AGGREGATE STABILITY AND AGGREGATE-ASSOCIATED CARBON IN NO-TILL AND REDUCED TILLAGE PRACTICE IN FINLAND

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Abstract

No-till (NT) and reduced tillage (RT) treatments can potentially enhance soil organic carbon (SOC) stabilization and soil aggregation. The turnover rate of SOC is affected by soil aggregate stability and the distribution of SOC across different aggregate-associated soil fractions. Carbon turnover rate slows down when soil aggregation increases and C is protected within stable microaggregates (53–250 µm). We studied the long-term (~10 yrs) effect of NT and RT practice on SOC stabilization in four soils typical for the boreal region. Distribution of SOC in different soil fractions was analyzed by wet sieving and further isolating microaggregates (mM) from large (>2000 µm, LM) and small (250–2000 µm, sM) macroaggregates. Aggregate stability decreased in the order of NT > RT > CT at all study sites. A general trend of redistribution of SOC was found at all study sites, i.e., the LM fraction gained SOC whereas the sM fraction lost SOC under NT compared to CT, while three out of the four sites did not show any significant changes in total SOC content under NT compared to CT. Our results show no increase in the amount of mM fraction in NT practice. On the other hand, our hypothesis that there would be more SOC incorporated in mM fraction in NT and RT treatments compared to CT practice was corroborated at three of the four study sites. Overall, our results indicate that the potential to accumulate SOC under NT or RT compared to CT is limited in boreal agroecosystems.

Keywords: no-till; reduced tillage; microaggregates; soil aggregation; C sequestration

Introduction

The increasing amount of CO_2 concentration in the atmosphere has led to an increased interest in mitigating greenhouse gas emissions while maintaining sustainable agricultural production. The amount of CO_2 released to the atmosphere from agricultural soils is mainly dependent on the rate of soil organic carbon (SOC) formation versus decomposition (1). This key role in the soil-atmosphere carbon cycling makes preservation of SOC an essential component of sustainable cropping systems. Minimum tillage practices, including no-till (NT) and reduced tillage (RT) practices, have received attention due to their ability to increase C sequestration in agricultural soils by increasing aggregate stability (2). This has been found especially in the tropics (3, 4) and temperate regions of the world (5). According to Freibauer et al. (6), the potential for NT and RT management practices to sequester SOC in European (EU15) agricultural soils is 0.3–0.4 ± 0.1 Mg C ha^{-1} $year^{-1}$ and < 0.4 Mg C ha^{-1} $year^{-1}$, respectively, which are in the same range as the estimate of 0.2–0.4 Mg C ha^{-1} $year^{-1}$ for conservation tillage practices reported by Watson et al. (7) for Australia, USA and Canada. Conventional tillage (CT) on the other hand is considered a practice that enhances losses of SOC (8, 9, 10). It has been suggested that the increase in total SOC under NT is a result of two driving factors 1) a greater amount of C-rich macroaggregates under NT treatment and 2) a reduced rate of macroaggregate turnover (11). Microaggregates within macroaggregates (mM) are a crucial part of long-term sequestration and storing of SOC (11, 12). Denef et al. (13) found that over 90% of the difference in SOC content between CT and NT management practices was associated with mM fractions in different soils types ranging from temperate to tropical region of the world.

Farmers in Finland have been widely and rapidly converting to NT cropping systems in recent years with 14% of cereal crop production area already being under NT (14). The objectives of this study are to gain better understanding about the changes in the soil C dynamics between different agricultural practices in the boreal region. We hypothesized that 1) NT and RT soils would have more macroaggregates and 2) there would be more stable microaggregates within macroaggregates in NT and RT soils and 3) these microaggregates would have more SOC incorporated compared to CT soils.

Material and Methods

Differences in soil aggregation and C content were determined in four pairs of tilled (CT) and no-till (NT) fields in southwestern Finland with the addition of a reduced tillage (RT) treatment at sites 1 and 2. Minimum tillage practices had been applied for a decade. Soils at sites 1-3 were classified as Vertic Cambisol and soil at site 4 as Eutric Regosol (15). In the CT plots, the soil was tilled to a depth no deeper than 20 cm and in the RT plots to about 10 cm once a year. A randomized balanced incomplete block design was used with four replicates of CT and NT treatments at all sites and an additional four replicates of RT treatment at sites 1 and 2. Soil texture and soil bulk density are shown in Table 1.

Table 1. Soil texture and soil bulk density between different management practices at all study sites.

Field	Treatment	Soil Texture (%)			BD[a]
		Clay (< 2 µm)	Silt (2–60 µm)	Sand (> 60 µm)	(g cm^{-3})
Site 1	CT	47.0	38.0	15.0	1.31
	NT	48.8	39.3	11.8	1.32
	RT	39.8	34.3	25.9	1.30
Site 2	CT	59.4	26.2	14.5	1.26
	NT	67.3	21.6	11.1	1.20
	RT	60.9	27.1	12.0	1.21[b]
Site 3	CT	48.2	46.9	4.9	1.26
	NT	48.6	46.4	5.0	1.34
Site 4	CT	19.1	67.2	13.7	1.29[b]
	NT	14.7	65.8	19.5	1.33

[a] 0-20 cm soil layer; from Sheehy et al. (16) [b]values from 2011

Soil samples were taken in October 2009 after harvest but before tillage operations at all study sites. The samples were taken to a depth of 20 cm. The aggregate size distribution was analyzed by wet sieving according to Elliot et al. (17). Before wet sieving, the field moist soil samples were sieved carefully through an 8 mm sieve and then air-dried. A subsample of 80 g was taken for the wet sieving process which was done through a series of three sieves that separated the samples into four different soil fractions; large macroaggregates (LM; >2000 µm), small macroaggregates (sM; 250–2000 µm), microaggregates (m; 53–250 µm) and silt and clay (s+c; <53 µm). Prior to wet sieving, the samples were submerged into deionized water on top of the 2000 µm sieve for a period of 5 min. The sieving was done manually and the fraction remaining on top of the sieve was collected and oven dried. Organic material floating on the water after sieving with the 2000 µm was discarded as it is not considered SOM by definition. The sieving was then repeated with the remaining sieves by pouring the water and soil from the earlier sieving through the next one.

Microaggregates within LM and sM fractions (mM) were further isolated with a method described in Six et al. (11). The goal of this method was to break down the macroaggregates while avoiding the breakdown of the released microaggregates. A combined subsample of 10 g was taken from LM and sM fractions and then put into deionized water on top of a 250 µm mesh and shaken in a reciprocal shaker with a continuous flow of running water with 50 stainless steel beads. The microaggregates and other released material went through the mesh screen with running water ending up on a 53 µm sieve that was sieved as in the wet-sieving method. This was continued until all the macroaggregates were broken down (2–3 min of shaking). As a result three different fractions were separated: coarse particulate organic matter (cPOM, > 250 µm), microaggregates within macroaggregates (53–250 µm) and silt and clay (< 53 µm).

The mean weight diameter (MWD) was calculated according to (18). Carbon content of all fractions from wet sieving and microaggregate isolation was analyzed with a CN-analyzer (CN-2000 LECO Corp., St Joseph, MI, USA). Because of smaller sample sizes, a few samples (13 out of 280) were analyzed using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK) which required less C for analysis. The SOC content of the different aggregates and the total C from the aggregates were calculated using the equivalent soil mass method according to Ellert and Bettany (19) and Lee et al. (20). Statistical differences in SOC content among separated soil fractions were analyzed using linear analysis of variance (ANOVA) with a significance level of p=0.05. PASW Statistics 18.3 was used for the statistical analyses of the data.

Results

Aggregate stability decreased after wet sieving in the order of NT > RT > CT at all study sites (Table 2). Statistically significant differences were found at site 1 and 4 between CT and NT (p=0.022 and p=0.000 respectively). The RT treatment did not significantly differ compared to CT. In general, aggregate stability was higher at sites 2 and 3, while the lowest values were found at site 4. Site 1 had a higher amount of total C in NT compared to CT with less aggregation compared to site 4 where total C was lower but a lot of macroaggregates were formed under NT. The amount of macroaggregates (M) was higher in NT compared to CT treatment at all study sites but a statistically significant difference was only found at site 4 (p=0.000). No significant difference in the amount of M was found in RT in comparison to CT. Small macroaggregates were the dominant physical fractions at sites 2 and 3 where sM fraction was more than half of the sample size (53% and 55%, respectively), whereas free microaggregates dominated at sites 1 and 4 occupying 47% and 65% of the soils, respectively. On the other hand, at site 4, microaggregates were the dominant fraction only in CT but macroaggregates were dominating under NT, whereas at sites 2 and 3, macroaggregates were dominating under both treatments. This suggests that soils at sites 2 and 3 were fairly stable compared to site 4 where NT greatly changed the aggregate balance of the soil. After microaggregate isolation, the mM fraction was the dominant fraction. In general, however, NT did not significantly increase the amount of mM fraction present in the soils compared to CT.

Table 2. Mean Weight Diameter (MWD) with standard error after wet sieving (Part A) and total C (Mg C ha^{-1} ± standard error) for all study sites.

Field	Treatment	MWD (mm) Part A	Total C (Mg C ha^{-1})
Site 1	CT	0.55 ± 0.07^{a}	57.3 ± 3.5^{a}
	NT	0.84 ± 0.10^{b}	61.2 ± 2.5^{a}
	RT	0.59 ± 0.06^{ab}	61.2 ± 2.8^{a}
Site 2	CT	1.36 ± 0.27^{a}	59.7 ± 1.3^{a}
	NT	2.10 ± 0.20^{a}	60.8 ± 0.6^{a}
	RT	1.36 ± 0.15^{a}	56.9 ± 1.2^{a}
Site 3	CT	1.20 ± 0.17^{a}	83.7 ± 3.9^{a}
	NT	1.58 ± 0.18^{a}	69.4 ± 4.1^{a}
Site 4	CT	0.28 ± 0.0^{a}	53.0 ± 0.3^{a}
	NT	0.58 ± 0.03^{b}	49.5 ± 1.5^{a}

*Statistically significant differences between management practices are indicated by lower case letters within each study site.

The total C stocks in the 0–20 cm soil layer did not differ between management practices (Table 2). This is in contrast to most studies finding that NT management stabilizes soil C. For example, increases in soil C under NT has been found in agricultural soils including Oxisols (12) and in integrated crop-livestock systems after intensifying agricultural land use (21).

On the other hand, some studies in the temperate regions of the world have shown that the positive effects of NT management may only be realized a decade after the transition (22). The difference between arid and humid regions was clearly shown in a data compilation in Canada where NT practice increased soil C stock only in the west (23). Cool and humid climatic conditions may also prevent SOC depletion under CT (24, 25). The amount of crop residues stratified in the topsoil in NT might accelerate microbial activity (26) and decomposition rate, which leads to SOC losses (27). Angers et al. (28), however, suggested that the decomposition rate of crop residues incorporated deep into the soil slows down under CT due to limited aeration under cool and humid climatic conditions. Our results show a very low total C content for the coarse soil of site 4 compared to the other study sites which might be explained by the different soil type. Clayey soils usually have better water holding capacity which is supported by the results reported in Sheehy et al. (16) where WFPS was higher especially at site 2 compared to site 4. This implies that the overall potential for site 4 to accumulate SOC is smaller compared to the other study sites since lower soil moisture content affects the soils capacity to produce plant biomass. The changes in aggregation and the amount of C stored by the mM fraction at site 4 in NT, however, indicate a potential to store SOC.

Enrichment of SOC was observed in the LM fraction at all study sites with statistically significant differences at sites 1, 2 and 4 ($p=0.009$; $p=0.036$; $p=0.001$ respectively) (Fig. 1A). On the other hand, this effect was diluted at some sites by a loss of SOC in the sM fraction with a statistically significant depletion at site 3 ($p=0.023$). This suggests that a lot of the action after transition to NT happens in the LM fraction. This could mean that especially the clayey soils in Finland already have a fairly stable soil structure. High SOC content of clayey soils is also generally acknowledged (29). Agroecosystems under NT may also experience reduced yields which may in turn negatively affect C sequestration rates (30, 31). Reduced yields were found at sites 1, 2 and 3, where the average yield since transition have been 4%, 12% and 22% lower, respectively under NT compared to CT (results not shown). This might be one of the key factors affecting SOC depletion in NT, especially at site 3. Furthermore, every agroecosystem has its own equilibrium SOC stock and therefore a limit to sequester added C (32). Long-term studies have shown that soil C stock does not always increase with higher C inputs (33, 34) and the efficiency to stabilize SOM decreases in soils with high C levels compared to soils with lower C levels under the same management practices (35, 36). It is possible that the clayey soils of sites 1–3 have a low saturation deficit and therefore less potential to accumulate SOC.

According to Denef et al. (13), the mM fraction serves as a good indicator for C sequestration in NT systems. Significantly more C in the mM fraction was also found in their later study (12), supporting the potential for the mM fraction to sequester C in the long-term. In contrast, our results show no increase in the amount of mM fraction in NT practice. On the other hand, there was more SOC incorporated in the mM fraction in NT and RT compared to CT at sites 1, 2 and 4 (Fig 1B). There were no statistically significant changes at site 3. However, site 3 had relatively the largest amount of mM fraction within M (g mM fraction g^{-1} M) with 63 % in CT and 64 % in NT treatment but at the same time was the only site with a decreasing trend in the SOC content when transitioning from CT to NT treatment. Relatively the highest mM per g of macroaggregates was found at site 4 in comparison to the other sites. This would indicate towards a higher potential for soil aggregation and accumulation of SOC in NT treatment at this site.

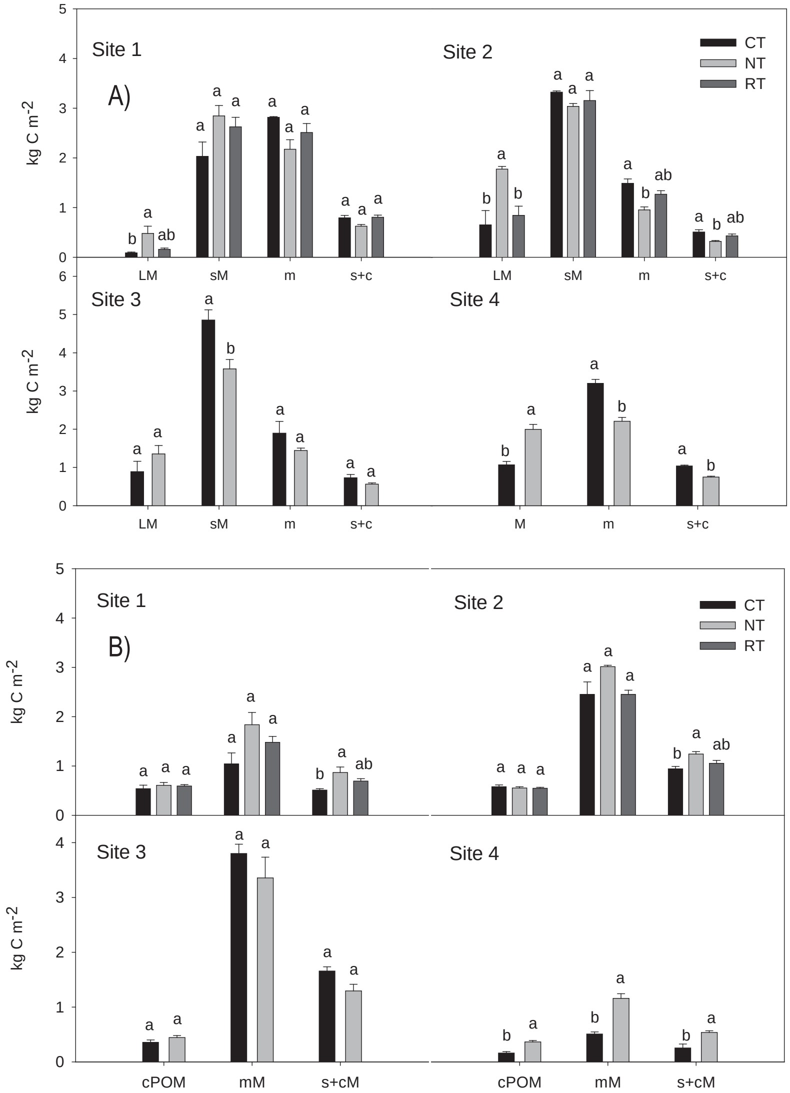

Figure 1. A) SOC content (kg C m^{-2} ± standard error) of large macroaggregates (LM), small macroaggregates (sM) (M = LM+sM), microaggregates (m) and silt and clay (s+c) in conventional tillage (CT), no-till (NT) and reduced tillage (RT) treatments. B) SOC content (kg C m^{-2} ± standard error) of coarse particulate organic matter (cPOM), microaggregates within macroaggregates (mM) and silt and clay within macroaggregates (s+cM) in CT, NT and RT treatments.

Conclusions

The results emphasize that aggregate stability and aggregate-associated C play an important role in determining the long-term C sequestration potential of agroecosystems in Northern European boreal climate. According to these results the aggregate stability is enhanced in NT cropping systems compared to CT or RT. However, the total amount of SOC did not increase under NT or RT management for a decade. Three of the studied sites had lower crop yields in NT resulting in decreased amount of C inputs and clayey soils likely close to the saturation point. These factors may have impacted the ability of NT management to increase SOC accumulation. However, NT practice was able to increase the amount of SOC in microaggregates within macroaggregates in the coarse soil underlining a potential for future C accumulation in this soil type.

Our results show a limited potential for minimum tillage practices to enhance SOC sequestration in agriculture in the boreal region.

Acknowledgements

This study was funded by Maj and Tor Nessling Foundation, Finland and MTT Agrifood Research Finland and done in cooperation with University of Helsinki, Finland and University of California, Davis, USA. Many thanks to the staff of MTT and the personnel of Johan Six Lab at UC Davis for all the support and advice throughout the process. Special thanks to Pauline Chivenge and Robert Russeau for valuable advice in the laboratory. The staff of the research center of Yara Finland, and the farmers Timo Rouhiainen and Ilmari Seppälä are greatly appreciated for giving us the chance to use their experimental fields as a part of this study.

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