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Relative importance of organic carbon, land use and moisture conditions for the aggregate stability of post-glacial clay soils

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ABSTRACT

Erosion and colloidal particle loss from cultivated clay soils in cool humid climate pose a risk to soil productivity and surface water quality. To enhance soil management practices that effectively reduce clay soil erosion, we need to understand the interrelations between the key variables on which clay soil aggregate structure depend. The objective of our study was to quantify the relative importance of OC content, land use and soil wetness, for the aggregate stability of post-glacial clay soils. We estimated the potential effect of five different land uses (cereal cropping with variable tillage and crop rotation, permanent grassland and forest as a control) on clay soil aggregate stability as measured by the percentage of water-stable aggregates (WSA% of 2–5 mm fraction) and colloid detachment (turbidity, NTU%), after controlling for the differences in organic carbon content (OC%) and Clay%/OC% ratio between the land uses through covariance analysis. Further, we assessed how aggregate structure in differently managed soils with different OC% tolerates the varying moisture conditions. The higher OC% was reflected in all cultivated soils by increased aggregate stability, implying that OC inputs may positively affect soil structure even in low additions. When compared at equal OC%, the mean WSA% was lower in cereal cropping than in soils under forest or permanent grass, clearly showing the negative effect of tillage frequency on the aggregate stability. The detachment of colloidal particles from aggregates was higher in soils with a high Clay%/OC% ratio, and thus the Clay%/OC% ratio may offer an easily measurable indicator for the risk of clay dispersion, and thereby soil erosion and the export of particle-bound nutrients from cultivated fields. When compared at an equal Clay%/OC% ratio, colloid detachment from aggregates representing cereal fields was two- to threefold as compared to permanent grassland. Cultivated soils with less than 4–6% OC were very sensitive to waterlogging, highlighting the role of proper drainage in erosion control. The results demonstrate that an increase in OC content and proper drainage would help to improve the aggregate stability of cultivated clay soils in cool humid climate, but the effective improvement of the present situation would require drastically reduced soil disturbances for areas with the highest erosion risk.

1. Introduction

Soil erosion leads to loss of fertile soil from agricultural fields, carries phosphorus (P) to water bodies and is an indicator of poor structural stability. To prevent the degradation of both agricultural land and surface waters, several methods to reduce soil loss through runoff have been adopted. Common ways of protecting the soil surface are increasing the soil cover with straw or by, using catch crops in winter (Bechmann et al., 2005; Stevens and Quinton, 2009) or by reduced tillage and no-till (Puustinen et al., 2005; Richardson and King, 1995). The effectiveness of these methods is highly variable and may depend on prevailing conditions. Surface cover alone may not be as effective in reducing soil erosion in gently sloping areas with low rainfall intensity and high clay content in the soil as it is in areas with high rainfall intensities and steeper slopes (Turtola et al., 2007). Along with the cover, an essential part of erosion control would be to recognize the soil properties and managements that increase the aggregate stability of the topsoil surface and thus reduce the detachment of colloidal particles when exposed to rain or runoff.

Macro aggregates and their stability are an integral part of the soil structure, affecting both agronomic productivity and the environmental risks of crop production. It is generally believed that clay soils will develop favorable structure, as a minimum clay

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content of 15% is needed for the abiotic development of the aggregate structure (Oades, 1993). However, the risk for clay dispersion increases at high clay contents (Kjaergaard et al., 2004; Schjønning et al., 2012). Similarly, soil organic matter (OM) is known to play a crucial role in soil structure formation and aggregate stability (Abid and Lal, 2008; Chaney and Swift, 1984; Heinonen, 1955; Bissonnais and Le Arrouays, 1997; Tisdall and Oades, 1982). Although the post-glacial soils of Northern Europe have a relatively high OM content, a continuous reduction of organic carbon (OC) content of cropland soil has been detected (Heikkinen et al., 2013). In addition to changes in OC content, aggregate stability in cultivated soils is affected by mechanical disturbances due to agricultural management (Abdollahi et al., 2014; Wang et al., 2015; Watts et al., 1996), and Schjønning et al. (2012) suggested that agricultural management (e.g., tillage) may be as decisive for soil structural strength as the depletion of OC.

The present warming of the winter season in northern climates exposes soils more frequently to wetness and winter runoff. At higher soil water contents aggregate stability is lowered (Coote et al., 1988; Rasiah et al., 1992) and mild winters with frost-free soil and little snow have been reported to lead to increased erosion (Puustinen et al., 2007). Furthermore, the breakdown of aggregate structure may lead to surface crusting, reduced infiltration and lower water conductivity (Agassi et al., 1981; Dexter, 1988; McIntyre, 1958; Shainberg et al., 1992)—consequences that further enhance the future risk for the formation of saturated conditions. To find indicators for aggregate stability and the associated erosion risk, and to enhance soil management that effectively reduces clay soil erosion, knowledge is needed on the interrelations between the key variables that are essential for clay soil aggregate structure in cool humid climate.

The objective of our study was to quantify the relative importance of OC content, land use and soil wetness, in their practical ranges for the aggregate stability of post-glacial clay soils. We aimed to discover the importance of change in OC content as the causal mechanism in producing differences in aggregate stability between land uses. The differences in aggregate stability disappearing after adjustment by OC content would suggest the land use differences to simply be a reflection of the differences produced by the OC content. The results enable to evaluate whether the lowered aggregate stability of soil under intensive cereal production can be improved just by increasing the soil OC content with e.g., organic soil amendments or if it is also necessary to reduce the mechanical disturbance of soil to improve stability against erosion. Secondly, keeping in mind the impact of climate change, we aimed to find out how aggregate structure in differently managed soils and soils with different OC content tolerate the varying moisture conditions. The aggregate stability, measured as the share of water-stable aggregates (WSA%) and detachment of colloidal-sized particles (turbidity, NTU) of five alternative soil managements was studied, after controlling for their differences in OC% and Clay%/OC% ratio through covariance analysis. Further, to estimate the vulnerability of the alternatively managed soils to wetness, we exposed the aggregates to variable moisture conditions before measuring WSA% and turbidity.

2. Methods and material

2.1. Soil samples

The soil samples represented the following land uses: (1) forest soil (forest) as the control; (2) permanent grassland (grassland); (3) cereal cropping with no-till (no-till, cer); (4) cereal cropping with conventional tillage and grass in crop rotation (plough, cer/grass); (5) cereal monoculture with conventional tillage (plough, cer) (Table 1). The samples were collected in autumn 2010 from the uppermost 10 cm of the soil surface of 9000-year-old post-glacial clay soils of acidic rock origin in southwestern Finland, where field cropping has been performed, depending on the site, for approximately 70–500 years. Sampling locations were selected so as to include as many of the abovementioned five land uses as possible that were located near each other in a uniform landscape with the same parent material and relatively uniform clay percentage. In the area, the most common clay minerals are mica and chlorite, and the exchangeable cations are dominated by calcium (Ca) and magnesium (Mg) (>90%) (Sippola, 1974). Samples were collected using a spade from three points at each location and land use type and bulked to form one sample. The samples thus represented nine forest soils, eight permanent grasslands, six no-till cereal fields, six conventionally tilled fields with grass in crop rotation and six conventionally tilled cereal monocultures (Supplementary material 1). The studied sites had never been irrigated. According to our knowledge, eight of the nine forest sites had never been under agriculture and at the time of sampling the age of the current tree stand (mostly spruce with some deciduous trees) was over 60 years. One forest site was previously a field edge and the tree stand (mostly deciduous) was only 15 years old. The age of permanent grassland sites varied from 8 to 50 years (management before the prevailing grassland included ploughing) and no-till from 4 to 32 years. The ploughed fields with or without grass in crop rotation had mostly the same cropping history for over 20 years. However, the time from the last grass year varied between 0 and 8 years in the former case, and the duration of the grass varied between 2 and 6 years.

In the laboratory, the field-moist clay soil samples were gently broken apart by hand, all visible plant material and roots were removed and the soil samples were homogenized as field moist. Each sample was weighed and a sub-sample was taken for the moisture content analysis. A part of the homogenized sample was air-dried and used for particle-size analysis (Elonen, 1971) and total carbon (TC) measurement (dry combustion with a VarioMax CN analyzer). While the soils were very low in carbonates, TC is assumed to be representative of the total OC. We also measured pH and electrical conductivity (1:2.5$_{H_2O}$).

The clay and silt content, electrical conductivity, pH and OC content in the soils varied between 28 and 79%, 15–63%, 0.06–

Table 1
The number (n) of sampled sites, arithmetic means and ranges for the selected properties of sampled soils under five land use types (forest, permanent grassland, no-till in cereal production, ploughing in cereal production with grass in rotation and ploughing in cereal monoculture).

		Clay		OC		Clay%/OC%		pH		EC	
	n	%	Range	%	Range		Range		Range	dS m^{-1}	Range
Forest	9	50	28–71	7.6	3.4–11.6	8	2–16	5.5	4.5–6.7	0.12	0.08–0.16
Grassland	8	58	41–79	4.3	2.6–7.3	15	9–27	5.8	5.1–6.7	0.11	0.06–0.16
No-till, cer	6	57	38–77	3.7	2.9–5.0	16	12–20	5.8	5.2–6.3	0.10	0.08–0.13
Plough, cer/grass	6	53	42–63	3.5	2.8–4.6	15	12–18	6.0	5.5–6.7	0.09	0.08–0.12
Plough, cer	6	60	40–74	4.3	2.3–8.3	15	9–20	6.1	5.7–6.6	0.10	0.07–0.14