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Abstract: The effects of soil organic matter on the water contents for tillage were investigated by sampling soils with a uniform texture, but a range of soil organic carbon (SOC) from two long-term field experiments at Highfield in Rothamsted Research, UK and Askov Experimental Station, Denmark. The treatments studied in Highfield were Bare fallow (BF), Continuous arable rotation (A), Ley-arable (LA) and Grass (G); and in Askov: unfertilized (UNF), $\frac{1}{2}$ mineral fertilizer ($\frac{1}{2}$ NPK), 1 mineral fertilizer (1NPK), and $1\frac{1}{2}$ animal manure ($1\frac{1}{2}$ AM). Minimally undisturbed soil cores (100 cm³) were sampled per plot in both locations from 6-10 cm depth to generate water retention data. Soil blocks were also sampled at 6-15 cm depth to determine basic soil properties and to measure soil aggregate strength parameters. The range of soil water contents appropriate for tillage were determined using the water retention and the consistency approaches. SOC content in Highfield was in the order: G>LA=A>BF, and in Askov: $1\frac{1}{2}$ AM>1NPK= $\frac{1}{2}$ NPK>UNF. Results showed that different long-term management of the silt loam Highfield soil, and fertilization of the sandy loam Askov soil affected the mechanical properties of the soils— for Highfield soil, aggregates from the G treatment were stronger in terms of rupture energy when wet (-100 hPa matric potential) than the BF treatment. As the soil dried (-300 and -1000 hPa matric potentials), soil aggregates from the G treatment were relatively weaker and more elastic than the BF soil. Our study showed, for both Highfield and Askov soils, a strong positive linear increase in the range of water contents for tillage with increasing contents of SOC. This suggests that management practices leading to increased SOC can improve soil workability by increasing the range of water contents for tillage. We recommended using the consistency approach over the water retention approach for determining the range of water contents for tillage because it seems to give realistic estimates of the water contents for tillage.

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Dear Editor,

Submission of manuscript

I would like to submit to you our manuscript titled: “*Soil organic matter widens the range of water contents for tillage*” to be considered for publication in your reputable journal. The manuscript is based on original research carried out by the authors. Some of the key findings of our study are:

- The soil consistency approach provided more reliable estimates of tillage limits (upper, lower and optimum soil water contents) than the water retention approach because using the latter, soil was either too dry or too wet, and therefore may not be workable.
- Management practices leading to increased SOC content can improve soil workability by increasing the range of soil water contents for tillage ($\Delta\theta_{\text{RANGE}}$) —SOC explains 78 and 87% of the variation in $\Delta\theta_{\text{RANGE}}$ for the studied soils.

The manuscript has not been published by any journal and neither is it currently under consideration in any journal. The authors declare that they have no conflict of interest.

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Thank you.

Sincerely,

Peter Bilson Obour

Highlights

- Soil organic carbon (SOC) affected the mechanical properties of soil aggregates.
- Water contents for tillage is determined using water retention and consistency approaches.
- There is a strong positive relation between SOC and range of water contents for tillage ($\Delta\theta_{\text{RANGE}}$).
- $\Delta\theta_{\text{RANGE}}$ determined based on the consistency approach is recommended over the water retention approach.

1 **Soil organic matter widens the range of water contents for tillage**

2

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17

18 **Abstract**

19 The effects of soil organic matter on the water contents for tillage were investigated by sampling
20 soils with a uniform texture, but a range of soil organic carbon (SOC) from two long-term field
21 experiments at Highfield in Rothamsted Research, UK and Askov Experimental Station,
22 Denmark. The treatments studied in Highfield were Bare fallow (BF), Continuous arable rotation
23 (A), Ley-arable (LA) and Grass (G); and in Askov: unfertilized (UNF), ½ mineral fertilizer (½
24 NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM). Minimally undisturbed soil
25 cores (100 cm³) were sampled per plot in both locations from 6–10 cm depth to generate water
26 retention data. Soil blocks were also sampled at 6–15 cm depth to determine basic soil properties
27 and to measure soil aggregate strength parameters. The range of soil water contents appropriate
28 for tillage were determined using the water retention and the consistency approaches. SOC
29 content in Highfield was in the order: G>LA=A>BF, and in Askov: 1½
30 AM>1NPK=½NPK>UNF. Results showed that different long-term management of the silt loam
31 Highfield soil, and fertilization of the sandy loam Askov soil affected the mechanical properties
32 of the soils— for Highfield soil, aggregates from the G treatment were stronger in terms of
33 rupture energy when wet (-100 hPa matric potential) than the BF treatment. As the soil dried (-
34 300 and -1000 hPa matric potentials), soil aggregates from the G treatment were relatively
35 weaker and more elastic than the BF soil. Our study showed, for both Highfield and Askov soils,
36 a strong positive linear increase in the range of water contents for tillage with increasing contents
37 of SOC. This suggests that management practices leading to increased SOC can improve soil
38 workability by increasing the range of water contents for tillage. We recommended using the
39 consistency approach over the water retention approach for determining the range of water
40 contents for tillage because it seems to give realistic estimates of the water contents for tillage.

41 **Keywords:** Soil organic carbon; water retention approach; consistency approach.

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46 **1 Introduction**

47 Tillage plays an important role in arable farming. One of the primary purposes of tillage is for
48 seedbed preparation, where operations are designed to alter soil bulk density, aggregate size
49 distribution and other soil physical characteristics to create soil conditions and environment
50 favoring crop establishment, germination and growth (Johnsen and Buchle, 1969).

51

52 Tillage can be performed over a range of water content ($\Delta\theta_{\text{RANGE}}$) where soil is workable. In this
53 study, soil workability is defined as the ease of working with a well-drained soil to produce
54 desirable seedbeds (Dexter, 1988), i.e. not consisting of fragments that are either too fine or too
55 coarse for crop establishment. $\Delta\theta_{\text{RANGE}}$ is the difference between the wet tillage limit (WTL) and
56 the dry tillage limit (DTL). WTL and DTL are the upper and lower water contents for tillage,
57 respectively. Optimum water content for tillage (θ_{OPT}) is the water content where tillage
58 produces maximum number of smaller fragments and minimum number of large fragments
59 (clods) (Dexter and Bird, 2001). Russell (1961) suggests that small soil fragments that create
60 ideal seedbeds as those consisting 1–5 mm in size. The water contents for tillage have been
61 estimated using the water retention approach (e.g., Dexter and Bird, 2001) and the consistency
62 approach (e.g., Munkholm et al., 2002).

63

64 Performing tillage when soil is too wet can lead to structural damage due to remolding and
65 puddling (Dexter and Bird, 2001). Likewise, executing tillage when soil is too dry requires high
66 specific energy because soil is strong (Hadas and Wolf, 1983). Therefore, knowledge of WTL
67 and DTL and the effects of soil physical properties on these limits are crucial. Such knowledge

68 can provide practical information on the satisfactory $\Delta\theta_{\text{RANGE}}$ over which tillage operations
69 produce desirable soil structures for crop establishment and growth (Obour et al., 2017). Further,
70 knowledge of the suitable water contents for tillage can be used in a decision support system to
71 reduce the risk of structural damage, and the use of excessive energy during tillage (Sørensen et
72 al., 2014).

73

74 Soil organic carbon content (SOC) is a critical soil property that affects many other soil physical
75 properties and functions. Organic binding agents such as roots and fungal hyphae play an
76 important role in soil aggregation and stabilization (Tisdall and Oades, 1982), and improves soil
77 resistance and resilience to external stresses (Gregory et al., 2009). SOC also affects soil
78 mechanical properties such as soil strength, bulk density, inter-aggregate or structural porosity,
79 and enhances better soil fragmentation during tillage (Abdollahi et al., 2014). It also influences
80 infiltration, drainage and water storage — it improves water retention due to high absorptive
81 capacity for water (Murphy, 2015), and increases soil strength in wet conditions, which increases
82 WTL. In soils with small content of SOC, clay dispersion is higher (Jensen et al., 2017; Watts
83 and Dexter, 1997), which may increase soil strength due to crusting and cementation on drying,
84 consequently affecting the DTL. There are few studies that have investigated the effect of SOC
85 on the water contents for tillage. Although Dexter and Bird (2001) investigated the water
86 contents for tillage for a silt loam in Highfield using the water retention approach, and
87 Munkholm et al. (2002) a sandy loam soil in Askov using the consistency approach, they did not
88 evaluate this effect statistically. There remains a need for more quantitative information on the
89 SOC/water content relationship and its influence on tillage (Obour et al., 2017). Such
90 information will help improve knowledge on how the physical condition of soil for tillage

91 changes with changing SOC. In the present study, we investigated the effect of SOC on the water
92 contents for tillage using both the water retention and consistency approaches to expand the
93 findings of the previous studies. Our study focuses on water contents for secondary tillage used
94 for seedbed preparation. It relates to unconfined fragmentation of soil aggregates rather than
95 shearing of bulk soil.

96

97 The objectives of this study were to: (i) quantify the effect of SOC on the mechanical behavior of
98 soil aggregates and the water contents for tillage, and (ii) evaluate the water retention and
99 consistency approaches for determining the range of water contents for tillage. We hypothesized
100 that the range of water contents for tillage increases with increasing SOC content.

101

102 **2 Materials and methods**

103

104 2.1 The experiments

105 Soil samples were taken from two long-term field experiments; the Highfield long-term,
106 ley/arable experiment at Rothamsted Research, UK (51°80'N, 00°36'W) and from the Askov
107 long-term experiment on animal manure and mineral fertilizers at Askov Experimental Station,
108 Denmark (55° 28' N, 09°07'E). These soils had uniform textures, but a range of SOC.

109

110 The soil from Highfield is a silt loam classified as Chromic Luvisol according to the World
111 Reference Base (WRB) soil classification system (Watts and Dexter, 1997). The experimental

112 site was originally established with grass, but for ~56 years prior to sampling, each of the plots
113 has an unbroken history under its present management. As a consequence, the soil has a wide
114 SOC gradient in the topsoil along the Bare fallow (BF), Continuous arable rotation (A), Ley-
115 arable (LA) and Grass (G) treatments in the order: G>LA=A>BF (Table 1). The G treatment has
116 been known as Reseeded grass, but throughout this paper, it will be called ‘Grass (G)’ treatment.
117 The A, LA and G treatments were included in a randomized block design with four field
118 replicates, whereas the four BF replicates were not part of the original design and were located at
119 one end of the experimental site.

120

121 The soil from the Askov experimental site is a sandy loam classified as an Aric Haplic Luvisol
122 according to the WRB classification system (IUSS Working Group WRB, 2015). The
123 experiment includes the following four nutrient treatments: Unfertilized plots (UNF), and plots
124 that have received ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal
125 manure (1½AM). The experiment utilizes a randomized block design with three field replicates.
126 The different levels of nutrients applied results in a SOC gradient among the treatments in the
127 order: 1½AM>1NPK=½NPK>UNF plots (Table 1). Crop management has been a four-course
128 rotation of winter wheat (*Triticum aestivum*), silage maize (*Zea mays*), spring barley (*Hordeum*
129 *vulgare*), and a grass-clover mixture (*Trifolium hybridum*, *Medicago sativa*, *Lotus corniculatus*,
130 *Lolium perenne*, *Festuca pratensis* and *Phleum pratense*) used for cutting in the following year
131 (Jensen et al., 2017).

132

133 Table 1 shows the basic characteristics of the studied soils. For a more detailed description of the
134 experiment and treatments in Askov and in Highfield reference is made to Jensen et al. (2017)
135 and Jensen et al. (2018), respectively. From here on the soils are referred to with the treatment
136 labels explained above.

137

138 2.2 Sampling

139 At Askov, sampling took place in September 2014 following a winter wheat crop. At Highfield,
140 sampling was done in March 2015. At both Askov and Highfield, soil cores (6.1 cm diameter,
141 3.4 cm high, 100 cm³) were taken from 6–10 cm depth by inserting steel cylinders gently into the
142 soil. Six soil cores were sampled per plot at both locations. In addition, soil blocks were sampled
143 at 6–15 cm depth: Two soil blocks (4000 cm³) per plot in Askov, and three blocks (2750 cm³)
144 per plot in Highfield. The soil cores were stored in a field moist condition in a 2 °C room until
145 analysis. Portions of the soil blocks per plot were spread out on a table and carefully fragmented
146 by hand along natural planes of weakness and left to dry in a ventilated room ~20 °C.

147

148 2.3 Basic chemical and physical analysis

149 Air-dry soil samples from each plot was crushed to <2 mm and SOC was determined by dry
150 combustion using Flash 2000 NC Soil Analyzer (Thermo Fisher Scientific, Waltham, MA,
151 USA). Soil texture was determined on portions of the <2 mm samples using a combined
152 hydrometer/sieving method after removal of SOM by hydrogen peroxide (Gee and Or, 2002).

153

154 2.4 Soil water retention

155 To obtain water retention curves, water content was measured from the six soil cores per plot
156 from Askov at -10, -30, -100 and -300 hPa matric potentials; and at -10, -30, -100, -300 and -
157 1000 hPa matric potentials for Highfield soil on tension tables, vacuum pots and pressure plates
158 (Dane and Hopmans, 2002). Water content at -15000 hPa matric potential was determined from
159 air-dry <2 mm samples using WP4-T Dewpoint Potentiometer (Scanlon et al., 2002). Following
160 equilibrium at each water potential the soil cores were oven dried at 105° C for 24 h. Soil bulk
161 density of each soil core was calculated from the mass of the oven-dried soil divided by the total
162 soil volume. Bulk density was corrected for stone weight and volume for Highfield soil samples
163 because they contained a significant amount of stones. Porosity was estimated from bulk density
164 and particle density, where particle density was measured on one plot from each treatment using
165 the pycnometer method (Flint and Flint, 2002). For the remaining plots, the particle density was
166 predicted from SOC by a linear regression model. The pore size distributions of the soils were
167 estimated from the water retention measurements, assuming the approximate relation:

168
$$d = -3000/\psi \tag{1}$$

169 where d is equivalent cylindrical pore diameter (μm) and ψ is the soil matric potential (cm H_2O).

170

171 2.5 Plastic limit

172 Plastic limit (PL) was determined using the standard ASTM (Casagrande) test procedure
173 (McBride, 2007). In brief, for each plot, about 15 g of air-dry soil was sieved to <1 mm and then
174 mixed with water until it became plastic and easily molded into a ball. About 8 g of the soil was
175 rolled between the fingers and a smooth glass plate. PL was determined as the gravimetric water

176 content where the soil began to crumble when rolled into a thread of approximately 3.2 mm in
177 diameter (McBride, 2007).

178

179 2.6 Calculations of water contents for tillage

180 The water contents for tillage were determined using two approaches: (i) water retention
181 approach, and (ii) consistency approach.

182

183 *2.6.1 Water retention approach*

184 Dexter and Bird (2001) and Dexter et al. (2005) suggested that the water contents for tillage can
185 be estimated from the parameters of the soil water retention curve using the van Genuchten
186 (1980) water retention equation. The van Genuchten (1980) equation was fitted to each set of
187 water retention data obtained from each plot at Highfield and Askov.

188 The gravimetric water content (θ , kg kg⁻¹) corresponding to each matric potential (hPa) was
189 calculated as:

$$190 \quad \theta = (\theta_{SAT} - \theta_{RES}) [1 + \alpha h]^n]^{-m} + \theta_{RES} \quad (2)$$

191 where θ_{SAT} and θ_{RES} are the water contents at saturation, i.e. at $h=0$, and the residual water
192 contents, $h=\infty$, respectively, α is a scaling factor for h ; and n and m are parameters that control
193 the shape of the curve. θ_{RES} was set equal to zero. Values of the parameters were obtained using
194 the curve-fitting program, RETC (van Genuchten et al., 1991). We fitted the van Genuchten
195 equation with the Mualem (1976) restriction:

196 $m = 1 - \frac{1}{n}$ (3)

197 The θ_{WTL} was estimated as follows:

198 $\theta_{WTL} = \theta_{INFL} + 0.4(\theta_{SAT} - \theta_{INFL})$ (4)

199 θ_{OPT} was estimated as water content at the inflection point of the soil water retention curve

200 (θ_{INFL}):

201 $\theta_{INFL} = (\theta_{SAT} - \theta_{RES}) \left[1 + \frac{1}{m} \right]^{-m} + \theta_{RES}$ (5)

202 $h_{DTL} \approx \frac{2}{\alpha} \left[\frac{1}{m} \right]^{\frac{1}{n}} n^{1.1}$ (6)

203 θ_{DTL} was estimated by putting the value of h_{DTL} from equation (6) into equation (2)

204 The range of water contents for tillage using the water retention approach ($\Delta\theta_{RANGE}$ (water
205 retention)) was calculated as:

206 $\Delta\theta_{RANGE}$ (water retention) = $\theta_{WTL} - \theta_{DTL}$ (7)

207

208 2.6.2 Consistency approach

209 The water contents for tillage based on the consistency approach were determined as follows:

210 θ_{WTL} and θ_{OPT} were determined according to Dexter and Bird (2001):

211 $\theta_{PL} = \theta_{WTL}$ (8)

212 $\theta_{OPT} = 0.9 \theta_{PL}$ (9)

213 θ_{DTL} was graphically determined for each plot as water content at twice the strength at θ_{OPT}
214 from the relation between natural logarithm of tensile strength (Y) of 8–16 mm soil aggregates
215 and gravimetric water content measured at different matric potentials (Munkholm et al., 2002).
216 Examples of how it was determined are shown in section 3.5.

217

218 The range of water contents for tillage using the consistency approach ($\Delta\theta_{RANGE}$ (consistency))
219 was calculated as described by Munkholm et al. (2002):

$$220 \Delta\theta_{RANGE}(\text{consistency}) = \theta_{WTL} - \theta_{DTL} \quad (10)$$

221

222 2.7 Aggregate tensile strength

223 2.7.1 Highfield soil

224 We crushed portions of the air-dry soil using the rolling method suggested by Hartge (1971). The
225 crushed soil was passed through a nest of sieves with 8–16, 4–8, 2–4 and 1–2 mm of apertures to
226 obtain four different aggregate size fractions. Some of the 8–16 mm air-dry aggregates were
227 selected randomly from each sampling plot, saturated by capillarity and then drained to -100, -
228 300 and -1000 hPa matric potentials using tension tables, vacuum pots and pressure plates,
229 respectively. Fifteen aggregates were selected at random from each size fraction of the air-dry
230 aggregates (8–16, 4–8, 2–4 and 1–2 mm), and the 8–16 mm aggregates equilibrated at the three
231 matric potentials. These aggregates were used to measure tensile strength (Y) using the indirect
232 tension test (Rogowski, 1964). This test assumes brittle fracture theory and we checked we did
233 not exceed the 20% maximum strain limit for onset of plastic deformation (Kuhn and Medlin,
234 2000); particularly when aggregates were tested at a wetter state (-100 hPa matric potential).

235 Each of the aggregates was weighed individually and subjected to indirect tension testing by
236 crushing the individual aggregates between two parallel plates (Rogowski, 1964) using an
237 automatically operated mechanical press (Instron Model 5969, Instron, MA,USA). The point of
238 failure for each aggregate was automatically detected when a continuous crack or sudden drop in
239 force (40% of the maximum load) was read. The maximum force at failure was automatically
240 recorded by a computer program. After the test, the crushed aggregates were oven-dried at 105
241 °C for 24 h to determine their gravimetric water content.

242

243 2.7.2 Askov soil

244 Portions of the field-moist soil was fragmented by hand and sieved to obtain 8–16 mm
245 aggregates. These aggregates were divided into three groups based on their moisture status: air-
246 dry, air-dry rewetted to field capacity (-100 hPa matric potential (Munkholm and Kay, 2002))
247 and field moist aggregates. Aggregate tensile strength for Askov soil was measured as described
248 in Jensen et al. (2017).

249

250 For both Highfield and Askov soils, aggregate Y was calculated from the equation suggested by
251 Dexter and Kroesbergen (1985):

$$252 \quad Y=0.567F/d^2 \quad (11)$$

253 where 0.576 is the proportionality constant resulting from the relation between the compressive
254 load applied and the tensile stress exerted on the aggregate. F is the maximum force (N) at
255 failure and d is the effective diameter of the spherical aggregate (m); it was obtained by adjusting
256 the aggregate diameter according to the individual masses (Dexter and Kroesbergen, 1985):

257 $d = d_1(m_0/m_1)^{1/3}$ (12)

258 where d_1 is the diameter of aggregates defined by the average sieve sizes (e.g., 0.012 m for 8–
259 16 mm aggregates), m_0 is the mass (g) of the individual aggregate and m_1 is the mean mass of a
260 batch of aggregates of the same size class (in this case 15 aggregates for each size fractions).

261

262 Rupture energy (E_r) was calculated from the area under the stress-strain curve (Vomocil and
263 Chancellor, 1969):

264 $E_r \approx \sum_i F(s_i) \Delta s_i$ (13)

265 where $F(s_i)$ denotes the mean force at the i th subinterval and Δs_i the displacement length of the
266 i th subinterval. The mass specific rupture energy (E_{sp}) was defined on gravimetric basis from the
267 equation:

268 $E_{sp} = E_r/m$ (14)

269 where m is the mass of the individual aggregates.

270

271 Young's modulus (E) was determined to obtain a quantitative measure of stiffness (elasticity) of
272 the aggregates (determined only for the Highfield samples). It was estimated from the gradient of
273 the stress-strain curve to the elastic limit, assuming linearity up to that point:

274 $E = \sigma / \varepsilon$ (15)

275 where σ is stress (Pa) and ε is strain.

276

277

278

279 2.8 Statistical analysis

280 All statistical analyses were carried out in R software package (R Core Team, 2017). The Y , E_{sp}
281 and E data were log-transformed (\ln) to yield normal distribution. The Highfield data were fitted
282 to a linear mixed effect model, which comprised treatment as fixed and block as random factors.
283 The Kenward-Roger method was used to calculate degrees of freedom. For the Askov data,
284 treatment effects were analyzed using a linear model which comprised block as a fixed effect.
285 We used $p < 0.05$ as a criterion for statistical significance of treatment effects. Where effect of
286 treatment was found to be significant, further analyses were made to identify which treatment
287 means were different (pairwise comparison) using the general linear hypotheses (*glht*) function
288 implemented in R multcomp package. For the four BF replicates which were not included in the
289 randomized block design, a paired t -test was used to investigate if the treatment significantly
290 differed from the A, LA and G treatments. We acknowledged that the paired t -test statistics
291 performed to compare statistical significance difference between the BF treatment on one hand
292 and the A, LA and G treatment on the other hand was a less robust test.

293

294 **3 Results**

295 3.1 Basic properties of the investigated soils

296 Soil bulk density was significantly greater for the BF and A soils than the LA and G treatments,
297 and for the UNF and $\frac{1}{2}$ NPK compared to the 1NPK and $1\frac{1}{2}$ AM treatments (Table 1). There were
298 more large pores $>30 \mu\text{m}$ in the LA treatment compared to the G and A treatments from
299 Highfield, and for the 1NPK than the UNF and $\frac{1}{2}$ NPK soils. Pores $<30 \mu\text{m}$, generally, increased
300 with SOC. θ_{PL} was lower for the BF treatment than the other treatments at Highfield (Table 1).

301 θ_{PL} increased with an increase in SOC at Highfield ($R^2=0.82, p<0.001$). The same was also seen
302 at Askov, although not significant ($R^2=0.15, p=0.21$).

303

304 3.2 Tensile strength parameters of air-dry aggregates

305 In this section and in section 3.3 and 3.4, only results from Highfield are presented. Tensile
306 strength parameters of the Askov soil have previously been reported in another study by Jensen
307 et al. (2017). Y and E_{sp} values for all the aggregate size fractions measured did not differ between
308 the treatments (Table 2). Geometric mean of E_{sp} value of all size fractions was greater for the G
309 treatment (19.1 J kg^{-1}) compared to the A and BF treatments (15.4 and 14.9 J kg^{-1} , respectively).
310 Aggregates for the size fraction 2–4 mm were more elastic for the G treatment than the A and
311 LA treatments, whereas for 4–8 mm size fraction, the LA treatment was more elastic compared
312 to both the A and G treatments. Geometric mean values of all size fractions showed that the G
313 and LA treatments had lower E (high elasticity) compared to the BF treatment (Table 2).

314

315 -----*Table 1 near here*-----

316

317 -----*Table 2 near here*-----

318

319 3.3 Tensile strength parameters of rewetted aggregates

320 As expected, for all treatments, Y , E_{sp} and E all increased as the soil dries: the soils become
321 stronger and stiffer. At wet and wet–moist state (-100 and -300 hPa matric potentials), Y values
322 did not differ significantly between treatments, whereas at moist–dry state (-1000 hPa matric
323 potential), aggregates for the LA and G soils had lower Y compared to the A treatment (Table 3).
324 Conversely, the G soil with large SOC had higher E_{sp} at -100 hPa matric potential than the other
325 treatments. On the other hand E_{sp} was not significantly different between treatments when
326 aggregates were tested at -300 and -1000 hPa matric potentials (Table 3). Similar to the air-dry
327 aggregates, lower E was observed for the G aggregates at -300 and -1000 hPa matric potentials
328 compared to the BF treatment (Table 3).

329

330 -----Table 3 near here-----

331

332 3.4 Relationship between strength parameters of air-dry aggregates and soil organic carbon

333 Geometric mean of Y , E_{sp} and E across the four aggregate size fractions (8–16, 4–8, 2–4 and 1–2
334 mm) were related to SOC content. There was a negative linear decrease in Y with increasing
335 SOC content ($p<0.05$). A stronger negative linear relationship was found between SOC and E
336 ($p<0.001$). In contrast, there was a positive linear increase in E_{sp} with increasing SOC content,
337 although not significant ($p=0.07$) (Fig. 1a– c). Overall, 29%, 22% and 61% of the variation in Y ,
338 E_{sp} , and E , respectively of aggregates could be explained by SOC (Fig. 1a– c).

339

340 -----Fig. 1 near here-----

341

342 3.5 Water contents for tillage

343 Water content at DTL for each plot was graphically determined from the relationship between Y
344 of aggregates in the 8–16 mm size range and the gravimetric water content at -100, -300, -1000
345 hPa matric potentials and at air-dry state. Examples of how we determined water content at twice
346 the strength at θ_{OPT} for the BF and G soils from Highfield, and the UNF and 1½AM soils from
347 Askov are presented in Fig. 2a– d. For these examples, water content at DTL for the BF soil was
348 0.16 kg kg⁻¹ and 0.22 kg kg⁻¹ for the G soil. DTL for the UNF and 1½AM soil were 0.09 and
349 0.10 kg kg⁻¹, respectively.

350

351 -----Fig. 2 near here-----

352

353 The $\Delta\theta_{RANGE}$ (water retention) and $\Delta\theta_{RANGE}$ (consistency) are presented in Fig. 3a and b for
354 Highfield soil, and Fig. 3c and 3d for Askov soil. θ_{DTL} , θ_{OPT} , θ_{WTL} at treatment levels are
355 also shown for the two approaches. The G treatment with high SOC content had wider $\Delta\theta_{RANGE}$
356 compared to the BF treatment at Highfield; and for the 1½AM compared to the UNF at Askov.
357 Based on the water retention approach, $\Delta\theta_{RANGE}$ for the G and BF treatments were 0.18 and 0.06
358 kg kg⁻¹, respectively (Fig. 3a), and 0.08 and 0.07 kg kg⁻¹ for the 1½AM and UNF treatments
359 (Fig. 3c). Similar trends were seen for the consistency approach indicating that $\Delta\theta_{RANGE}$
360 (consistency) for the G treatment was 0.11 kg kg⁻¹ compared to 0.03 kg kg⁻¹ for the BF treatment,

361 and 0.06 kg kg⁻¹ for the ½AM treatment compared to 0.05 kg kg⁻¹ for the UNF treatment (Fig. 3b
362 and d).

363

364 -----Fig. 3 near here-----

365

366 SOC content had a highly significant positive effect on $\Delta\theta_{\text{RANGE}}$ (Fig. 4a– d). The effect of SOC
367 content on $\Delta\theta_{\text{RANGE}}$ (consistency) was more significant and more of the variation was explained
368 (Fig. 4b and d) than with $\Delta\theta_{\text{RANGE}}$ (water retention) (Fig. 4a and c).

369

370 -----Fig. 4 near here-----

371 **4 Discussion**

372 4.1 Effect of soil organic carbon content on aggregate strength parameters

373 The indirect tension test causes soil aggregates (or cores) to fail along pre-existing failure zones,
374 and planes of weakness making Y a potentially sensitive measure of soil structural condition.

375 Results showed that SOC had a negatively and a significant effect on geometric mean of Y across
376 the four aggregate size classes when air-dry (Fig. 1a). This can be interpreted as Y reflects the
377 degree of aggregation in a soil; it is influenced by aggregate porosity and bonds, failure planes
378 within the aggregates and abundance of internal micro-cracks within the aggregates, which in
379 turn are influenced by SOC (Blanco-Canqui and Lal, 2006; Watts and Dexter, 1998). Studies
380 investigating the effect of SOC on aggregate strength show that for soil with less SOC, Y
381 decreases with increasing soil moisture content whereas for soil with large SOC, aggregates are

382 relatively stronger when wet and weaker when dry. For examples, Munkholm et al. (2002) and
383 Causarano (1993) found that for sandy loam and clay soils, respectively with large SOC content,
384 aggregates were stronger at water content at field capacity and weaker when air-dry. This may
385 imply that wet soils do not slump under their own weight when wet during the winter and are
386 relatively weak when dry; leading to easier root penetration and tillage. For the silt loam soil
387 investigated in here, aggregate Y did not significantly differ between the treatments at -100 and -
388 300 hPa matric potentials (Table 3). However, when tested at -1000 hPa, aggregate Y was lower
389 for the G treatment, 25.9 kPa compared to the BF and A treatments, 38.5 and 45.1 kPa,
390 respectively (Table 3). Our results are consistent with Jensen et al. (2017) who found no
391 significant difference in Y between the 1½ AM with large SOC content and the UNF treatment
392 with small SOC content for aggregates at field capacity (-100 hPa matric potential) for the sandy
393 loam soil at Askov. Results here suggest that the range of water content for measurement of Y is
394 important to study the effect of SOC on soil aggregate strength.

395
396 Perfect and Kay (1994) suggested using rupture energy for the statistical characterisation of
397 aggregates in tillage studies. They argued that, unlike Y , E_{sp} does not involve any assumption of
398 the mode of failure, making it more appropriate for estimating the strength of dry aggregates.
399 Munkholm and Kay (2002) highlighted that E_{sp} is also appropriate for estimating the strength
400 and fragmentation of wet aggregates. We observed that at -100 hPa matric potential, E_{sp} was
401 significantly greater for the G compared to the other treatments at Highfield. This could be
402 ascribed to the influence of SOC including organic binding and bonding materials such as
403 polysaccharides fungal hyphae and roots (Tisdall and Oades, 1982). Previous study of the BF, A
404 and G treatments showed more diverse and active root biomass in the G treatment compared to

405 the A soil (Hirsch et al., 2009). The results from the Highfield contrast with Jensen et al. (2017)
406 who found that for the sandy loam soil at Askov, E_{sp} of aggregates did not significantly differ
407 between the UNF, ½ NPK, 1NPK and 1½AM treatments at field capacity (-100 hPa matric
408 potential). Our results showed that geometric mean of E_{sp} across the four aggregate size classes
409 in air-dry state increased with increasing SOC content, although the relationship was weak (Fig.
410 1b). In the wet state (-100 hPa matric potential), aggregates from the G treatment were stronger
411 based on E_{sp} than aggregates from the BF, A and LA treatments. The stronger aggregates implies
412 that the G soil is less susceptible to plastic deformation resulting from applied strain energy
413 when wet. Lower E was observed for the G aggregates at -300 and -1000 hPa matric potentials
414 compared to the BF treatment. This can be interpreted as the G soil aggregates were more elastic
415 than the BF soil. The influence of SOC on aggregate elasticity is further illustrated in Fig. 1c
416 showing a strong negative linear decrease in E with increasing SOC content. Gregory et al.
417 (2009) reported that compressed remolded soil cores from the G treatment were more elastic than
418 the A treatment. Further, the authors found that the G soil cores rebounded following the
419 removal of the compression stress more than the A soil, an indication that the former was more
420 resilient to deformation.

421

422 4.2 Effect of soil organic carbon on water contents for tillage

423 The G and 1½AM soils with large SOC content had wider $\Delta\theta_{\text{RANGE}}$ compared to their
424 counterpart BF and UNF soils, respectively that had small SOC contents (Fig. 3a and b,
425 Highfield soil; and Fig. 3c and d, Askov soil). The results support our hypothesis that increased
426 SOC widens the range of water contents for tillage. Our results agreed with Munkholm et al.
427 (2002) who determined $\Delta\theta_{\text{RANGE}}$ using the consistency approach for soil from two of the

428 experimental fields in Askov, which have the same sandy loam texture as the field investigated
429 in the present study. The authors also reported that for both fields, $\Delta\theta_{\text{RANGE}}$ was wider for the
430 animal manure (AM) soil (0.09 kg kg^{-1}) than the UNF soil (0.06 kg kg^{-1}). The wider $\Delta\theta_{\text{RANGE}}$
431 (consistency) for the G soil at Highfield (0.11 kg kg^{-1}) compared to what was reported by
432 Munkholm et al. (2002) can be explained by the differences in soil type, i.e., the silt loam soil at
433 Highfield compared to sandy loam soil at Askov, as well as the wider range of SOC content for
434 the Highfield soil compared to the Askov soil. The positive linear relation between SOC and
435 $\Delta\theta_{\text{RANGE}}$ showed that increase in SOC content potentially improves the window of opportunity
436 for tillage operations by increasing $\Delta\theta_{\text{RANGE}}$ over which tillage can be satisfactorily executed.
437 Mosaddeghi et al. (2009) reported that SOC has greater absorptive capacity for water and
438 improves water-holding capacity of soil thereby increasing θ_{WTL} , θ_{OPT} , θ_{DTL} and $\Delta\theta_{\text{RANGE}}$.
439 Moreover, SOC influences the plastic behavior of soil by shifting the plastic limit to greater
440 water content (Kirchhof, 2006).

441

442 We observed that using the water retention approach, the DTL was very dry, especially for the A
443 treatment (0.08 kg kg^{-1}), whereas it was very wet (wetter than -100 hPa matric potential) for the
444 BF soil (Fig. 3a); which seems unrealistic. Similarly, we observed that DTL estimated from the
445 water retention approach was wetter than -100 hPa matric potential for all the treatments studied
446 in Askov (Fig. 3c). Mueller et al. (2003) reported that θ_{OPT} estimated using the water retention
447 approach was, generally, wetter than other approaches such as the consistency approach
448 evaluated for 80 soils with differences in terms of geographical origin, parent material, texture,
449 bulk density and SOC content. They found that θ_{OPT} was outside the suitable range of soil
450 workability in the field. It must however, be emphasized that Mueller et al. (2003) only estimated

451 θ_{OPT} using different approaches, but did not investigate θ_{DTL} , θ_{WTL} and $\Delta\theta_{RANGE}$ as done in
452 this study.

453

454 As for the consistency approach, θ_{WTL} was estimated from remolded soil (where air-dry soil
455 sieved to 1 mm was remolded) destroying the soil structure and therefore, does not represent
456 soils with intact structure. Moreover, PL does not take into consideration pre-existing cracks
457 which are important in soil fragmentation (Keller et al., 2007).

458

459 With respect to the determination of DTL, even though Dexter et al. (2005) provided a reasoning
460 for defining DTL as water content at which soil strength is twice its value at the θ_{OPT} as done in
461 this study, the approach provides an arbitrary way of determining DTL.

462

463 4.3 Utilization of water contents for tillage and SOC information in farm management

464 Knowledge of the water contents (wet and dry limits) for tillage is useful for determining the
465 range of water contents over which soil is workable, i.e., tillage can be performed satisfactorily.

466 In temperate regions like Northern Europe, where soil workability is likely to be limited by
467 excessive moisture, information on θ_{WTL} is of utmost importance to: (1) avoid producing soil
468 seedbed dominated by large smeared fragments during tillage, which are of less agronomic value
469 in terms of crop establishment (Dexter and Birkas, 2004); and (2) reduce the risk of soil puddling
470 and remolding leading to excessive soil deformation and damage to the soil microstructure.

471

472 On the other hand, knowledge of θ_{DTL} is useful to: (1) avoid soil pulverization during tillage
473 because seedbeds become dominated by both large intractable clods and very fine particles (dust)
474 leading to poor aeration, vulnerability to crusting and greater erodibility (Braunack and Dexter,
475 1989); and (2) prevent the use of excessive tillage energy because soil is too strong. In these
476 circumstances where clods are difficult to break down, considerable energy is expended to little
477 or no effect. In a nutshell, quantitative information on the water contents for tillage can be used
478 by farmers and environmental managers to improve their decision support system (DSS) for
479 planning and optimizing tillage operations (Edwards et al., 2016).

480

481 Mullins et al. (1988) reported that in practice, farmers can be faced with a narrow window of
482 opportunity to perform tillage operations, especially for hard-setting soils. Our results suggest
483 that for the same soil type, increase in SOC increased the $\Delta\theta_{RANGE}$. This information can provide
484 practical evidence to farmers to engage in farm management practices that improve SOC as a
485 way of widening the window of opportunity over which tillage can be performed satisfactorily.

486

487 It could be emphasized that for practical use and for purposes of application of our results in a
488 DSS, it is important that the consistency approach, which seems to be appropriate for
489 determining the range of water contents for tillage, is validated in field conditions. Also, more
490 knowledge is needed on the effect of SOC on different soil types and at different scales. It could
491 also be pointed out that the high values of SOC associated with the G treatment may be due in
492 part to the fact that it has not been cultivated. Cultivating it would lead to a sharp drop in SOC
493 over time. However, the scope of this study might be expanded to identify appropriate conditions
494 for grazing without risk of damage to the underlying soil structure.

495 **5 Conclusions**

496 This study showed that the different long-term management practices on two contrasting soils
497 lead to differences in soil organic carbon (SOC). This in turn led to major differences in soil
498 mechanical properties (aggregate tensile strength, rupture energy and Young's modulus and
499 elastic range) which are useful in identifying appropriate soil moisture conditions for tillage.

500 Two approaches were used to identify the range of soil water contents for tillage: (i) Based on
501 fixed points (water contents) generated from modeled water retention characteristics and (ii)
502 based on a combination of soil consistency relationships (plastic limit) and an estimate of tensile
503 strength of aggregates in the 8–16 mm size class. The evidence here suggests:

- 504 • The aggregates from the Grass (G) treatment with large SOC content were stronger based
505 on the mass specific rupture energy when soil was wet than the Bare fallow (BF) soil
506 with small SOC content.
- 507 • Aggregate tensile strength for the G treatment was significantly lower than the Arable
508 (A) and BF, and more elastic than the BF, A and Ley-arable (LA) treatments when soil
509 was moist.
- 510 • The soil consistency approach provided more reliable estimates of tillage limits (upper,
511 lower and optimum soil water contents) than the water retention approach because using
512 the latter, soil was either too dry or too wet, and therefore may not be workable.
- 513 • Management practices leading to increased SOC content can improve soil workability by
514 increasing the range of soil water contents for tillage ($\Delta\theta_{\text{RANGE}}$) —SOC explains 78 and
515 87% of the variation in $\Delta\theta_{\text{RANGE}}$ for the studied soils.

516

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524

525 **Conflicts of interest:** None.

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536 **References**

- 537 Abdollahi, L., Schjønning, P., Elmholt, S., Munkholm, L.J., 2014. The effects of organic matter
538 application and intensive tillage and traffic on soil structure formation and stability. *Soil
539 & Tillage Research* 136, 28-37.
- 540 Blanco-Canqui, H., Lal, R., 2006. Aggregates: Tensile strength, In: Lal, R. (Ed.), *Encyclopedia
541 of Soil Science*, pp. 45-48.
- 542 Braunack, M.V., Dexter, A.R., 1989. Soil aggregation in the seedbed: a review. II. Effect of
543 aggregate sizes on plant growth. *Soil & Tillage Research* 14, 281-298.
- 544 Causarano, H., 1993. Factors affecting the tensile strength of soil aggregates. *Soil & Tillage
545 Research* 28, 15-25.
- 546 Dane, J.H., Hopmans, J.W., 2002. Water retention and storage, In: Dane, J.H., Topp, G.C. (Eds.),
547 *Methods of Soil Analysis: Part 4 Physical Methods*. Soil Science Society of America,
548 Inc., Madison, Wisconsin, USA.
- 549 Dexter, A.R., 1988. Advances in characterization of soil structure. *Soil & Tillage Research* 11,
550 199-238.
- 551 Dexter, A.R., Bird, N.R.A., 2001. Methods for predicting the optimum and the range of soil
552 water contents for tillage based on the water retention curve. *Soil & Tillage Research* 57,
553 203-212.
- 554 Dexter, A.R., Birkas, M., 2004. Prediction of the soil structures produced by tillage. *Soil &
555 Tillage Research* 79, 233-238.
- 556 Dexter, A.R., Czyż, E.A., Birkás, M., Diaz-Pereira, E., Dumitru, E., Enache, R., Fleige, H.,
557 Horn, R., Rajkaj, K., de la Rosa, D., Simota, C., 2005. SIDASS project Part 3. The
558 optimum and the range of water content for tillage – further developments. *Soil & Tillage
559 Research* 82, 29-37.
- 560 Dexter, A.R., Kroesbergen, B., 1985. Methodology for determination of tensile-strength of soil
561 aggregates. *J Agr Eng Res* 31, 139-147.
- 562 Edwards, G., White, D.R., Munkholm, L.J., C.G. Sørensen, Lamandé, M., 2016. Modelling the
563 readiness of soil for different methods of tillage. *Soil & Tillage Research* 155, 339–350.
- 564 Flint, L.E., Flint, A.L., 2002. Porosity, In: Dane, J.H., Topp, G.C. (Eds.), *Methods of Soil
565 Analysis. Part 4. SSSA Book Ser. 5. . SSSA, Madison, WI*, pp. 241-255.

566 Gee, G.W., Or, D., 2002. Particle-Size Analysis, In: Dane, J.H., Topp, C.G. (Eds.), Methods of
567 Soil Analysis: Part 4 Physical Methods. Soil Science Society of America, Madison, WI,
568 pp. 255-293.

569 Gregory, A.S., Watts, C.W., Griffiths, B.S., Hallett, P.D., Kuan, H.L., Whitmore, A.P., 2009.
570 The effect of long-term soil management on the physical and biological resilience of a
571 range of arable and grassland soils in England. *Geoderma* 153, 172-185.

572 Hadas, A., Wolf, D., 1983. Energy efficiency in tilling dry clod-forming soils. *Soil & Tillage*
573 *Research* 3, 47-59.

574 Hartge, K.H., 1971. Die physikalische Untersuchung von Böden. Eine Labor- und
575 Praktikumanweisung. (in German.) F. Enke Verlag, Stuttgart.

576 Hirsch, P.R., Gilliam, L.M., Sohi, S.P., Williams, J.K., Clark, I.M., Murray, P.J., 2009. Starving
577 the soil of plant inputs for 50 years reduces abundance but not diversity of soil bacterial
578 communities. *Soil Biol Biochem* 41, 2021-2024.

579 IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015.
580 International soil classification system for naming soils and creating legends for soil
581 maps, World Soil Resources Reports. FAO, Rome.

582 Jensen, J.L., Schjonning, P., Christensen, B.T., Munkholm, L.J., 2017. Suboptimal fertilization
583 compromises soil physical properties of a hard-setting sandy loam. *Soil Research* 55,
584 332-340.

585 Jensen, J.L., Schjønning, P., Watts, C.W., Christensen, B.T., Peltre, C., Munkholm, L.J., 2018.
586 Relating soil C and organic matter fractions to structural stability. *Geoderma* (submitted).

587 Johnsen, C.E., Buchle, W.F., 1969. Energy in clod size reduction of vibratory tillage. *Trans.*
588 *ASAE* 12 371-374.

589 Keller, T., Arvidsson, J., Dexter, A.R., 2007. Soil structures produced by tillage as affected by
590 soil water content and the physical quality of soil. *Soil & Tillage Research* 92, 45-52.

591 Kirchhof, G., 2006. Plastic properties, In: Lal, R. (Ed.), *Encyclopedia of soil science*, 2 ed.
592 Taylor & Francis, New York, pp. 1311-1313.

593 Kuhn, H., Medlin, D., 2000. *ASM Handbook Vol. 8, Mechanical Testing and Evaluation*. ASM
594 Int., Ohio, Materials Park.

595 McBride, R.A., 2007. Soil consistency: upper and lower plastic limits, In: Carter, M.R.,
596 Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*, 2 ed. CRC Press, Boca
597 Raton, pp. 761-770.

598 Mosaddeghi, M.R., Morshedizad, M., Mahboubi, A.A., Dexter, A.R., Schulin, R., 2009.
599 Laboratory evaluation of a model for soil crumbling for prediction of the optimum soil
600 water for tillage. *Soil & Tillage Research* 105, 242-250.

601 Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous
602 media. *Water Resour. Res.* 12, 513-522.

603 Mueller, L., Schindler, U., Fausey, N.R., Lal, R., 2003. Comparison of methods for estimating
604 maximum soil water content for optimum workability. *Soil & Tillage Research* 72, 9-20.

605 Mullins, C.E., Ley, G.J., Lal, R., Young, I.M., Costigan, P.A., Bengough, A.G., 1988. Hard-
606 Setting Soils. *J Sci Food Agr* 44, 121-121.

607 Munkholm, L.J., Kay, B.D., 2002. Effect of water regime on aggregate-tensile strength, rupture
608 energy, and friability. *Soil Science Society of America Journal* 66, 702-709.

609 Munkholm, L.J., Schjønning, P., Deboz, K., Jensen, H.E., Christensen, B.T., 2002. Aggregate
610 strength and mechanical behaviour of a sandy loam soil under long-term fertilization
611 treatments. *European Journal of Soil Science* 53, 129-137.

612 Murphy, B.W., 2015. Impact of soil organic matter on soil properties—a review with emphasis
613 on Australian soils. *Soil Research* 53, 605-635.

614 Obour, P.B., Lamandé, M., Edwards, G., Sørensen, C.G., Munkholm, L.J., 2017. Predicting soil
615 workability and fragmentation in tillage: a review. *Soil Use and Management* 33, 288-
616 298.

617 Perfect, E., Kay, B.D., 1994. Statistical characterization of dry aggregate strength using rupture
618 energy. *Soil Science Society of America Journal* 58, 1804-1809.

619 R Core Team, 2017. *R: A language and environment for statistical computing*. R Foundation for
620 Statistical Computing, Vienna, Austria.

621 Rogowski, A.S., 1964. *Strength of soil aggregates*. Iowa State University of Science and
622 Technology, Ames, Iowa.

623 Russell, E.J., 1961. *Soil Conditions and Plant Growth* Longmans London

624 Scanlon, B.R., Andraski, B.J., Bilskie, J., 2002. Miscellaneous methods for measuring matric or
625 water potential, In: Dane, J.H., Topp, G.C. (Eds.), *Methods of soil analysis. Part 4.*
626 *Physical methods.* Soil Science Society of America, Inc, Madison, WI, pp. 643–670.

627 Sørensen, C.G., Halberg, N., Oudshoorn, F.W., Petersen, B.M., Dalgaard, R., 2014. Energy
628 inputs and GHG emissions of tillage systems. *Biosyst Eng* 120, 2-14.

629 Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. *European*
630 *Journal of Soil Science* 33, 141-163.

631 van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of
632 unsaturated soils. *Soil Science Society of America Journal* 44, 892-898.

633 van Genuchten, M.T., Liej, F.J., Yates, S.R., 1991. The RETC code for quantifying the hydraulic
634 functions of unsaturated soils. USDA, US Salinity Laboratory, Riverside, CA.

635 Vomocil, J.A., Chancellor, W.J., 1969. Energy requirements for breaking soil samples. *Trans.*
636 *ASAE* 12, 375–388.

637 Watts, C.W., Dexter, A.R., 1997. The influence of organic matter in reducing the destabilization
638 of soil by simulated tillage. *Soil & Tillage Research* 42, 253-275.

639 Watts, C.W., Dexter, A.R., 1998. Soil friability: theory, measurement and the effects of
640 management and organic carbon content. *European Journal of Soil Science* 49, 73-84.

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642

643

Table 1. Basic soil properties and water retention characteristics of the two soils investigated. Treatments labelled with different letters in a given row for each soil are significantly different. Pairwise comparison for differences between Arable (A), Ley-arable (LA) and Grass (G) treatments at Highfield and between unfertilized (UNF), ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM) treatments at Askov. Paired *t*-test for differences between Bare fallow (BF) and A, LA and G at $p < 0.05$. Values of A, LA and G with an asterisk (*) indicate it is significantly different from BF treatment based on the paired *t*-test.

	Highfield soil ¹				Askov soil ²			
	BF	A	LA	G	UNF	½NPK	1NPK	1½AM
SOC (g 100 g ⁻¹ minerals)	0.90	1.73a*	2.16a*	3.29b*	0.95a	1.07b	1.13b	1.33c
Clay < 2 µm (g 100 g ⁻¹ minerals)	27	26	26	26	9	10	10	10
Fine silt 2–20 µm (g 100 g ⁻¹ minerals)	25	26	26	27	9	10	9	10
Coarse silt 20–63 µm (g 100 g ⁻¹ minerals)	33	32	32	32	16	16	17	16
Sand 63–2000 µm (g 100 g ⁻¹ minerals)	15	16	16	15	65	64	64	65
Bulk density (g cm ⁻³)	1.45	1.39b	1.21a*	1.13a*	1.54a	1.51a	1.41b	1.42b
Pores <30 µm (m ³ m ⁻³)	0.31	0.39a	0.39a	0.46b	0.21	0.23	0.22	0.25
Pores >30 µm (m ³ m ⁻³)	0.15	0.09a	0.15b	0.10a	0.19a	0.19a	0.24b	0.21ab
θ _{PL} (kg kg ⁻¹ oven dried soil) ³	0.19	0.24a*	0.25a*	0.34b*	0.15	0.17	0.17	0.18

¹Data from Jensen et al. (2018).

²Data from Jensen et al. (2017).

³Data not reported in Jensen et al. (2017) and Jensen et al. (2018).

θ_{PL}: water content at plastic limit.

Table 2. Geometric means of tensile strength (Y), mass specific rupture energy (E_{sp}) and estimated Young's modulus (E) of air-dry soil aggregates. Geometric means of all size fraction for Y , E_{sp} and E are shown. Treatments labelled with different letters in a given row are significantly different. Pairwise comparison for differences between Arable (A), Ley-arable (LA) and Grass (G), and paired t -test for differences between Bare fallow (BF) and A, LA and G at $p < 0.05$. Values of A, LA and G with an asterisk (*) indicate it is significantly different from BF treatment based on the paired t -test.

Soil attribute	Aggregate size	BF	A	LA	G
Y (kPa)	1–2 mm	617	544	637	526
	2–4 mm	534	570	530	492
	4–8 mm	394	365	361	307
	8–16 mm	419	400	363	279
	Mean	483	462	459	386
E_{sp} (J kg ⁻¹)	1–2 mm	15.4	19.8	23.5	24.1
	2–4 mm	16.3	21.8	18.8	24.6
	4–8 mm	18.5	12	16.8	17.1
	8–16 mm	9.4	10.8	11.7	13.2
	Mean	14.9	15.4a	17.1ab	19.1b*
E (MPa)	1–2 mm	15.9	14.4	13.8	15.4
	2–4 mm	34.3	32.9b	32.6b	25.9a
	4–8 mm	36.1	44.5c	24.7a	34.7b
	8–16 mm	31.9	23.2	22.8	14.8
	Mean	28.2	26.4	22.4*	21.2*

Table 3. Geometric mean of tensile strength (Y), mass specific rupture energy (E_{sp}) and estimated Young's modulus (E) of 8–16 mm soil aggregates adjusted at -100, -300 and -1000 hPa matric potentials. Treatments labelled with different letters in a given row are significantly different. Pairwise comparison for differences between Arable (A), Ley-arable (LA) and Grass (G), and paired t -test for differences between Bare fallow (BF) and A, LA and G at $p < 0.05$. Values of A, LA, and G with an asterisk (*) indicate it is significantly different from BF treatment based on the paired t -test.

Matric potential	Soil attribute	BF	A	LA	G
-100 hPa	Y (kPa)	14.6	15.3	15.2	15.8
	E_{sp} (J kg ⁻¹)	0.55	0.62a	0.86a	1.64b*
	E (MPa)	0.83	0.83b	0.73a	0.68a
-300 hPa	Y (kPa)	23.0	27.3	23.5	20.1
	E_{sp} (J kg ⁻¹)	1.04	1.36	1.31	1.68
	E (MPa)	1.20	1.00	0.87*	0.82*
-1000 hPa	Y (kPa)	38.5	45.1b	30.7a	25.9a*
	E_{sp} (J kg ⁻¹)	1.49	2.05	1.50	2.15
	E (MPa)	2.43	1.81c	1.42b*	1.09a*

Jensen, J.L., Schjonning, P., Christensen, B.T., Munkholm, L.J., 2017. Suboptimal fertilization compromises soil physical properties of a hard-setting sandy loam. *Soil Research* 55, 332-340.

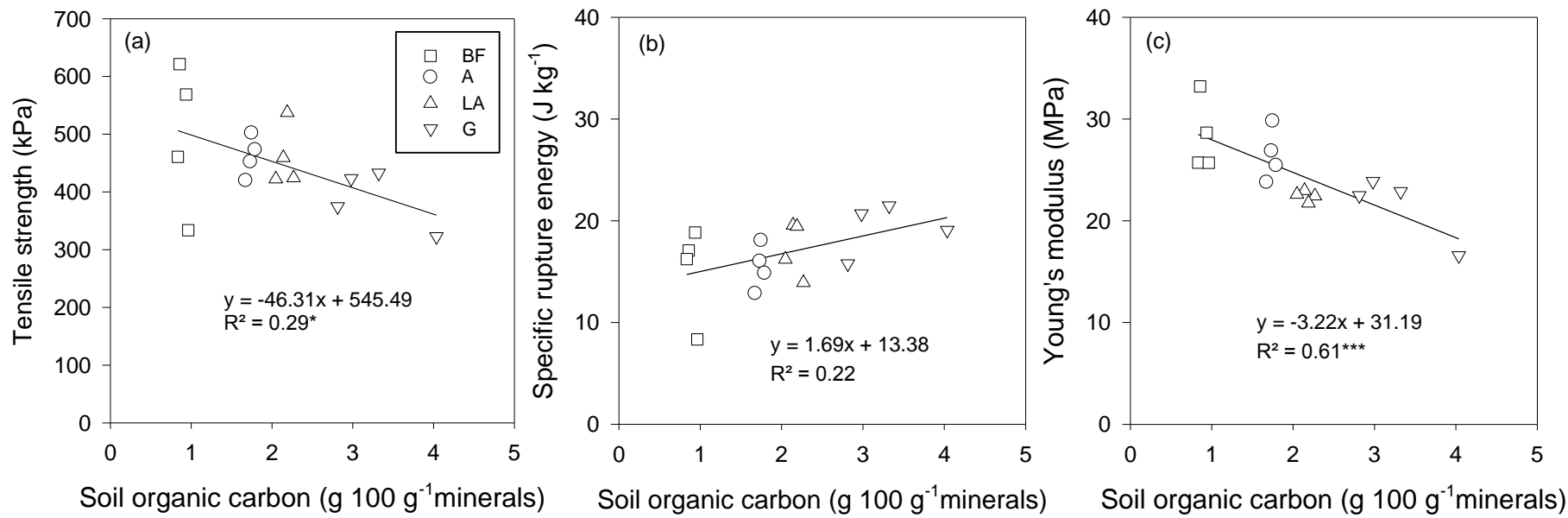
Jensen, J.L., Schjonning, P., Watts, C.W., Christensen, B.T., Peltre, C., Munkholm, L.J., 2018. Relating soil C and organic matter fractions to structural stability. *Geoderma* (submitted).

1 Fig. 1. (a) Tensile strength, (b) Mass specific rupture energy and (c) Young's modulus of air-dry
2 aggregates calculated as geometric means across the four aggregate classes (8–16, 4–8, 2–4 and
3 1–2 mm) for each plot as a function of soil organic carbon. Bare fallow (BF), Arable (A), Ley-
4 arable (LA) and Grass (G) treatments, and Unfertilized (UNF), ½ mineral fertilizer (½NPK), 1
5 mineral fertilizer (1NPK), and 1½ animal manure (1½AM) treatments. * $p < 0.05$ and *** $p < 0.001$

6 Fig. 2. Graphical approach for determining DTL: For Highfield, from natural logarithm of tensile
7 strength of 8–16 mm soil aggregates related to gravimetric water content determined on the
8 aggregates at -100, -300, -1000 hPa matric potentials and at air-dry state for (a) Bare fallow (BF)
9 soil and (b) Grass (G) soil. For Askov, from natural logarithm of tensile strength of 8–16 mm
10 aggregates related to gravimetric water content determined on the aggregates at field capacity,
11 field moist and air-dry state for (c) Unfertilized (UNF) soil and (d) 1½ animal manure (1½AM)
12 soil (n=4 for Highfield, n=3 for Askov).

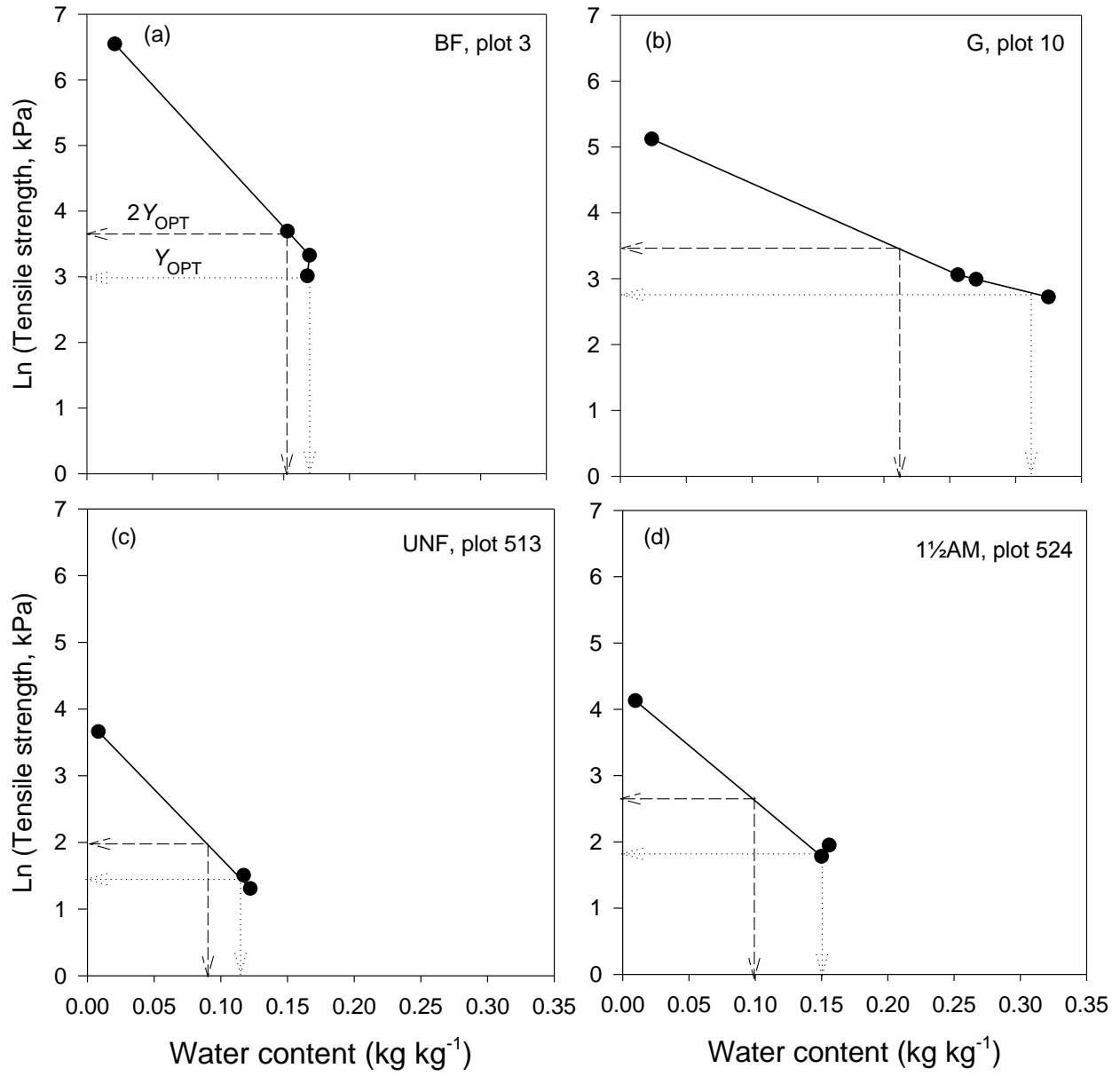
13 Fig. 3. Water contents for tillage based on the water retention approach (a and c), and the
14 consistency approach (b and d) for Highfield and Askov soils. DTL (dry tillage limit), OPT
15 (optimum water content for tillage) and WTL (wet tillage limit). Solid short vertical lines show
16 water content at -100 hPa matric potential. For Highfield soils, treatments labelled with different
17 letters are significantly different. Pairwise comparison for differences between Arable (A), Ley-
18 arable (LA) and Grass (G), and paired t -test for differences between Bare fallow (BF) and A, LA
19 and G at $p < 0.05$. Values of A, LA, and G with an asterisk (*) indicate it is significantly different
20 from BF treatment based on the paired t -test. At Askov: Unfertilized (UNF), ½ mineral fertilizer
21 (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM) treatments. Treatments
22 with different letters are significantly different ($p < 0.05$).

Fig. 4. $\Delta\theta_{\text{RANGE}}$ (water retention) and $\Delta\theta_{\text{RANGE}}$ (consistency) as a function of soil organic carbon content for the Highfield (4a and b) and the Askov (4c and d) soils. Bare fallow (BF), Arable (A), Ley-arable (LA) and Grass (G) treatments, and Unfertilized (UNF), $\frac{1}{2}$ mineral fertilizer ($\frac{1}{2}$ NPK), 1 mineral fertilizer (1NPK), and $1\frac{1}{2}$ animal manure ($1\frac{1}{2}$ AM) treatments. Lines indicate linear regression. *** $p < 0.001$.



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2

3 Fig. 1.



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5 Fig. 2.

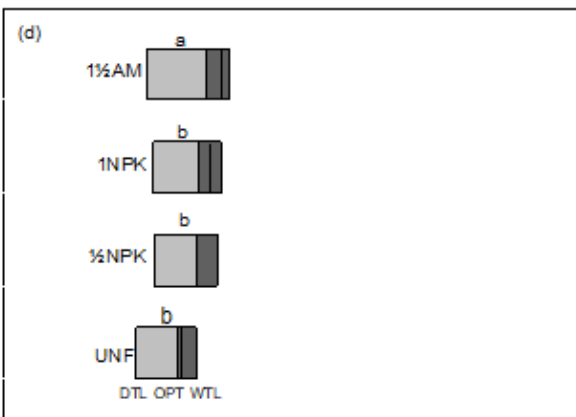
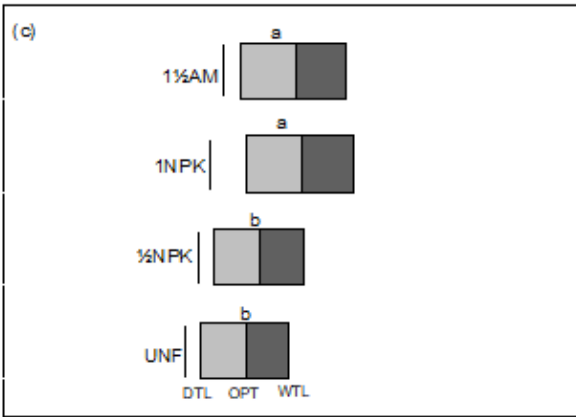
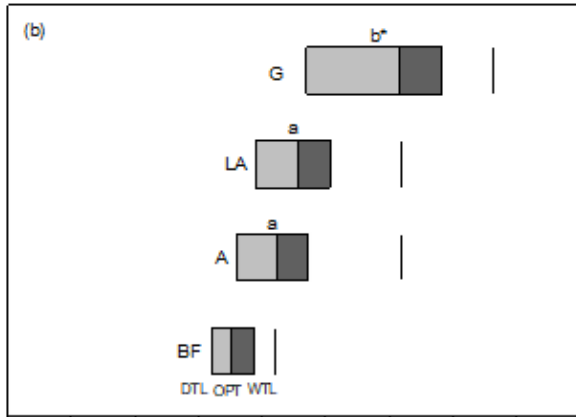
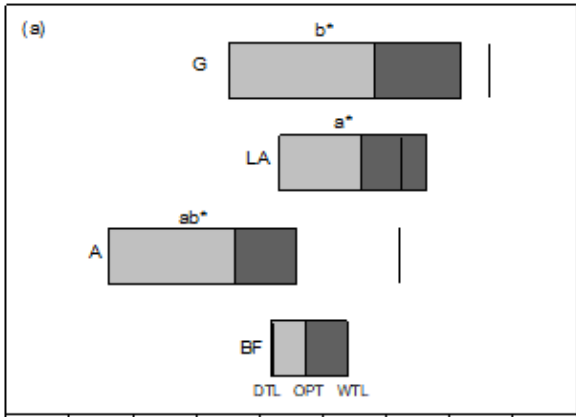
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0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.40 0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45
 Water content (kg kg⁻¹) Water content (kg kg⁻¹)

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12 Fig. 3.

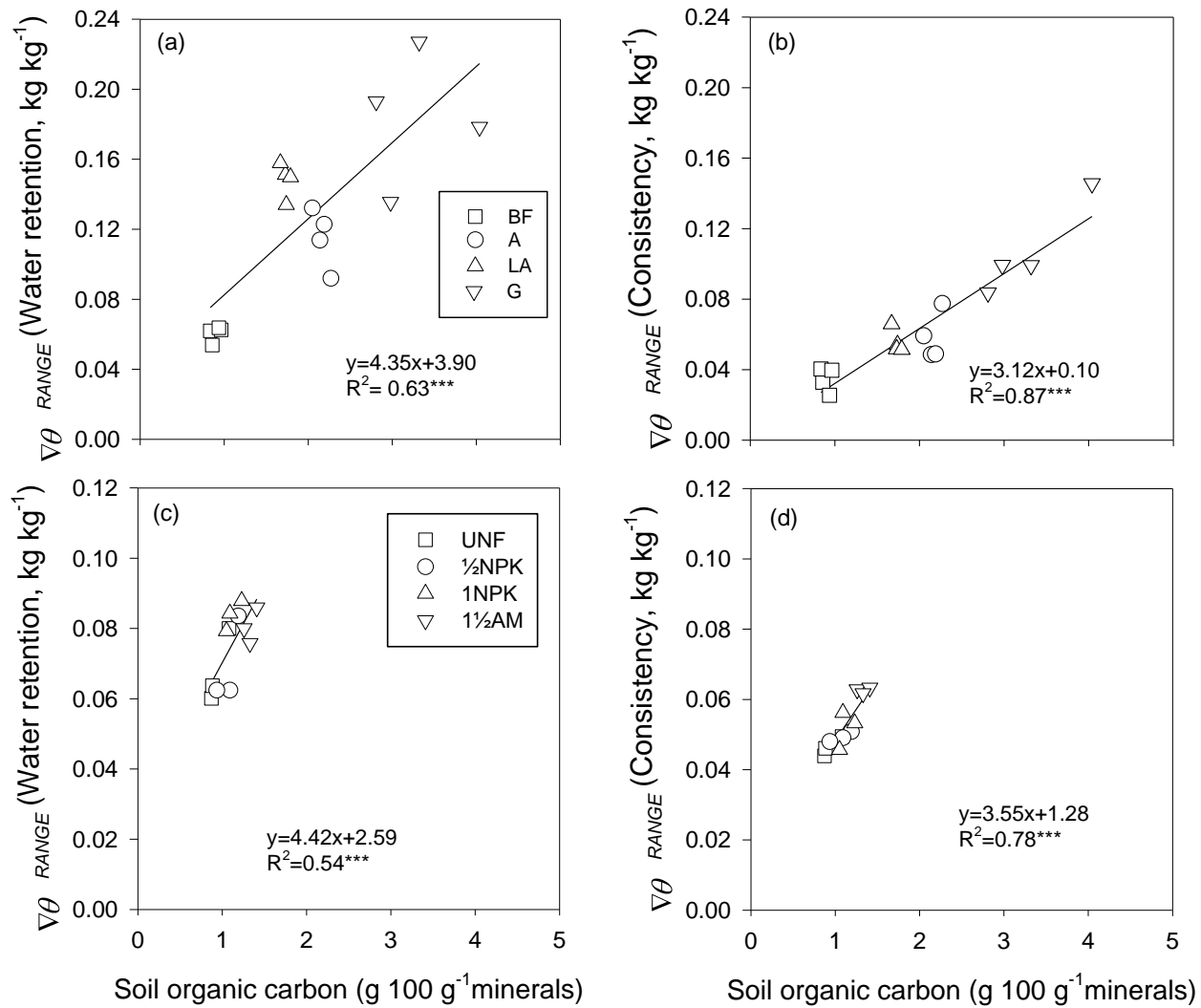


Fig. 4.