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1 **Relationship between soil aggregate strength, shape and porosity for soils under different long-**
2 **term management**

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16 Abstract

17 Soil aggregate properties, such as strength, shape and porosity, influence a range of essential soil
18 functions and there is a need for more detailed understanding of the effect of soil management on
19 these aggregate properties. There is also a need for improved knowledge on the link between
20 aggregate and bulk soil properties. The objective of this study was to quantify the long-term effect
21 of rotation and tillage on aggregate shape, strength and pore characteristics, to evaluate the
22 influence of aggregate shape and pore characteristics on aggregate strength and soil friability and to
23 correlate aggregate properties to bulk soil properties. Soil core samples were taken in spring 2010
24 from the long-term rotation and tillage trial (initiated in 1980) at the University of Guelph, Canada.
25 The rotations included were continuous corn (R1) and a diverse rotation (R6), and the tillage
26 treatments were mouldboard ploughing (MP) and no-tillage (NT). The soil cores were exposed to a
27 drop shatter test and air-dried before separation into different size fractions. Ten aggregates from
28 the 4-9.2 mm size fraction per core sample (i.e. 320 in all) were X-ray micro-CT scanned. The size,
29 shape and porosity of the aggregates were determined using image analysis with 40 μm voxel size.
30 Subsequently, aggregate tensile strength was determined in an indirect tension test. Rotation had a
31 more pronounced effect than tillage treatment on the different aggregate properties. The diverse
32 rotation resulted in higher aggregate total porosity and more rounded aggregates than the
33 continuous corn rotation. Surprisingly, there was no treatment effect on X-ray micro-CT resolvable
34 porosities. Aggregate strength decreased with both total and X-ray micro-CT resolvable porosity
35 even though the correlations were weak. Significant correlation was also found to aggregate
36 sphericity although only around 10% of the variation in tensile strength could be explained by this
37 property. Our study highlights that caution must be taken when trying to predict aggregate strength
38 from general aggregate characteristics. For both bulk soil and aggregates, the R6-MP had highest
39 and R1-NT lowest porosity. Tillage had strongest effect on bulk soil porosity, whereas aggregate
40 total porosity was only affected by rotation. Our results suggest that the scale of observation is
41 important when evaluating the influence of soil management. A strong correlation was found
42 between aggregate strength and pore characteristics and soil fragmentation in a drop shatter test, i.e.
43 55% of the variation could be explained. Our study indicates therefore that bulk soil fragmentation
44 behavior can be predicted from aggregate characteristics. It needs to be highlighted that our results
45 are based on one long-term experiment on a silt loam soil. The results need to be verified for soils
46 with different soil types, climates and management histories.

48 1. Introduction

49 Soil aggregate properties influence a range of essential soil functions such as erodibility (Kay and
50 Dexter 1990), seedbed quality (Braunack et al., 1989; Håkansson et al., 2002) and greenhouse gas
51 emissions (Ball, 2013). Despite the apparent key role of aggregates in soil, they are not easy objects
52 to study. First of all they are often not very distinct and may be organized in complex hierarchical
53 structures. As Young et al. (2001) pointed out “the existence of aggregates is probably a consequence
54 of how we choose to observe them”. Kay and Angers (2001) also reflected on the concept of
55 aggregates; they defined the term aggregate as a structural unit resulting from fragmentation of bulk
56 soil, induced by application of mechanical energy. This definition will also be applied in this paper.
57 Young et al. (2001) also questioned the use of aggregates as a surrogate of soil structure *per se* as the
58 observation of aggregates, extracted from the whole, only provides limited spatial information.
59 Munkholm (2011) expressed a similar concern in the study of soil friability and called for studies
60 exploring the correlations between observations at different scale.

61 The importance of aggregate structure to soil function has stimulated extensive research on the effect
62 of soil type, climate and soil management on aggregate characteristics at different scales of
63 observation. At the field level, there is a strong focus on qualitative assessment of size, shape and
64 strength of aggregates in relation to soil profile classification (FAO, 1990) as well as on soil structural
65 quality (Ball et al., 2007; 2015). Qualitative field assessments, have in many cases been supplemented
66 with or exchanged by more detailed observations on aggregate size and shape (Dexter, 1985), strength
67 (Braunack et al., 1979) and stability (e.g. Le Bissonnais, 1996). Dexter (1985) and Holden (1993)
68 presented methods to quantify the shape on 2D projected images. They focussed on quantification of
69 aspect ratio, sphericity and roundness based on 2D projected images and references also was drawn
70 to the standard charts to describe particle morphology (Krumbein and Sloss, 1963).

71 Roundness has been found, in a study on Australian and Dutch soils (Dexter, 1985), to decrease with
72 increasing clay and decreasing organic matter content. A study on a silt loam soil from Kentucky
73 showed that zero-tillage resulted in significantly more elongated aggregates than mouldboard
74 ploughing (Perfect et al. 1997). Holden (1995) indicated that aggregates from an old pasture varied
75 from year to year, in relation to surface roughness, but not in relation to roundness. More studies are
76 clearly needed to quantify effects of soil type and management on aggregate shape.

The vital importance of soil pore characteristics, for soil strength and fragmentation, has been shown in many cases (e.g. Munkholm et al., 2002a,b; Hallett et al., 1995). New advances in X-ray CT imagery have allowed visualization and quantification of the 3D structure of macropores within and between aggregates (e.g. Peth et al., 2008). A few studies have utilized this technique, to study the relationship between pore characteristics and aggregate tensile strength and soil fragmentation (Munkholm et al., 2012; Naveed et al., 2014). They confirm the major influence of pore space on strength and fragmentation. Surprisingly, there is a paucity of studies on the influence of aggregate shape on strength despite being recognized, for decades (Dexter and Kroesbergen, 1985), as major source of variation. Recently, Seben et al. (2013) found a clear influence of aggregate shape on aggregate strength and variation in strength, i.e. aggregates with flat surfaces were weaker and showed smaller variability. Novel X-ray CT imagery has opened up for 3D quantification of aggregate shape. Garbout et al. (2013) quantified the 3D shape of aggregate clusters in terms of thickness, sphericity and roundness, but they did not relate the shape properties to strength. More studies are clearly needed to evaluate and quantify the effect of shape and also the combined effect of shape and pore characteristics.

This paper will focus on the relationship between aggregate strength, shape and porosity for soils under different long-term soil management. The issue of scale will also be considered as links will be drawn to bulk soil porosity and fragmentation measured on minimal disturbed soil cores taken from the same treatments in the field (Munkholm et al., 2012; 2013).

The objectives of this study were: 1. To quantify the long-term effect of rotation and tillage on aggregate shape, strength and pore characteristics, 2. To evaluate the influence of aggregate shape and pore characteristics on aggregate strength and soil friability. 3. To correlate aggregate properties to bulk soil properties. Our hypotheses were: A. Rotation and tillage have a significant on aggregate strength, shape and pore characteristics, B. Aggregate strength decreases with porosity and variation in strength increases with irregularity, C. Aggregates resemble bulk soil pore and strength characteristics.

2. Materials and methods

2.1 The experiment

106 Samples were taken from the long-term rotation and tillage trial (initiated in 1980) at the University
107 of Guelph's Elora Research Station near Elora, Ontario, Canada (43°39' N, 80°25'W). The soil is
108 mapped as Woolwich silt loam and classified as a Grey Brown Luvisol (CSSC, 1998) or Albic
109 Luvisol (WRB, 2006). The particulate size distribution is on average: 16, 44, 40 and 2.13 g 100g⁻¹ of
110 clay, silt, sand and organic carbon, respectively. The 30-year average rainfall (1970-2000) was 920
111 mm, and the average monthly temperatures for January, April and July are -7.6, 5.9 and 19.7°C,
112 respectively.

113 The experimental design is a randomized split plot with four replicates. The main plot treatment is
114 rotation and the split plot treatment is tillage. Seven four-course rotations are included in the trial. In
115 this study we used rotation R1,(C-C-C-C) continuous corn (*Zea mays* L.) and rotation R6, (C-C-
116 O(RC), B(RC)) corn, corn, oats (*Avena fatua* L.), spring barley (*Hordeum vulgare* L.) with a red
117 clover (*Trifolium pratense* L.) cover crop underseeded in both oats and spring barley. The red clover
118 cover crop was terminated using glyphosate late October, 2009. In 2010, first year corn was grown
119 in R6. The tillage treatments included no tillage (NT) and conventional tillage with mouldboard
120 ploughing (MP). Mouldboard ploughing (20 cm) was carried out on November 18 2009. Secondary
121 tillage in MP consisted of two passes of a field cultivator (10cm) and packer within 1 day of crop
122 seeding. The tillage plots are 6x16.5 m and 8 rows of corn were sown in each of the studied plots on
123 May 7 2010. The corn crop was harvested at full maturity on October 19 and the yield was recorded.

124 2.4 Soil core sampling

125 Two minimally disturbed soil cores (Ø=6.4 cm, height=8.0 cm) were taken per at 10-20 cm depth in
126 R1 and R6 on May 28 2010. In all, 32 samples were taken (i.e. 8 samples for each of the rotation x
127 tillage treatments). The sampling depth was chosen to obtain soil affected by the tillage systems but
128 minimally affected by within season root growth. The samples were taken in the centre of the plots
129 in between rows, which had not been trafficked at the time of seeding (Munkholm et al., 2012). The
130 crop was at **corn at 6 leaf tip stage** at sampling and therefore few roots were observed in the cores.
131 The intact field moist samples were subjected to a drop shatter test after X-ray micro-CT scanning,
132 as outlined by Munkholm et al. (2013). From the drop shatter test we obtained four oven-dry
133 aggregate size fractions 0-1, 1-2, 2-4, 4-9.2 and 9.2-19 mm and used the 4-9.2 mm size fraction in
134 this study. For the 4-9.2 mm size fraction ten aggregates were randomly selected for each of the 32
135 samples and gently transferred to a PVC cylinder (Ø=6.4 cm) where they were laid one by one in one
136 side of the cylinder as shown in Figure 1. Ten aggregates from another sample were laid one by one

137 in the other side of the cylinder. Two pieces of cardboard were used to separate the aggregates into
138 four compartments with 5 aggregates in each. The cylinder was photographed (Figure 1) and this
139 picture was used to label and identify the single aggregates. Thereafter, a piece of cardboard was laid
140 on top of the first layer and new layer of aggregates were installed. All in all two layers of 20
141 aggregates were installed in each cylinder, i.e. aggregates from 4 samples in each cylinder.

142

143 *2.6 CT scanning, binary thresholding and image analysis*

144 The cylinders with aggregates were scanned using an EVS (now GE Medical, London, Canada)
145 micro-CT scanner, model MS8X-130. The samples were scanned at 120 kV, 170 mA and with a 3500
146 millisecond integration time, generating an axial sequence of X-ray attenuation imagery with 40 μm
147 voxel size. The final reconstructed image had also a voxel size of 40 μm .

148 Please consult Munkholm et al. (2012) for more details on the scanning procedure and image
149 reconstruction. The open source software programme ImageJ was used for binary thresholding and
150 image analysis (Rasband, 2005). Binary imaging was carried out using the standardized and
151 automated thresholding procedure developed by Elliott and Heck (2007) and as detailed by
152 Munkholm et al. (2012). In the case of high attenuation in cardboard shelving that could not be
153 separated by the method described above a special procedure was applied. The original image
154 sequence was thresholded manually to isolate voxels higher than air but lower than true solid (i.e.
155 aggregates). These values were set to zero; all else =1. This image was then multiplied (Image
156 Calculator) by the original segmented image. In some cases, aggregates were barely touching each
157 other within the scanned cylinders. If so a local area was chosen, using freehand selection, to ensure
158 the least amount of distortion to the volume and ellipsoid measurements. The Erode plug-in was
159 employed to separate the single aggregates.

160 For each cylinder scan, eight regions of interest (ROI) were created containing one compartment –
161 e.g. #11B in Figure 1. That is each ROI contained 5 aggregates. For analysing the individual
162 aggregates the 3D Particle Analyzer plug-in in ImageJ (Doubé et al, 2010) was used. The following
163 settings were chosen: Exclude on sides, Thickness, Surface area, Enclosed volume, Ellipsoids, Min
164 Volume=500000, Max Volume=infinity, Show particle stack. The latter was chosen to be able to
165 correlate individual aggregates with the photographic images showing the numbered aggregates –
166 e.g. Figure 1. An example of 2D images of segmented #11B aggregates is shown in Figure 2a. For

determining aggregate volume (i.e. enclosed pore space as well as solid) we first applied the Binary operation “Fill Holes” on segmented images (Figure 2b), and then again we used the Particle Analyser operation with the above mentioned settings. Thereby we were able to obtain information on the entire volume of the aggregates including surface connected pore space. This procedure also resulted in a markedly reduced surface area as the surface area for surface connected pore space was excluded for the “filled holes” images.

2.7 Porosity parameters

Based on the results from the segmented and the filled holes images we were able to calculate a number of porosity parameters. The isolated porosity (ε_I^{CT}) within the aggregates (i.e. not surface connected) derived from the X-ray micro-CT images was assessed from (Eq. 1) using data from the segmented images only.

$$\varepsilon_I^{CT} = 1 - V_S^s / V_T^s \quad \text{Eq. 1}$$

Where V_S^s is the number of solid voxels in the originally segmented images and V_T^s is the total number of enclosed voxels (solids and pores) within aggregates in the originally segmented images.

The total X-ray micro-CT (at 40 μm resolution) resolvable porosity within the aggregates (ε_T^{CT}), i.e. isolated plus surface connected, was determined by Eq 2 where V^f is the aggregate volume from the “filled holes” images and V_S^s is the number of enclosed solid voxels from the originally segmented images.

$$\varepsilon_T^{CT} = (V^f - V_S^s) / V^f \quad \text{Eq. 2}$$

The surface connected intra aggregate porosity ε_S^{CT} was then estimated by:

$$\varepsilon_S^{CT} = \varepsilon_T^{CT} - \varepsilon_I^{CT} \quad \text{Eq. 3}$$

The total porosity of the aggregates was estimated from:

$$\varepsilon_T^{agg} = 1 - (m_a / V^f) / 2.65 \text{ g/cm}^3 \quad \text{Eq. 4}$$

The parameters m_a (oven dry aggregate mass) and V^f had the units “g” and “ cm^3 ” and a particle density of 2.65 g/cm^3 was assumed.

192 2.8 Shape parameters

193 Based on the image analysis a range of shape characteristics were estimated. The shortest (l_1),
 194 intermediate (l_2) and longest (l_3) length of the single aggregates were used to calculate the ratio's l_1/l_3
 195 and l_2/l_3 . The equivalent cubic length (L_c) was proposed by Perfect et al. (1997) as an appropriate
 196 shape parameter given that aggregate aspect ratios in most cases are much closer to those for a cube
 197 than for a sphere.

$$198 \quad L_c = [l_1 \left(\frac{l_2}{\sqrt{2}} \right) \left(\frac{l_3}{\sqrt{3}} \right)]^{1/3} \quad \text{Eq. 5}$$

199 The sphericity, S_s , of the aggregates was estimated from (Wadell, 1935):

$$200 \quad S_s = [\pi^{1/3} (6V_T^f)^{2/3}] / A_T^f \quad \text{Eq. 6}$$

201 Where A_T^f is the aggregated surface area determined from the “filled holes” images.

202 Supplementary to S_s the sphericity of ellipsoidal objects, S_e was as determined according to Sneed
 203 and Folk (1958):

$$204 \quad S_e = \sqrt[3]{l_1^2 / l_2 l_3} \quad \text{Eq.7}$$

205 2.9. Tensile strength measurements

206 Tensile strength of the scanned air-dry aggregates was measured following the procedure
 207 described by Dexter and Kroesbergen (1985), which involved crushing the aggregates individually
 208 between two parallel plates in an indirect tension test. The aggregate tensile strength (Y) was
 209 calculated from the equation (Dexter and Kroesbergen, 1985):

$$210 \quad Y = 0.576 \times (F/d^2) \quad \text{Eq.8}$$

211 where F (N) is the polar force required to fracture the aggregate and d (m) is the mean
 212 aggregate diameter. In this study d [m] was estimated from:

$$213 \quad d = d_0 (m/m_x)^{1/3} \quad \text{Eq.9}$$

214 where d_0 [m] is the mean aggregate diameter (6.6 mm for the tested 4-9.2 mm size-class), m
215 [kg] is the mass of the individual aggregate and m_x [kg] is the mean mass of the 10 aggregates per
216 plot.

217 Friability index, FI, for the single size soil aggregate from each subplot was estimated from the
218 variation of the tensile strength data in relation to its mean (Watts and Dexter, 1998).

$$219 \quad FI = \sigma_y / \bar{Y} \quad \text{Eq.10}$$

220 where σ_y and $\bar{Y}$ are the standard deviation and mean, respectively, of soil tensile strength from each
221 experimental plot. Friability was classified according to Imhoff et al. (2002). $F < 0.1$ not friable, 0.1-
222 0.2 slightly friable, 0.2-0.5 friable, 0.5-0.8 very friable and >0.8 mechanically unstable.

223

224 *2.10 Statistical analysis*

225 All statistical analyses were carried out using SAS (Version 9.2, SAS Institute, Cary, NC) (SAS,
226 2005). We used PROC INSIGHT to test data for normality. The pore characteristics derived from
227 X-ray CT imagery and the tensile strength data were log-transformed to yield normality. All other
228 data were best fitted by a normal distribution. Averages were calculated for each plot and used in
229 the calculation of mean and standard error. The averages were used as input in general linear
230 models for test of treatment effects. For this purpose we used PROC MIXED in SAS. For the
231 aggregates four outliers with very high or very low bulk density (BD) were deleted from the
232 analysis, i.e. $n=316$. A significance level of $P<0.05$ was generally applied in this study.

233 *Results*

234 *3.1. Aggregate pore characteristics*

235 Rotation and tillage significantly affected some of the soil pore characteristics, whereas the
236 interaction between rotation and tillage was not significant in any case. The core data showed
237 significantly higher dry bulk density for NT (1.46 g cm^{-3}) compared with MP (1.28 g cm^{-3}) (Table
238 1, Munkholm et al. 2013). There was an insignificant ($P=0.18$) trend to higher BD for R1 than for
239 R6. For the aggregates a R1 tended to have higher bulk density ($P=0.09$) than R6 (i.e. 1.69 and 1.65
240 g cm^{-3} for R1 and R6, respectively). There was no significant effect of tillage ($P=0.14$). The bulk
241 density increased from 1.37 g cm^{-3} for the soil cores to 1.67 g cm^{-3} for the aggregates corresponding
242 to a decrease in total porosity from $49 \text{ m}^3 100 \text{ m}^{-3}$ to $37 \text{ m}^3 100 \text{ m}^{-3}$. No significant treatment effect

was found on the X-ray micro-CT resolvable porosities. The pore volume detected (ε_T^{CT}) was on average $9.6 \text{ m}^3 \text{ 100 m}^{-3}$, which was approximately 25% of the total pore volume for the aggregates. Most of the X-ray micro-CT resolvable pore space was connected to the surface of the aggregates, i.e. ε_S^{CT} was in average $7.9 \text{ m}^3 \text{ 100 m}^{-3}$. On average, $1.8 \text{ m}^3 \text{ 100 m}^{-3}$ of the CT resolvable porosity were enclosed within the aggregates (ε_I^{CT}), which corresponded to 19% of the CT resolvable porosity.

3.1.2. Aggregate shape and strength characteristics

For the aggregate shape characteristics, there was significant effect of rotation in some cases and of tillage in one case. The interaction between rotation and tillage was not significant for any of the parameters. Aggregates from the continuous corn rotation (R1) tended to have significantly ($P=0.07$) longest major length (l_3), significantly lowest aspect ratios ($P<0.05$) (l_1/l_3 and l_2/l_3) and displayed lowest sphericity of ellipsoid objects (S_E) ($P=0.08$) (Table 2). The major lengths were 12.1 mm and 11.1 mm for R1 and R6, respectively. The l_1/l_3 aspect ratios were 0.39 and 0.43, for R1 and R6 respectively and the l_2/l_3 aspect ratios were 0.65 and 0.69 respectively for R1 and R6. A tendency to higher ($P=0.07$) sphericity for spheres (S_S) was observed for NT (0.51) than for MP (0.49). There was no significant effect of treatment on aggregate strength and friability. The friability indices could for all treatments be considered as “friable” according to the Imhoff et al. (2002) classification.

3.2. Correlations between aggregate strength, porosity and shape

3.2.1. Aggregate strength vs. pore characteristics

Across all treatments, aggregate tensile strength ($\log Y$) decreased significantly with total porosity, ε_T^{agg} , X-ray CT resolvable porosity, ε_T^{CT} and with X-ray CT resolvable surface connected porosity, ε_S^{CT} (Table 3). The correlations were weak ($r<-0.18$). There was no overall significant correlation between tensile strength and X-ray CT resolvable isolated pore volume ε_I^{CT} . For the individual treatments, there was only significant correlation between strength and pore characteristics for the R1-NT treatment. In that case, there was relatively strong negative correlation to ε_T^{CT} ($r=-0.41$) and ε_S^{CT} ($r=-0.42$) and weaker correlation to ε_I^{CT} ($r=-0.22$). The correlation between $\log Y$ and the pore characteristics ε_T^{agg} , ε_T^{CT} and ε_S^{CT} is shown in Figure 3.

3.2.2. Aggregate strength vs. shape characteristics

Across all treatments there was a significant negative correlation between log Y and log values of intermediate (l_2), major (l_3) and the equivalent cubic length (L_c) (Table 3). The correlations were weak, i.e. r varied between -0.12 and -0.15. On the other hand, log Y increased significantly with the aspect ratio, l_2/l_3 , and with sphericity (S_s and S_E). Strongest correlation was found between log Y and S_s ($r=0.31$) corresponding to $R^2=10$. This correlation was significant for all combinations of rotation and tillage. The correlation between log Y, and l_2/l_3 and S_E were for the individual treatments only significant for R1-MP and R1-NT. Figure 4 shows correlations between log Y and the shape characteristics log l_3 , l_2/l_3 and S_s .

3.3. Correlation between drop shatter results and strength and pore characteristics

The aggregates used in this study derived from a drop shatter test on 32 intact soil cores taken from the field and dropped from 2m height on a concrete floor in the laboratory (see Munkholm et al., 2012 for further information). The surface area produced for the individual cores (DS_{SA}) was correlated to the mean or geometric mean aggregate parameters reported in this study. Across all treatments there was a significant negative correlation between DS_{SA} and log Y ($r=-0.65$) and a significant positive correlation between DS_{SA} and aggregate total porosity, ϵ_T^{agg} ($r=0.68$) as shown in Figure 5. This means that more than 40% of the variation in DS_{SA} could be explained by either log Y or ϵ_T^{agg} . When combining these two parameters, DS_{SA} could be estimated from:

$$surface\ area = 0.36 - 0.97 \log Y + 0.06 \epsilon_T^{agg} \quad R^2=0.55 \quad \text{Eq. 11}$$

There was no significant correlation to the other aggregate pore or shape characteristics.

4. Discussion

4.1. Treatment effects on soil pore characteristics

Tillage had strong and significant effect on bulk soil total porosity (i.e. highest for MP) whereas rotation only significantly affected aggregate porosity. This indicates that tillage primarily affected inter-aggregate whereas rotation mainly affected intra-aggregate pore space. Highest BD was found for R1-NT and lowest for R6-MP for both aggregates and cores. The strong effect of tillage on BD for bulk soil was not surprising as many other studies have shown a strong effect of tillage on inter-

300 aggregate pore space (e.g. Kadziene et al., 2011). The positive effect of a diverse rotation (R6) on
301 intra-aggregate pore space may be ascribed to higher inputs of organic carbon than in the
302 continuous corn rotation (R1). The R6 rotation has higher average corn yield, and also more active
303 crop growth during the year due to the inclusion of spring cereals and fall growth of red clover
304 cover crop (Meyer-Aurich et al., 2006). A more continuous input of root-associated soil structural
305 binding and bonding components may have stimulated aggregate formation and stabilization. A
306 significant effect of soil management on aggregate porosity has also been found in previous studies
307 (e.g. Munkholm et al., 2002; Blanco-Canqui and Lal, 2007 and Kravchenko et al., 2011). Blanco-
308 Canqui and Lal (2007) showed that aggregate density decreased with input of organic matter after
309 ten years of wheat straw incorporation.

310 The X-ray micro-CT resolvable porosities were $9.7 \text{ m}^3 100\text{m}^{-3}$ for images with $40 \mu\text{m}$ voxel size.
311 This is within the same range as reported by Naveed et al. (2014) for 8-16 mm natural aggregates
312 scanned with $30 \mu\text{m}$ resolution but smaller than the c. $14 \text{ m}^3 100\text{m}^{-3}$ measured for 5 mm natural
313 aggregates at $9 \mu\text{m}$ resolution by Zhou et al. (2013). In this study there was no significant effect of
314 treatment on X-ray micro-CT resolvable pore characteristics (Table 1). However, there was an
315 insignificant trend to larger $\varepsilon_{\text{T}}^{\text{CT}}$ for MP than for NT which is in correspondence with the results
316 from X-ray micro-CT scanning of soil cores used to generate the aggregates (Munkholm et al.,
317 2013). Others have found significant long-term effect of land use and soil management on CT
318 resolvable pore characteristics (Zhou et al., 2013; Naveed et al., 2014).

319 There was no treatment effect on the fraction of the CT resolvable pore space isolated within the
320 aggregates, i.e. c. 20% for all treatments. This is a lower level than reported for natural aggregates
321 by Zhou et al. (2013) (30-55%) and much lower than shown by Peth et al. (2008) (65-75%). This is
322 most likely due to difference in soil, scanning resolution and image analysis methodology.

323

324 4.2. Treatment effects on shape and strength characteristics

325 In general, the aggregates in this study were more elongated than found by others. The mean aspect
326 ratios were 0.41 for l_1/l_3 and 0.67 for l_2/l_3 , which were lower the values of 0.49-0.75 for l_1/l_3 and
327 0.67-0.87 for l_2/l_3 reported by Perfect et al. (1997) and references therein. More elongated
328 aggregates in our study may be related to soil type and/or the fact that we measured the lengths
329 automatically based on 3D images as compared to manual measurements in previous studies.

330 The aggregates from the diverse rotation, R6, were significantly more round than those from the
331 continuous corn, R1. This may be related to a higher input of organic matter input in R6 and would
332 thus be in agreement with observations by Dexter (1985). Tillage did not affect shape parameters,
333 except Ss, in this study. This contradicts with Perfect et al. (1997) who reported more elongated
334 aggregates for NT than for MP on a silt loam. However, there is in general paucity of data on soil
335 and management effects on aggregate shape properties.

336 4.3. Relationship between aggregate strength and microstructure

337 There was in general a poor correlation between aggregate tensile strength and microstructure
338 characteristics (Table 3; Figure 3 and 4), which was surprising given the well-known role of pore
339 characteristics on aggregate fragmentation. The negative but weak correlation to aggregate porosity
340 was as hypothesized. A much stronger correlation was observed by Naveed et al. (2014) for natural
341 aggregates and regenerated aggregates without organic matter treatment. However, regenerated
342 aggregates with organic matter treatment displayed no significant relationship in their study. It has
343 also to be mentioned that their study was based on much fewer aggregates (n=27) than our study
344 (n=316). An improved fit may have been found if we had been able to combine porosity with pore
345 morphology characteristics such as connectivity and orientation as found by Munkholm et al.
346 (2012) in relation to drop shatter of soil cores. However, the weak correlation between general
347 aggregate pore characteristics and tensile strength is probably due to the fact that fracture of the
348 aggregates is expected to start by an opening of a single crack (Hallett et al., 2013). This indicates a
349 strong dependence on local rather than general aggregate characteristics, which may cause
350 substantial variation in tensile strength. Our study indicates, therefore, that caution has to be taken
351 when trying to predict aggregate tensile strength from general aggregate pore characteristics.

352 Of the microstructure properties, sphericity showed the strongest correlation ($r=0.27-0.41$ for
353 individual treatments) to tensile strength (Table 2 and Figure 4). This means, that in general only
354 around 10% of the variation could be explained by sphericity. It confirms, however, that aggregate
355 shape is an important source of variation in tensile strength as earlier stated by e.g. Dexter and
356 Kroesbergen (1985).

357

358

359 4.4. Relationship between bulk soil fragmentation and aggregate properties

360 The surface area, produced by the drop shatter test, on minimal disturbed cores, could, to a large
361 extent, be explained by the strength and porosity of air-dry aggregates produced by the drop shatter
362 test ($R^2=0.55$). This implies that the occurrence of strong and dense aggregates have limited the
363 fragmentation of the soil cores.

364

365 5. Conclusions

366 This study confirmed the hypothesized effect of long-term tillage and crop rotation treatments on
367 aggregate shape and pore characteristics, but not on aggregate strength.. The diverse rotation
368 resulted in higher aggregate total porosity and more rounded aggregates than the continuous corn
369 rotation which may be related to higher inputs of organic matter. Surprisingly, there was no
370 treatment effect on X-ray micro-CT resolvable porosities.

371 Aggregate strength decreased as expected with both total and X-ray micro-CT resolvable porosity
372 even though the correlations were weak. Significant correlation was also found to aggregate
373 sphericity although only around 10% of the variation in tensile strength could be explained by this
374 property. Our study highlights that caution must be taken when trying to predict aggregate strength
375 from general aggregate characteristics.

376 There was correspondence between bulk soil and aggregate total porosity in the ranking of
377 treatment R6-MP with highest and R1-NT with lowest porosity. Tillage had strongest effect on bulk
378 soil porosity whereas rotation mainly affected aggregate total porosity. Thus, our study suggests
379 that the scale of observation is important when evaluating the influence of soil management. A
380 strong correlation was found between aggregate strength and pore characteristics and soil
381 fragmentation in a drop shatter test, i.e. 55% of the variation could be explained. Our study
382 indicates therefore that bulk soil fragmentation behavior can be predicted from aggregate
383 characteristics.

384 The conclusions in this study are based on observations from one long-term field experiment on a
385 silt loam soil. More studies are needed to evaluate the long-term effect of management and the
386 relationship between measurements at different scales.

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Table 1. Treatment effects on soil pore characteristics. BD_{core} and BD_{agg} are dry bulk density values for soil cores and aggregates, respectively. The parameters ϵ_T , ϵ_T^{CT} , ϵ_s and ϵ_i are total porosity for the aggregates, X-ray CT resolvable porosity, surface connected X-ray CT resolvable porosity and isolated X-ray CT resolvable porosity. Figures with different letters within treatments are significant at $P < 0.05$ level

Treatment	BD_{core}^*	BD_{agg}	ϵ_T^{core*}	ϵ_T^{agg}	ϵ_T^{CT}	ϵ_s^{CT}	ϵ_i^{CT}
	$g\ cm^{-3}$		$m^3\ 100m^{-3}$				
R1-NT	1.48 ^a	1.70	44.2	36.0	9.5	7.6	1.8
R1-MP	1.31 ^b	1.68	50.6	36.7	10.4	8.5	1.9
R6-NT	1.43 ^a	1.67	46.0	36.9	9.1	7.4	1.8
R6-MP	1.25 ^b	1.62	52.8	38.4	9.7	7.9	1.7
Averages across rotation							
R1	1.40	1.69	47.2	36.3	10.0	8.1	1.8
R6	1.34	1.65	49.4	37.6	9.4	7.6	1.8
Averages across tillage							
NT	1.46 ^a	1.68	44.9 ^a	36.5	9.3	7.5	1.8
MP	1.28 ^b	1.66	51.7 ^b	37.5	10.0	8.2	1.8

*From Munkholm et al. 2013.

Table 2. Treatment effects on shape and strength characteristics. The parameters l_1 , l_2 , l_3 are geometric mean values for the minor, intermediate and major length of the aggregates. L_c is the equivalent cubic length, l_1/l_3 and l_2/l_3 are aspect ratios, S_s and S_e are sphericity estimates for spheres and ellipsoids, respectively, Y is the tensile strength geometric mean values and FI is friability index. Figures with different letters within treatments are significant at $P < 0.05$ level..

Treatment	l_1	l_2	l_3	L_c	l_1/l_3	l_2/l_3	S_s	S_e	Y	FI
	mm	mm	mm	mm					kPa	
R1-NT	4.4	7.4	11.9	5.5	0.38	0.63	0.51	0.60	84	0.45
R1-MP	4.5	8.0	12.3	5.8	0.40	0.67	0.48	0.61	89	0.36
R6-NT	4.5	7.5	10.9	5.5	0.42	0.68	0.52	0.63	88	0.47
R6-MP	4.7	7.5	11.4	5.4	0.44	0.71	0.49	0.65	63	0.43
Averages across rotation										
R1	4.5	7.7	12.1	5.6	0.39 ^b	0.65	0.49	0.61	86	0.41
R6	4.6	7.5	11.1	5.4	0.43 ^a	0.69	0.51	0.64	75	0.45
Averages across tillage										
NT	4.4	7.4	11.6	5.5	0.40	0.66	0.51	0.62	86	0.46
MP	4.6	7.8	11.5	5.6	0.42	0.69	0.49	0.63	75	0.40

Table 3. Pearson correlations between tensile strength (log values) and porosity and shape parameters. The bold values are significant at the $P < 0.05$ level.

	R1		R6		All
	MP	NT	MP	NT	
	n=79	n=78	n=80	n=79	n=316*
$\varepsilon_T^{\text{agg}}$	-0.13	-0.20	-0.10	-0.16	-0.18
$\varepsilon_T^{\text{CT}}$	-0.05	-0.41	-0.12	-0.03	-0.12
$\varepsilon_S^{\text{CT}}$	-0.08	-0.42	-0.16	-0.06	-0.16
$\varepsilon_I^{\text{CT}}$	0.11	-0.22	-0.05	0.11	0.04
Log l_1	0.05	-0.11	0.06	-0.09	0.01
Log l_2	-0.22	-0.21	-0.02	-0.07	-0.12
Log l_3	-0.27	-0.35	-0.06	-0.08	-0.15
Log L_c	-0.22	-0.21	-0.01	-0.11	-0.12
l_1/l_3	0.08	0.19	0.05	0.07	0.06
l_2/l_3	0.26	0.37	0.08	0.06	0.14
S_S	0.41	0.27	0.29	0.30	0.31
S_E	0.26	0.35	0.09	0.02	0.14

*Results from four aggregates were excluded from the analysis as these were considered outliers.

Figure Captions

Figure 1. Photo showing the placement of aggregates from sample #11 and #12 in the cylinder used for X-ray micro-CT scanning. The aggregates were from treatment mouldboard ploughing (MP), diverse rotation (R6).

Figure 2. An example (#11B compartment –samples 6-10) showing an image from X-ray micro-CT scanning at 40 μm resolution. The aggregates were from treatment mouldboard ploughing (MP), diverse rotation (R6). A: X-ray micro-CT scanning image. B: Binary X-ray micro-CT scanning “filled holes” image.

Figure 3. Correlation between aggregate tensile strength ($\log Y$) and aggregate pore characteristics: total porosity, ϵ_T^{agg} , total X-ray CT resolvable porosity, ϵ_T^{CT} and X-ray CT resolvable surface connected porosity, ϵ_S^{CT} .

Figure 4. Correlation between aggregate tensile strength ($\log Y$) and aggregate shape characteristics: $\log$ major length (l_3), aspect ratio l_2/l_3 and sphericity S_s .

Figure 5. Correlation between surface area (DS_{SA}) produced in a drop shatter test and the aggregate characteristics: total porosity, ϵ_T^{agg} and tensile strength ($\log Y$).

Figure 1. Photo showing the placement of aggregates from sample #11 and #12 in the cylinder used for X-ray micro-CT scanning. The aggregates were from treatment mouldboard ploughing (MP), diverse rotation (R6).

Figure 2. An example (#11B compartment –samples 6-10) showing an image from X-ray micro-CT scanning at 40 μm resolution. The aggregates were from treatment mouldboard ploughing (MP), diverse rotation (R6). A: X-ray micro-CT scanning image. B: Binary X-ray micro-CT scanning “filled holes” image. Examples of a isolated and surface connected pore at 2D scale is illustrated.

Figure 3. Correlation between log aggregate tensile strength, (Y , kPa) and aggregate pore characteristics: total porosity, ϵ_T^{agg} , total X-ray CT resolvable porosity, ϵ_T^{CT} and X-ray CT resolvable surface connected porosity, ϵ_S^{CT} .

Figure 4. Correlation between log aggregate tensile strength (Y , kPa) and aggregate shape characteristics: log major length (l_3), aspect ratio l_2/l_3 and sphericity S_s .

Figure 5. Correlation between surface area (DS_{SA}) produced in a drop shatter test and the aggregate characteristics: total porosity, ϵ_T^{agg} and log tensile strength Y (kPa) .