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Consolidation and surface sealing of nine harrowed Swedish soils

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ABSTRACT

The structure of agricultural topsoils varies considerably throughout the year due to interactions between climatic and biological factors and agricultural management practices. Tillage generally decreases soil density and increases macroporosity, but the resulting arrangement of clods and aggregates is unstable and the soil eventually reverts back to its denser pre-tillage condition. Accounting for post-tillage changes in soil structure and related hydraulic properties could greatly improve model predictions of hydrological and transport processes. Model testing, development and parameterization is, however, currently hampered by a lack of direct measurements of the changes occurring in the structural pore system. We subjected repacked samples of soil collected from the harrowed layer of nine different fine- and medium-textured Swedish mineral soils to subsequent wetting and drying cycles in the laboratory. Initial wetting and equilibration at −30 cm pressure potential was followed by three cycles of simulated rainfall (5 mm h^{-1} for 4 h) and equilibration. X-ray tomography was used to quantify changes in surface and total porosity, pore size distribution (PSD) and connectivity of structural pores.

Total porosity decreased (by 2–24%) in all soils except for two clay soils where in one case the porosity increased slightly (3%) and remained unchanged in the other. In six of the soils, the PSD shifted significantly towards smaller pore sizes, and in four of these soils the connectivity of the pore network decreased. Soil surface porosity decreased most markedly in two silt loam soils (by 73% and 75%). For the nine soils changes were strongly correlated with silt content. Only weak correlations were found between the changes in total porosity and soil texture and organic carbon content. Changes in the PSD appeared to be mainly controlled by the initial structure of the sample created at the time of tillage and sample preparation.

1. Introduction

Tillage is performed to create favourable conditions for crop growth, water infiltration and gas exchange by reducing soil density and increasing macroporosity, but the resulting loose arrangement of soil clods and aggregates is unstable and the effect is thus transient. With time, the soil reverts back to its denser pre-tillage conditions due to cycles of wetting and drying under natural rainfall or irrigation (Ahuja et al., 2006; Franzluebbers et al., 1995; Mapa et al., 1986; Onstad et al., 1984). Various processes of aggregate destabilization upon wetting and the disruptive forces of drop impact also cause surface sealing and crust formation on soils with low aggregate stability (Assouline, 2004; Gronsten and Borresen, 2009; LeBissonnais, 1996). Structural changes due to sealing and consolidation occurring at or close to the soil surface may have large effects on soil hydraulic and transport properties and severely reduce infiltration rates (e.g. Alletto and Coquet, 2009; Fohrer et al., 1999), thereby both increasing the risk of generating surface runoff and affecting flow and transport processes in the soil.

Accounting for temporal variability in the hydraulic properties of tilled soil layers could, as indicated by Xu and Mermoud (2003), Schwen et al. (2011a) and Alletto et al. (2015), improve model predictions of soil water dynamics as well as related processes such as contaminant transport, nutrient cycling and plant growth. Whereas soil surface sealing has been extensively investigated and a large number of models have been suggested (reviewed by Assouline, 2004), relatively few attempts have been made at modelling the post-tillage structural changes associated with soil consolidation, presumably largely owing to the complexity of the processes involved. A mechanistic model describing the coalescence (deformation under plastic conditions) of soil aggregates as driven by the capillary forces generated during cycles of wetting and drying has been presented by Ghezzehei and Or (2000) and Or and Ghezzehei (2002). In this model, where soil rheological properties control the rate of changes as well as the onset and cessation of consolidation, swelling/shrinking and slaking due to rapid wetting are assumed to be negligible. Or et al. (2000) have also suggested a

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stochastic modelling framework for describing post-tillage changes in the pore size distribution (PSD), in which the Fokker-Planck equation is used to account for decreases of the median pore diameter and changes in the variance of the PSD, as well as reductions of total porosity. The advantage of such an approach is that the processes driving the structural changes don't need to be explicitly known and modelled. Application for predictive purposes however requires a robust method for estimating the values of the empirical coefficients that control the rate by which the features of the PSD change. Another relatively simple model is the empirical equation originally developed by Onstad et al. (1984) which describes the successive post-tillage decrease in porosity as a function of cumulative rainfall amount. Variations of this equation are implemented in the soil erosion prediction models EPIC (Williams et al., 1984) and WEPP (Alberts et al., 1995) and in the agricultural systems model RZWQM (Hanson et al., 1998). However, the evaluation and parameterization of these existing models and the development of new and improved models is currently hampered by the lack of direct measurements of post-tillage soil consolidation and sealing. A large number of studies have measured changes in topsoil hydraulic properties on soils spanning from coarse to very fine textures (among many Alletto and Coquet, 2009; Das Gupta et al., 2006; Mapa et al., 1986; Moret and Arrue, 2007; Mubarak et al., 2009; Schwen et al., 2011b) but to our knowledge very few studies have quantified changes occurring in the pore structure itself. One exception is Sandin et al. (2017) who used X-ray tomography to quantify post-tillage changes of soil pore space in the harrowed layer of a clay loam soil during one growing season in the field. However, in this study, temporal changes were to some extent obscured by the large spatial variability in the parameters describing the imaged pore space.

The aims of the present study were therefore to i) generate data on temporal variations in porosity, PSD (and related parameters such as the connectivity of the pore space) that could be used to develop, parameterize and test models of post-tillage soil consolidation of the harrowed layer and ii) investigate the effects of soil texture and organic carbon content on consolidation and surface sealing. To this end, we measured the structural changes occurring in samples collected from the harrowed layer of nine different fine- and medium-textured Swedish soils subjected to subsequent wetting and drying cycles in the laboratory. X-ray tomography was used to directly quantify changes in total porosity, the PSD and the connectivity of structural pores. We carried out repeated measurements performed on the same sample, thus overcoming the problem of distinguishing temporal variability from spatial variability (e.g. Bormann and Klaassen, 2008; Sandin et al., 2017).

2. Material and methods

2.1. Soils and sampling

Samples from the harrowed layer (0–6 cm depth) of 9 Swedish mineral soils (Table 1) chosen to cover a wide range of medium- and fine-textured soils were collected from five different sites (Röbäcksdalen, 63°48′N, 20°14′E; Ålbo, 54°55′N, 16°18′E; Ultuna, 59°49′N, 17°39′E; Säby 59°50′N, 17°42′E; and Krusenberg 59°43′N, 17°41′E;) in the spring of 2015. All sampled fields had been mouldboard ploughed to an approximate depth of 20–25 cm in the preceding autumn, and with the exception of one organically farmed field (soil CL II, see Table 1), they were all conventionally farmed. Since the soil in a newly harrowed layer is in a loose and fragmented state we did not consider it meaningful to take intact soil columns. The samples were, hence, taken with a garden spade. All samples were collected within 5 days after harrowing before any significant rainfall event had influenced the structure of the harrowed layer. Samples were stored in sealed plastic containers until the start of the experiments. Organic carbon contents were analysed by dry combustion (ISO 10,694) on a TruMac CN (LECO Corp.) and particle size distribution was determined by the pipette method.

Table 1
Properties of the nine soils investigated in this study. Samples were collected from the harrowed layer (0–6 cm depth)

Soil	Sampling location	Coordinates	Soil type (USDA)	Clay content (%)	Silt content (%)[a]	Sand content (%)	SOC (%)	Initial dry bulk density ($g\,cm^{-3}$)[b]	Initial (field) water content ($cm^3\,cm^{-3}$)[b]
Cl I	Säby	59°50′24″N; 17°42′7″E	Cl	57.3	38.5 (28.7)	4.2	2.4	0.95	0.17
Cl II	Ultuna	59°49′33″N; 17°39′34″E	Cl	54.0	26.1 (21.4)	19.9	1.5	1.21	0.10
Cl III	Ultuna	59°48′46″N; 17°39′9″E	Cl	50.7	37.6 (27.6)	11.7	1.2	1.10	0.13
SiClLo I	Säby	59°50′1″N; 17°42′8″E	SiClLo	35.1	58.8 (27.1)	6.1	3.3	0.92	0.20
ClLo	Krusenberg	59°43′60″N; 17°41′21″E	ClLo	33.7	32.4 (19.4)	33.9	1.4	0.98	0.20
SiClLo II	Säby	59°50′14″N; 17°42′35″E	SiClLo	32.2	58.2 (21.8)	9.6	2.5	0.93	0.20
SaClLo	Ultuna	59°49′24″N; 17°38′42″E	SaClLo	23.2	17.5 (11.7)	59.3	1.2	1.33	0.09
SiLo I	Ålbo	59°55′49″N; 16°18′33″E	SiLo	21.5	66.6 (52.8)	11.9	1.6	0.99	0.15
SiLo II	Röbäcksdalen	63°48′27″N; 20°14′21″E	SiLo	7.1	74.7 (25.8)	18.2	4.0	0.73	0.26

[a] % fine silt (2–20 μm) given within parenthesis.
[b] Average for three replicate samples.