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Does maize and legume crop residue mulch matter in soil organic carbon sequestration?

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ABSTRACT

Soil management techniques, such as mulching, are used to enhance soil organic carbon sequestration. However, we demonstrate that the potential of crop residue mulching to increase soil organic carbon (SOC) sequestration varies by cropping system and soil type in Austrian agricultural soils. Effects of mulch (as harvested crop residues applied at 1.0 t C ha^{-1}) on soil and microbial carbon (C) and nitrogen (N) and soil $\delta^{13}C$ were measured in an Austrian Cambisol field experiment with sole maize or vetch or vetch-maize rotation cropping systems after five years with or without mulching to elucidate how SOC is affected. The direct role of mulch on SOC in different soil types was also investigated in a similar greenhouse mesocosm study with controlled moisture using the same Cambisols and an Austrian agricultural Chernozem. Only sole maize cropping in the field experiment resulted in higher SOC with mulching and when legumes were included in a legume-maize rotation SOC did not improve. Mulching in the field experiment only resulted in higher SOC in the top 0–5 cm of soils with sole maize cropping (by 22%) compared to soils without mulch. Although mulch did not increase SOC in vetch-maize rotation, the $\delta^{13}C$ of SOC was less negative with mulch indicating larger C contribution from maize than vetch mulch. After four years of annual soybean-maize rotation in the mesocosm experiment, no significant differences in SOC were observed in Cambisols with or without mulch. Again, $\delta^{13}C$ of both soil types was less negative with mulching indicating a larger C contribution from maize than soybean mulch. No relationships between microbial biomass C and N and SOC were observed in either experiment and only soil N concentration was positively correlated with SOC. Together these studies indicate that maize can increase SOC when crop residues are applied in Austrian Cambisols but that inclusion of legume production and legume mulch in rotation can mute these benefits.

1. Introduction

Mulching, such as with crop residue retention, is considered a sustainable soil management technique that prevents soil erosion, retains water, buffers temperature fluctuations, restores biodiversity increases fertility and improves soil structure- all of which are important for improving plant growth (for review see Erenstein, 2003). Additionally, mulching with crop residues increases soil organic carbon (SOC) and carbon (C) storage thus reducing anthropogenic greenhouse gas emissions to the atmosphere (Smith *et al.*, 2008). These benefits of plant residue retention are of significance in agricultural systems, as roughly 70% of agricultural land around the globe is moderately to highly degraded (Delgado, 2010; FAO, 2011). However, the effectiveness of mulching in improving SOC stocks varies depending on the type of mulch and environment, both of which can affect rates of decomposition and retention (Mando and Stroosnijder, 1999; Ossoml et al., 2001). The benefits of mulching are also often very slow, with no observable improvements even after six growing seasons or longer (Affholder et al., 2009; Kihara *et al.*, 2012).

In agricultural systems, growth of different types of crops can affect rates of SOC sequestration (Zhang et al., 2010) and the type of residue (associated with crop type) applied as mulch can also greatly influence SOC retention. Specifically, it has been proposed that maize crop residues may increase buildup of SOC (Mathew *et al.*, 2017) but that legume crop residues might be more likely to stabilize soil C (Drinkwater et al., 1998). This is because the magnitude of SOC increase depends upon the quantity of organic matter produced and returned to soil (Studdert and Echeverria, 2000; Brandani *et al.*, 2015) as well as the quality of these C sources that can affect microbial activity and decomposition (Balesdent et al., 1988; De Clercq et al., 2015). Model simulations support this theory and indicate that long-term increases in SOC due to crops and crop residues may in fact be higher in cereal-

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legume intercrops compared to sole maize crops (Oelbermann et al., 2017). However, other studies such as a meta-analysis by West and Post (2002) suggest that enhanced rotation complexity from maize to maize-soybean may not result in a significant increase in SOC due to a decrease in residue production and carbon input in maize-soybean rotation compared to continuous maize systems.

Because the effects of mulching vary depending on the type of plant material and environment and often develop slowly, it is important to measure the effectiveness of this sustainable practice thoroughly in different agricultural settings and to evaluate it over longer terms. However, it is difficult to issue a method to evaluate the effectiveness of this soil management technique due to the typically slow development of mulch effects. Isotopic techniques can help elucidate potential long-term effects of mulching before shifts in soil C pools can be observed. For over three decades stable isotopes have been used to evaluate the turnover of C and organic matter in soils (Balesdent et al., 1988; Natelhoffer and Fry, 1988). Studies measuring the isotopic composition of C in soil components at natural abundance levels can elucidate contribution of plant residues and roots to SOC (Spaccini et al., 2000; Jin et al., 2017). Furthermore, soil $\delta^{13}C$ analysis can identify differences in plant contribution of C to soils by different plants, particularly when there is a shift in plant composition between plants with C_3 photosynthesis and C_4 photosynthesis (Barthès et al., 2004; Sisti et al., 2004; Christensen et al., 2011). Because C_3 plants have a $\delta^{13}C$ of approximately −28‰ as opposed to C_4 plants that have a $\delta^{13}C$ of approximately −14‰ (O'Leary and Osmond, 1988), an increase or decrease in soil $\delta^{13}C$ that follows a change in C_3 and C_4 plant composition can be indicative of each plant type's contribution to soil C.

We used these isotopic techniques in combination with classic soil analytical techniques to elucidate how SOC levels are affected by maize and legume residue mulch. This was done by evaluating the effects of mulch on soil and microbial C and N and soil $\delta^{13}C$ in Austrian field and greenhouse studies with maize and legume monocrops as well as rotation cropping. We hypothesized that mulching would improve SOC and N status, since the two are tightly linked (Cleveland and Liptzin, 2007), in all cropping systems but that more SOC would be stored in soils with mulch and legume-maize rotation due to the relatively higher production of organic material by maize as well as higher quality, low C:N residues produced by legumes. We also hypothesized that the soil with lower organic matter and a higher potential to accumulate C in the mesocosm study would improve SOC content with mulching more than the soil with higher organic matter. Furthermore, we predicted that mulching in legume-maize rotation would result in a soil $\delta^{13}C$ more similar to legumes since it has a higher quality residue that may be more stabilizing than maize mulch.

2. Materials and methods

2.1. Field experiment

The field experiment was conducted at the AGES (Austrian Agency for Health and Nutritional Security) agricultural site located in Ruprechtshofen, Austria (48°08′N,15°13′E). The site is dominated by C_3 native grasses, has a mean annual precipitation range of 600–700 mm (Kilk and Konecny, 2013) and the soil can be classified as a Eutric Cambisol (IUSS-WRB, 2014) with a pH of 6.7, no inorganic C and a bulk density in the top 15 cm of 1.31 g cm^{-3} (for methods on measuring bulk density, see IAEA, 2016). Our experiment was established in March of 2012 in three experimental blocks (10 × 12 m^2 per block) (Fig. 1). Initial SOC and total N in soils from 0 to 5 and 5–15 cm for each block is described in Table 1 and SOC $\delta^{13}C$ was approximately -27.4‰. Each of the three blocks contained six plots (6.25 m^2 per plot); one with an annual sole vetch monocrop with mulch, an annual sole maize monocrop with mulch and an annual vetch-maize rotation crop with mulch and another three plots with the same cropping systems without mulch.

Prior to each planting, soils were prepared with a rotary cultivator to a depth of approximately 10 cm. Annual vetch (*Vicia sativa*, a C_3 legume species) was planted in April and maize (*Zea mays* L., a C_4 species) was planted in June. Vetch was grown in plots at 120 kg seed ha^{-1} and maize was grown at 102 kg seed ha^{-1}. Phosophorous (P) and potassium (K) fertilizer was applied at the time of vetch planting at 33 kg P ha^{-1} (as triple superphosphate) and 95 kg K ha^{-1} (as K_2SO_4) and N, P and K fertilizer was applied at 120 kg N ha^{-1} (as urea), 43 kg P ha^{-1} and 190 kg K ha^{-1} at the time of maize planting. Fertilizer application was kept similar to that typically used at the agricultural site.

Vetch was harvested before maize planting in June and maize was harvested at the end of September. At each harvest, vetch was cut with a sickle bar mower and maize cobs were first removed by hand and maize was cut with sickles. Fresh weight of harvested leaf and stem material (crop residues) was measured on site before being mechanically chopped to make mulch (Viking GB 460 C; STIHL Company m.b.H., Austria). Fresh vetch and maize mulch was applied to mulch treated soils immediately after harvest at 9.7 kg (2.7 t dry mulch ha^{-1}, or 1.0 t C ha^{-1} and 0.7 t N ha^{-1}) and 6.6 kg (2.2 t dry mulch ha^{-1}, or 1.0 t C ha^{-1} and 0.3 t N ha^{-1}) per plot, respectively, in their associated treatments. Soils that were not treated with mulch were left bare during fallow periods.

A subsample of annual harvested mulch was also dried at 65 °C to record the dry weight to calculate plant yield (tons dry biomass per hectare) and was then submitted for C and N analysis. Mean C and N concentration of maize and vetch mulch was 0.44 ± 0.002 g C and 0.012 ± 0.0004 g N and 0.38 ± 0.008 g C and 0.025 ± 0.0001 g N per gram of mulch, respectively. In 2017, after five years of crop production with or without mulch treatments, five 2.5 cm diameter soil cores were collected from each plot and 0–5 cm and 5–15 cm soils were placed on ice for transport back to the laboratory for further soil sample processing and analysis of C and N.

2.2. Greenhouse mesocosm experiment

A similar study as that described in the field experiment was performed in a controlled greenhouse setting to determine the direct effect of mulch on soils with consistent soil moisture. This was done using two soils, the Cambisol from the field experiment as well as another Austrian Chernozem with relatively higher organic matter concentration to determine if soil response to mulch treatments was consistent regardless of the quality of organic matter. The second soil was collected from the International Atomic Energy Agency Laboratories experimental fields in Seibersdorf, Austria (47°58′ N, 16°30′ E). The site was also originally dominated by C_3 native grasses, has a mean annual precipitation range of 400–500 mm (Kilk and Konecny, 2013) and the soil is characterized as a haplic Chernozem (IUSS-WRB, 2014) with a pH of 6.8, and inorganic C as $CaCO_3$.

Topsoils from 0 to 30 cm were collected in 2012 from the Cambisol and Chernozem field sites, homogenized and sieved to 4 mm. Mesocosms with a 49 cm diameter were then filled with soils to a height of 70 cm with a bulk density of 1.4 g cm^{-3} and were set up in three blocks with four mesocosms per block in a greenhouse. Each mesocosm contained either the Cambisol or Chernozem soil and was used to produce an annual soybean-maize rotation with or without mulch, with 3 replicates per soil type and mulch treatment following a randomized complete block design (Fig. 2). Soybean (*Glycine max* (L.) Merr, a C_3 legume species) and maize (*Zea mays* L., a C_4 species) were grown annually in rotation with 16 soybean planted in April and one maize planted in June in each mesocosm. Due to logistical reasons, we only focused on a legume-maize rotation and did not include mesocosms with sole maize or legume monocrops. Additionally, soybean was used instead of vetch due to the smaller size of the mesocosms compared to field plots. Similar to the field experiment, fertilizer was applied when soybeans were first planted at 50 kg P ha^{-1} (as triple superphosphate) and at 120 kg K ha^{-1} (as K_2SO_4) and at 43 kg P ha^{-1}, 190 kg K ha^{-1} and 120 kg N ha^{-1} (as urea) at the time of maize planting. Soil moisture was