/N analyzer, ELEMENTAR, Langenselbold, Germany). The soil samples from the Histosol were additionally analyzed for inorganic carbon after destroying all organic carbon (Vuong et al., 2016). The data for SOC associated with large, medium and small macroaggregates were combined into a single value for macroaggregate-associated SOC.

2.4 Statistical analyses

The statistical analyses were performed with R version 3.5.1 (R Core Team, 2018). Analyses of variance for the factor crop (and block in the case of the field experiment) were done separately for each date and study site because of the different experimental layout of the sites, resulting in pseudo-replicates at the farmers’ fields. In all cases, residuals of the model were checked for homoscedasticity by Levene’s test and for normal distribution by the Shapiro–Wilk test.

3 Results

3.1 Soil aggregation

In the Luvisol, no differences were found between cup plant and maize concerning soil aggregation (Fig. 1). In both the Chernozem and the Histosol, cup plant showed a significantly higher aggregation than maize in April. In September both crops in both soils exhibited similar levels of aggregation (Fig. 1).

3.2 SOC in bulk soil and soil aggregates

The SOC concentrations in the Luvisol were significantly higher under cup plant than under maize for most sampling dates (Tab. 1). There was no indication for a further SOC increase under cup plant over the sampling period from October 2016 to March 2019. Averaged over this entire period, the SOC levels under cup plant amounted to 0.98% SOC, while
maize had 0.88% SOC, which was significantly less ($p < 0.01$).

The aggregate-associated SOC concentrations in the Luvisol were at no time significantly different between cup plant and maize (Tab. 2). In the Chernozem and Histosol, however, aggregate-associated SOC concentrations were higher under cup plant than under maize in September.

### 4 Discussion

The lack of differences in aggregation between cup plant and maize in the Luvisol is in accordance with the findings of Schrama et al. (2016), who also found no significant difference between perennial Miscanthus and annual maize in a similar soil. Ontl et al. (2015) showed that increases in organic matter in soil aggregates, in particular in macroaggregates, under perennial energy crops (PECs) depend on the soil texture, with stronger effects in fine-textured soils. According to Tiemann and Grandy (2015), large macroaggregates under PECs in sandy soil are unstable and it takes more time to achieve stable aggregates than in a silty loam soil. The missing trend to further SOC accumulation in the bulk soil under cup plant might also indicate that the Luvisol was close to carbon saturation, which seems quite possible in view of the rather coarse texture (Wiesmeier et al., 2014) and would in turn limit the possibility to further increase SOC by the choice of the crop. Generally, the dry weather during the study was highly disadvantageous for aggregate formation and stability in a sandy loam (Kaiser et al., 2015; Linsler et al., 2015).

Higher soil aggregation under cup plant in the Chernozem and Histosol is in accordance with findings of Tiemann and Grandy (2015) and McGowan et al. (2019), comparing PECs with maize on similar soils. Reasons for the higher aggregation could be a higher fungal and microbial biomass stimulating aggregate formation (McGowan et al., 2019). The higher aggregate stability over winter might be attributed to the cup plant root system which partially survives the winter (Schoo et al., 2017). The similar aggregation under cup plant and maize in the Chernozem and the Histosol in July and September indicates no longer lasting negative effect of ploughing the maize in spring, possibly due to increased microbial activity (Andruschkewitsch et al., 2014), likely further increased by the incorporation of organic fertilizer in maize (Grunwald et al., 2016). The lack of N fertilization of the cup plant fields in the study year could in turn have caused N limitation for microbial decomposition processes and thus might have hampered aggregate formation. Despite this drawback, soil aggregation under cup plant was at no time lower than under maize. The higher aggregation under cup plant in spring improves water infiltration and helps to prevent soil erosion and flooding at this time, which is a constant risk in maize cropping during heavy rain events (Grunwald et al., 2020).

Higher post-harvest microaggregate-associated SOC concentrations under cup plant compared to maize in both the Chernozem and the Histosol might indicate an increased formation of microaggregates in macroaggregates under cup plant, due to a higher macroaggregate stability in the absence of tillage (Andruschkewitsch et al., 2014). Due to the longer turnover times of microaggregates compared to macroaggregates (John et al., 2005), an increase in the SOC associated with the microaggregate fraction indicates a more durable SOC sequestration.

### Table 2: Soil organic carbon concentrations (% SOC) in the macroaggregates (> 250 µm) and microaggregates (53–250 µm) of soil samples taken from the 0–25 cm soil horizon in cup plant and maize plots for three sites and three sampling dates in the year 2018. Data shown are means ($n = 4$) with standard deviations in brackets. Different letters indicate significant ($α < 0.05$) differences between crops for the given sampling month.

| Fraction         | Sampling date | Braunschweig (Luvisol) | Giesen (Chernozem) | Hedeper (Histosol) |
|------------------|---------------|-----------------------|--------------------|--------------------|
|                  |               | Cup plant | Maize   | Cup plant | Maize   | Cup plant | Maize   |
| Macroparaggregates | April         | 0.4 (0.1) | 0.3 (0.1) | 3.9 (0.6) | 4.5 (0.5) | 13.4 (1.1) | 12.6 (1.5) |
|                  | July          | 0.5 (0.0) | 0.5 (0.0) | 3.9 (0.5) | 3.3 (0.2) | 12.7 (4.5) | 11.4 (1.9) |
|                  | September     | 0.5 (0.0) | 0.5 (0.1) | 4.5 (0.1) | 3.4 (0.1) | 14.1 (0.6) | 10.8 (1.1) |
| Microaggregates  | April         | 0.8 (0.1) | 0.8 (0.1) | 3.3 (0.7) | 4.2 (0.6) | 13.1 (2.0) | 12.0 (1.4) |
|                  | July          | 1.0 (0.1) | 0.9 (0.1) | 3.8 (0.5) | 3.2 (0.2) | 12.2 (4.7) | 11.2 (1.8) |
|                  | September     | 0.9 (0.1) | 0.9 (0.1) | 4.6 (0.2) | 3.4 (0.1) | 13.7 (0.6) | 10.6 (0.8) |

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Overall, cup plant, contrary to maize, seems to be able to improve soil structure and enhance carbon sequestration in soils with silty loam texture even with lower or no input of organic fertilizer, making it a reasonable choice for soil amelioration at sites with a high risk of soil erosion or low SOC levels. However, the study period was characterized by unusually dry weather and two of three study sites were farmers’ fields with an extensive cup plant management and without a proper experimental design. Therefore, further research at sites with contrasting soil properties and optimal fertilizer input over several growing periods is necessary to obtain robust results.

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Data Availability Statement

Research data are not shared.

References

Andruschkewitsch, R., Koch, H.-J., Ludwig, B. (2014): Effect of long-term tillage treatments on the temporal dynamics of water-stable aggregates and on macro-aggregate turnover at three German sites. Geoderma 217, 57–64.

Cambardella, C. A., Elliott, E. T. (1993): Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57, 1071–1076.

Grunwald, D., Kaiser, M., Ludwig, B. (2016): Effect of biochar and organic fertilizers on C mineralization and macro-aggregate dynamics under different incubation temperatures. Soil Till. Res. 164, 11–17.

Grunwald, D., Panten, K., Schwarz, A., Bischoff, W.-A., Schittenhelm, S. (2020): Comparison of annual and perennial bioenergy crops with regard to soil and water protection. GCB Bioenergy 12, 694–705.

Haag, N. L., Nägele, H. J., Reiss, K., Bier tümpfel, A., Oechnser, H. (2015): Methane formation potential of cup plant (Silphium perfoliatum). Biomass Bioenerg. 75, 126–133.

Harris, Z. M., Spake, R., Taylor, G. (2015): Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. Biomass Bioenerg. 82, 27–39.