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# Evaluation of temporal changes in hydrostructural properties of regenerating permanent grassland soils based on shrinkage properties and µCT analysis

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ABSTRACT

In this study, structural recovery of degraded cropland, which was converted to permanent grassland and managed under no-till and no-renovation condition, was evaluated. We combined hydrostructural parameters with shrinkage characteristics and X-ray computed microtomography (µCT) analysis at three depths, to determine the mechanism for soil structural recovery over a 19-year period. The results showed that the total porosity and hydraulic properties were improved, with the age of the regenerating grassland, due to a better rearrangement of soil particles which in combination with the shrinkage induced realignment of pores in the soil matrix, resulted in better pore continuity. Changes in hydraulic stresses were most pronounced in the intensely rooted soil layers with further enhancement of the soil structure during restoration. This was similarly observed in the reconstructed images, which further highlight the strong contribution from the root development and organic matter conversion to the improved pore networks. Our result also showed that ignoring the depth and time dependent shrinkage behaviour of within the soil matrix resulted in overestimation of water retention potential in the first 8 years since the commencement of the restoration programme, and in the underestimation of water retention in the structurally stable soil beyond this period The results from these combined analyses; allowed a more methodical, detailed, quantitative and qualitative assessment of temporal soil structural recovery in naturally recovering grassland soil.

## 1. Introduction

Tillage often affects soil's biological and physical quality negatively, with consequences on ecosystem processes and services. The extent of these damages has been increasing in last decades, due to repeated (and sometimes more frequent) field traffic with increasingly heavier machinery (Tilman et al., 2002; Bindraban et al., 2012; Šarapatka and Bednář, 2015). Thus, the rate of soil structure degradation worldwide has accelerated, with negative consequences on carbon sequestration and greenhouse gas (GHG) emission in agricultural soils (Chan et al., 2003; Lal, 2004; Mordhorst et al., 2014; Stavi and Lal, 2014). Also, more intense release of occluded organic material is being detected, while the problem of high flooding due to intense rainfall and impeded infiltration is occurring more often (Wiesmeier et al., 2012; Stavi et al., 2011; Linsler et al., 2013; Rogger et al., 2017).

To ameliorate degraded agricultural soils, several regenerative and naturally ameliorating methods are implemented, with the main aim of stimulating the structural re-development and reconsolidation of the soil layers. Methods, such as the conversion of degraded cropland into permanent grassland are noted to increase microbial biomass and soil productivity, as well as augment mineral-associated SOC concentrations in the recovering soils (Guo and Gifford, 2002; Schwartz et al., 2003; Don et al., 2009; Acharya et al., 2012; Lugato et al., 2014; Linsler et al., 2015). Also, the practice of zero tillage (no-till) on naturally ameliorating grasslands is expected to rapidly enhance the recovery of soil structure (Lal, 2004; Murugan et al., 2013; Ajayi and Horn, 2016), because there would be no further disruption during formation and strengthening of soil aggregates. Moreover, long term practice of no-till management could enhance the ability of soil to reduce the net global warming potential (GWP) (Cole et al.,1997; Six et al., 2004). In addition, seeding of such ameliorating permanent grassland with species that have diverse and niche complementarity, would influence the

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restoration timeline and improve ecosystem functioning (Tilman et al., 2001).

In order to appropriately conceptualise and represent soil's structural re-development processes, it is essential to correlate changes in the physical and mechanical properties with the hydraulic functions of the soil (Horn et al., 1995; Peng and Horn, 2005; Krümmelbein et al., 2006; Gregory et al., 2010). For instance, the extent of soil structure recovery at the different soil depths, depend on the hydraulic stresses concomitant with soil swelling and shrinkage, as a consequence of natural wetting and drying cycles. The swell-shrink process will largely moderate the interaction and rearrangement of soil particles and regulates the water content – pore water pressure relationships (i.e. water retention function) (Horn et al., 1995; Piccolo et al., 1997; Pires et al., 2007; Peng et al., 2010).

Typically, the swell-shrinkage behaviour in soils can be characterised by soil shrinkage curves (SSC), since the SSC represents the concomitant decrease in soil volume and water mass during drying and the shape of the SSC depends on soil structure and composition (organic and mineral) (Haines, 1923; Deeb et al., 2016). Therefore, appropriate analyses of SSC could provide pertinent indices of soil structural recovery in naturally ameliorating grassland soils (Braudeau et al., 2004; Bensallam et al., 2012), as it is similarly applied in the characterisation of soil structure degradation (McGarry and Daniells, 1987; Schäffer et al., 2008). During wetting due to rainfall, snowmelt or root exudation, "soil mellowing" (breakdown of massive clods or compacted depths) occurs, producing a friable aggregated seedbed (Dexter, 1991; Barzegar et al., 1995; Majdalani et al., 2008). With subsequent shrinkage during drying in the summer months, the pore system is expected to be reinforced, thereby increasing the soil strength (Barzegar et al., 1995; Baumgartl, 1998; Whalley et al., 2008; Alaoui et al., 2011). A more detailed description of the theory and application of soil shrinkage analysis in monitoring soil structural changes can be found in Braudeau et al. (2004), Peng and Horn (2005), Peng et al. (2007), Chertkov (2012) and Deeb et al. (2016).

Recent developments in X-ray computed microtomography (µCT) and quantitative image analyses (Peth et al., 2008; Peth, 2010), have made it possible to non-invasively investigate the time dependence of aggregate and soil structure development under changing natural boundary conditions (Garbout et al., 2012, 2013; Naveed et al., 2013; Pagenkemper et al., 2014) and particularly in grassland soils (Kuka et al., 2013). Using XRCT techniques in bauxite residues, Zhu et al. (2016) observed that by the implementation of natural regeneration process, stable aggregates and continuous pores were formed. Similarly, Ma et al. (2015) used synchrotron-based X-ray micro-computed tomography (SR-µCT) to evaluate the effect of soil pore characteristics on wet aggregate stability and tensile strength during repeated wetting and drying. They demonstrated that pore characteristics and soil clay content provide useful insights for an improved understanding of the change in topsoil microstructure as a consequence and wetting and drying. Moreover, Pagenkemper et al. (2014) used XRCT to analyse and to quantify the development of soil structure in the subsoil following the cultivation of three different preceding crops (alfalfa, chicory, fescue). The authors showed that pore networks changed with crop type and duration of cultivation; not only because of the root generated biopores, but also due to crack formation through an enhanced root water uptake.

In this study, structural recovery of degraded cropland which was converted to permanent grassland and managed under no-till and no-renovation condition was evaluated. We combined measurements of soil physical properties, shrinkage characteristics (hydraulic properties) and X-ray computed tomography at three depths and for three sward ages, to characterise the extent of soil structural recovery and obtain a mechanistic understanding of structure re-development following conversion to permanent grassland. We hypothesised that SSC shape during the natural amelioration period, is related to the age of the swards (time since conversion to permanent grassland) and can be used to monitor the effectiveness and timespan of the recovery process. Structural recovery is visualised and quantified by 3D microscale analyses and its effect on soil functional descriptors for pore scale morphologies like cumulative pore size distribution and air capacity are described. The obtained data will be valuable to formulate models that could characterise soil structure recovery in ameliorating grassland.

## 2. Material and methods

### 2.1. Study site

Sampling of undisturbed soil cores was carried out at the experimental farm of the Faculty of Agriculture, Christian Albrechts University Kiel, located in Lindhof (54°27`N, 9°57`E; 15 m a.s.l.), near the Baltic Sea. The climate of the area is classified as oceanic, with moderately cool summers and comparatively warm winters. The long-term average annual temperature is 8.7 °C, while the average annual precipitation is 785 mm (Linsler et al., 2015). As a consequence of the soil's geological origin, the soil types vary over short distances between Cambisols, Eutric Luvisols, Stagnosols and Anthrosols. The plots sampled for this study were dominated by Eutric Luvisols, consisting of 10 ± 0.8% clay, 23 ± 0.7 % silt and 67 ± 1.3% sand in the Ap /E horizon (0–40 cm), and a pH value of 5.74 ± 0.05 (Ziogas, 1995).

The Lindhof experimental farm was for several decades used to grow potatoes (*Solanum tuberosum* L.), oats (*Avena sativa* L.) and winter wheat (*Triticumaestivum* L.), under conventional tillage management (i.e. mechanical ploughing and harrowing) and inorganic fertilisation. However, from 1994 onwards, the farm was converted from intensely tilled cropland to permanent grassland in phases, providing the opportunity to study structural changes along a chronosequence. The established grassland, is managed organically, in accordance with the guidelines of the German organic growers association (Bioland, 2012) and different renovation treatments were implemented (Linsler et al., 2014, 2015). During each phase of the conversion, the various renovation treatments were installed on 6 m x 18 m experimental plots (swards), with 3 replicates arranged in a randomised plot design (Linsler et al., 2014). Simultaneously, grasslands managed under no-till, no fertilization and no-renovation, were installed as control plots during each phase of coversion. In this study, we sampled from the control plots established in 1994, 2004 and 2012. Thus, the sward ages were: 1, 8 and 19 years at the time of sampling in 2013.

### 2.2. Sampling

Two sets of undisturbed soil cores were collected at each of the three studied depths (0–5 cm; 10–15 cm; 20–25 cm), and in the differently aged swards (1, 8 and 19 years). The first set of samples, consisted of 40 Nos. undisturbed cores, collected in stainless steel rings; (4 cm height, 5.65 cm diameter). They were used in the determination of water retention, saturated hydraulic conductivity (ks), air conductivity and to characterise the shrinkage behaviour. The second set of samples consisted of similar 5 Nos undisturbed cores collected in transparent acrylic rings (4 cm height, 5.65 cm diameter), and used in µCT measurement. At each depth, the samples were collected by gently pushing the sampling rings into the soil and carefully digging them out. The extracted soil-filled rings were wrapped in polythene sheets, and placed in a safe transport box, to avoid structural disturbance during transport. The samples were thereafter stored in a pre-conditioned room (at about 10°C) prior to further handling in the laboratory.

### 2.3. Water retention and shrinkage characteristics

Water retention properties and shrinkage characteristics for the sampled depths in the different sward ages, were determined with 25 undisturbed soil cores each. The samples were slowly saturated by capillary rise with de-aired water. After saturation, the soil samples were