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Effect of long-term tillage treatments on the temporal dynamics of water-stable aggregates and on macro-aggregate turnover at three German sites

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ABSTRACT

The protection of organic material within aggregates against microbial decomposition is regarded as an important process in soil organic carbon stabilization but detailed knowledge about this process is still lacking. The objective of our study was to determine the longer and short-term impacts of three different tillage treatments (conventional tillage, mulch tillage and no-tillage) on water stable aggregate size distribution. Soils from three sites with long-term tillage trials on loess soils in Germany, planted with sugar beet followed by two years of winter wheat, were sampled in 0–5 cm, 5–25 cm and 25–40 cm depth in April 2010 (wheat stand on all sites), September 2011 (before tillage, after wheat harvest or in the sugar beet), November 2011 (bare soil after tillage or after tillage and sowing of winter wheat) and April 2012 (bare soil or wheat stand). Generally, the soils under no tillage and mulch tillage showed higher yields of macro-aggregates and carbon contents of macro-aggregates in 0–5 cm soil depth than under conventional tillage for all sampling dates, probably mainly due to litter accumulation in the topsoil under reduced tillage treatments. Tillage in November 2011 showed no effect on macro-aggregate yield in comparison to earlier sampling in September 2011. This suggests that either the physical impact of the mouldboard plough did not markedly affect macro-aggregate dynamics or that high macro-aggregate rebuilding rates due to litter incorporation and soil mixing under conventional tillage counterbalanced the physical impact. In 0–5 cm soil depth the carbon content of the micro-aggregates within macro-aggregates was higher under reduced tillage treatments, indicating accelerated macro-aggregate turnover under conventional tillage. In contrast, it was lower in 5–25 cm under no tillage and 25–40 cm under mulch tillage and no tillage than under conventional tillage. Overall, the pattern of yields of macro-aggregates and carbon contents within macro-aggregates over time and depth suggests that the interaction of soil disturbance and litter incorporation of the different tillage treatments created a steady state in terms of macro-aggregate turnover within the different tillage treatments.

1. Introduction

Increased C sequestration in soils may provide several ecosystem services related to higher carbon contents such as retention of nutrients and water, prevention of erosion and increased soil biodiversity (Christensen, 2001; Janzen, 2004; Lal and Kimble, 1997).

Aggregate formation in soils is considered to be an important process in soil organic carbon (SOC) stabilization (Alvaro-Fuentes et al., 2009; Lützow et al., 2006; Tisdall and Oades, 1982) and can be influenced in agricultural soils by litter input, type of litter, tillage and crop rotation (Balesdent et al., 2000; Grandy and Robertson, 2007; Malhi et al., 2008; Samahadthai et al., 2010). Micro-aggregates (<250–53 μm) are formed within macro-aggregates (>250 μm) (Golchin et al., 1994) as demonstrated by Angers et al. (1997) who traced $^{13}C^{15}N$-labelled wheat straw into macro- and micro-aggregates under field conditions. With time, the binding agents in macro-aggregates degrade, resulting in a breakdown of the macro-aggregates and release of micro-aggregates, which become the building blocks for the next cycle of macro-aggregate formation. Micro-aggregates are much less susceptible to external influences than macro-aggregates (Barbera et al., 2012; Christensen, 2001; Oades, 1988; Six et al., 2000). Several researchers have concluded that declining SOC contents and declining contents of macro-aggregates in arable soils are caused by physical disruption of carbon-rich macro-aggregates due to tillage and the exposure of previously protected organic material to microbial decomposition processes (Balesdent et al., 2000; Cambardella and Elliott, 1993; Mikha and Rice, 2004; Six et al., 2000; Tisdall and Oades, 1982; Zotarelli et al., 2007).

Conventional tillage (CT) has been reported as a cause for macro-aggregate disruption in comparison to no-tillage (NT) treatments, the latter yielding a greater content of macro-aggregates (Alvaro-Fuentes et al., 2008a; Oorts et al., 2007a; Tan et al., 2007; Zotarelli et al., 2007). Further, increased CO_2-evolution rates were measured after tillage events in situ (Alvaro-Fuentes et al., 2007; La Scala et al., 2008; Morell et al., 2010) as well as under simulated conditions during incubation

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studies (De Gryze et al., 2006; Plante and McGill, 2002b). This provided some evidence that tillage causes physical disruption of macro-aggregate structures and increased decomposition rates of former incorporated organic material. However, apart from aggregate disruption, tillage also influences aggregate size distribution in arable soils by several interacting factors. For instance, CT influences the gravimetric moisture content, there being lower values after tillage (Hermawan and Bomke, 1997), which in turn affects soil aggregation (Yoo and Wander, 2008). Furthermore, tillage management directly affects soil mixing and litter distribution within the soil layer. The litter may be mainly concentrated on the soil surface under NT or distributed relatively evenly within the plough layer under CT (Alvarez, 2005; Luo et al., 2010; Morell et al., 2010), which influences the decomposition rates (Coppens et al., 2006; Oorts et al., 2007b) and microbial activity (Bossuyt et al., 2002) in different soil depths. Moreover, the mulch layer under NT offers some protection against rainfall (Alvaro-Fuentes et al., 2008b) and freeze/thaw cycles during winter (Layton et al., 1993), and during the growing season aggregation is affected by root growth (Alvaro-Fuentes et al., 2008b; Denef et al., 2002; Plante and McGill, 2002a).

Increased SOC contents in surface soils under NT systems may not only exist due to higher contents of carbon-rich macro-aggregates, but also due to reduced rates of macro-aggregate turnover under NT compared to CT systems (Alvaro-Fuentes et al., 2009; Plante and McGill, 2002b; Six et al., 2000; Zotarelli et al., 2007). Six et al. (2000) suggested that slower macro-aggregate turnover may promote the formation of stable micro-aggregates within macro-aggregates, which in turn leads to a long-term SOC stabilization. The micro-aggregate associated SOC content occluded within macro-aggregates may serve as an indicator for management-induced changes in macro-aggregate turnover and C stabilization (Denef et al., 2004; Kong et al., 2005).

Up to now, insufficient field data have been available that quantify the direct impact of tillage both on macro-aggregate content directly after tillage and on macro-aggregate turnover. An understanding of these effects is essential for questions regarding the relationship between aggregation and soil SOC stabilization (Alvaro-Fuentes et al., 2009; Denef et al., 2007).

The objective of our study was to investigate the effects of CT in relation to reduced (mulch tillage, MT) and NT treatments on temporal changes in water stable aggregate distribution and on macro-aggregate turnover in three different long term tillage trials with almost identical experimental setups.

2. Materials and methods

2.1. Experimental sites

In the 1990s three commercial fields, cultivated by the agricultural division of the Südzucker AG Mannheim/Ochsenfurt, were selected for the establishment of a series of long-term soil tillage experiments. The sites, namely Friemar and Luettewitz (both established in 1992/93) and Zschortau (established in 1997/98), are located in arable loess regions of eastern Germany. Annual precipitation ranges from 512 to 572 mm and the mean annual temperature from 7.8 to 8.8 °C (Table 1). The soils are Phaeozem (Friemar) and Luvisols (Luettewitz and Zschortau). Silt is the dominant size fraction in the soils and decreases in the order Luettewitz (78%) > Friemar (65%) > Zschortau (56%) (Table 1). Additional information on the sites and the experimental setup are given in Koch et al. (2009).

During the study period from 2010 to 2012, the gravimetric moisture contents (averaged for the four sampling dates, in %, mean values of the three sites ± standard errors) of the different tillage treatments ranged from 13 ± 2 to 20 ± 2 under CT, from 15 ± 2 to 24 ± 4 under MT and from 15 ± 1 to 24 ± 2 under NT. The bulk densities in the three different depths (averaged for the four sampling dates, mean values of the three sites and ±standard errors) of the different tillage treatments ranged from (1.1 ± 0.0) g cm^{-3} to (1.4 ± 0.0) g cm^{-3} under CT, from (1.0 ± 0.1) g cm^{-3} to (1.5 ± 0.0) g cm^{-3} under MT and from (1.0 ± 0.1) g cm^{-3} to (1.5 ± 0.0) g cm^{-3} under NT.

2.2. Crop rotation and management

The same crop rotations were set up at each site, which consisted of sugar beet (*Beta vulgaris* L.) – winter wheat (*Triticum aestivum* L.) – winter wheat. The crop rotations for the three sites from 2010 to 2012 were: Friemar and Luettewitz: winter wheat–winter wheat–sugar beet, and Zschortau: winter wheat–sugar beet –inter wheat.

One large field per site was divided into three different tillage-plots with the following tillage treatments per plot:

(i) CT with annual mouldboard ploughing to 25–30 cm,
(ii) MT with a cultivator or disc harrow 10–15 cm deep, and
(iii) NT with direct drilling.

Due to higher demands in seedbed quality in the NT treatment, a 3–5 cm deep cultivation was carried out before sugar beet sowing.

In all treatments, the crop residues remained on the field and the crop management, including the use of pesticides, was carried out following the regional standards of agricultural practice. The different treatments at each site were fertilized equally but the nitrogen fertilization varied between the sites and ranged from 50 kg N ha^{-1} in Luettewitz (wheat in 2011) over 69 kg N ha^{-1} in Friemar (wheat) to 191 kg N ha^{-1} in Zschortau (sugar beet) in the year 2011.

2.3. Soil sampling

Sampling took place on four different dates from April 2010 to April 2012:

(1) April 2010 (wheat stand on all sites),
(2) September 2011 (before tillage, after wheat harvest in Friemar and in the sugar beet stand in Luettewitz and Zschortau),
(3) November 2011 (bare soil after tillage in Friemar or after tillage and sowing of winter wheat following sugar beet in Luettewitz and Zschortau), and
(4) April 2012 (bare soil before sugar beet planting in Friemar and in the wheat stand in Luettewitz and Zschortau).

The four sampling dates allowed us to evaluate both longer term (April 2010 and 2012) and short term (Sept 2011, before tillage vs. Nov 2011, after tillage) effects of tillage on aggregation dynamics.

Three subsamples were taken from every plot per site. Each subsample consisted of a composite sample from three soil cores, taken with a core sampler of 8 cm in diameter. Samples were taken from 0 to 5 cm, 5–25 cm and 25–40 cm soil depths.

Table 1
Site characteristics, pH ($CaCl_2$) and texture are mean values of the three treatments per site with standard error in brackets (n = 3), soil data refer to the 0–25 cm depth.

Site	Year trial started	Soil type	Mean annual temperature (°C)	Annual precipitation (mm)	pH ($CaCl_2$)	Sand (%)	Silt (%)	Clay (%)
Friemar	1992/93	Haplic Phaeozem	7.8	517	7.1 (0.14)	5 (1)	65 (3)	31 (3)
Luettewitz	1992/93	Haplic Luvisol	8.6	572	6.7 (0.18)	12 (1)	78 (2)	14 (2)
Zschortau	1997/98	Gleyic Luvisol	8.8	512	7.1 (0.1)	28 (2)	56 (1)	16 (1)