

**Significant structural development of a long-term fallow soil  
in response to agricultural management practices requires  
at least 10 years after conversion**

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1 **Significant structural development of a long-term fallow soil in response to agricultural**  
2 **management practices requires at least 10 years after conversion**

3 Running title: Structural development of long-term fallow soils

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18

19 **Abstract (250 words, currently 232)**

20 Agricultural practices can have significant effects on the physical and biological properties of  
21 soil. The aim of this study was to understand how the physical structure of a compromised  
22 soil, arising from long-term bare-fallow management, was modified by adopting different  
23 field management practices. We hypothesised that changing agricultural practice from bare-  
24 fallow to arable or grassland would influence the modification of pore structure *via* an  
25 increase in porosity, pore connectivity, and a more homogenous distribution of pore sizes;  
26 and that this change exerts a rapid development of soil structure following conversion. Soil  
27 aggregates (< 2 mm) collected in successive years from field plots subjected to three  
28 contrasting managements were studied; *viz.* bare-fallow, bare-fallow converted to arable, and  
29 bare-fallow converted to grassland. Soil structure was assessed by X-ray Computed  
30 Tomography on the aggregates at 1.5  $\mu\text{m}$  resolution, capturing detail relevant to soil  
31 biophysical processes. The grassland system increased porosity, diversity of pore sizes, pore-  
32 connectivity and pore-surface density significantly over the decade following conversion.  
33 However, measured at this resolution, the development of most of these metrics of soil  
34 structure required approximately 10 years post-conversion to show a significant effect. The  
35 arable system did not influence soil structural development significantly. Only the pore size  
36 distribution was modified in grassland in a shorter time frame (2 years post-conversion).  
37 Hence development of the soil structural characteristics appears to require at least a decadal  
38 timescale following conversion to grassland.

39

40 **Key words:**

41 Soil structure, 3D pore characteristics, agricultural management practices, X-ray Computed  
42 Tomography, porosity

43

44

45 **Highlights:**

- 46 - The physical structure of a compromised soil was modified by adopting plant-based  
47 field management practices.
- 48 - Conversion to grassland increased pore size diversity after 2 years.
- 49 - Porosity, pore connectivity and pore surface density showed a significant  
50 modification between 7 to 10 years after conversion.
- 51 - Bare fallow soil management for this extreme period (> 50 years) is detrimental to  
52 physical soil properties and the regeneration of the soil structure requires more than  
53 10 years after being reconverted to arable and grassland.

54

55 **Introduction**

56 Agricultural practices can have beneficial or detrimental effects on soil functions when  
57 applied for decades, depending on the nature of such practices (Ashworth et al., 2017;  
58 Bronick and Lal, 2005; Deneff et al., 2009; Pagliai et al., 2004). Agricultural management  
59 generally aims to increase - or at least stabilise - crop yield, but intensive farming can lead to  
60 soil degradation, erosion, compaction and pollution (Bronick and Lal, 2005). Conventional  
61 tillage can lead to a decline in soil aggregation and soil structure (Watts et al., 2001), as well  
62 as depletion of nutrients and organic carbon within soil (Coleman et al., 1997). Addition of  
63 organic matter or crop rotations can prevent soil disruption from tillage by improving soil  
64 porosity and aggregation (Abdollahi et al., 2014; Pagliai et al., 2004). In some cases,  
65 modification of crop management can have beneficial impacts on soil functions. For example,  
66 after 50 years of continuous cultivation, a desert aeolian sandy soil was managed into a  
67 sustainable agricultural soil by increasing silt and clay content (a determinant for aggregate  
68 formation), soil organic matter and nutrient retention (Su et al., 2010). Moreover, soil

69 aggregate stability is a key factor for soil fertility and physical resilience from external forces,  
70 e.g. wind and water (Abivent et al. 2009).

71 Soil structure plays a fundamental role in the distribution of carbon, soil microorganisms,  
72 water and nutrient accessibility (Rabot et al. 2018; Smith et al. 2017). Analysis of soil  
73 structure indicates that pore size distribution, assessed by X-ray Computed Tomography  
74 (CT), plays an important role in aggregate stability (Menon et al. 2020). Increased diversity  
75 of pore sizes (i.e. a more homogenous distribution of pores) is associated with a more  
76 complex pore network. This leads to an increase in the number of storage and transmission  
77 pores resulting in greater water and nutrient flux (Kravchenko et al. 2014; 2019). The  
78 modification of pore size distributions appears to also play a key role in the decomposition of  
79 organic matter (Quigley et al. 2018; Smith et al. 2017; Toosi et al. 2017a; 2017b). For  
80 example, the presence of small (13-32  $\mu\text{m}$ ) and large (136-260  $\mu\text{m}$ ) pores decreases organic  
81 matter decomposition within macro-aggregates (Toosi et al. 2017b). Pore connectivity is also  
82 one of the most important factors, alongside porosity and pore size distribution, to understand  
83 soil functions (Rabot et al. 2018). Modification of pore connectivity can have a significant  
84 effect upon the distribution and the transport of gas and water (Lucas et al. 2020; Müller et al.  
85 2019; Pires et al. 2019). Pires et al. (2017) demonstrated that pore connectivity was enhanced  
86 in zero tillage systems over conventional tillage systems, especially in the upper 10 cm.  
87 In the field, long-term management practices can have substantial impacts on soil structural  
88 dynamics (Bacq-Labreuil et al. 2018; Müller et al. 2019; Pires et al. 2019). For example, 50-  
89 years of management of a typical silty clay loam soil as bare fallow resulted in significant  
90 reductions of carbon and nitrogen, and in the abundance of biological communities (Hirsch et  
91 al. 2009) with soil structure also severely compromised (Bacq-Labreuil et al. 2018).  
92 Conversion from bare fallow to arable or grassland increased soil organic carbon, soil

93 nitrogen and the population of meso-fauna and fungi within 3 to 5 years following conversion  
94 (Hirsch et al. 2017), although, soil structure modification was not assessed in this experiment.  
95 The aim of this study was to establish how the micro-structure of a compromised silt-clay  
96 loam soil is modified by altered field management over time using soil aggregates (< 2 mm  
97 diameter). Three treatments were studied from the converted field of the long-term  
98 experiment: continuous bare-fallow, bare-fallow converted to arable, and bare-fallow  
99 converted to grassland. We hypothesised that: (1) plants are an active factor in increasing soil  
100 porosity, diversity of pore sizes and pore connectivity, and (2) structural development is more  
101 rapid in grassland than arable converted systems due to the greater and more persistent  
102 presence of vegetation. The precise time for soil structural development is unclear *a priori*,  
103 and we aimed to determine this by measuring structural properties on several successive  
104 years after conversion.

105

## 106 **Materials and Methods**

### 107 *Soil aggregate sampling*

108 Samples were obtained from conversion plots of the long-term Highfield Ley-Arable  
109 experiment at Rothamsted Research, Harpenden, UK (LATLONG 51.8103 N, -0.3748 E).  
110 The soil is a silty-clay loam (clay: 27%, silt: 58.4, sand: 14.6%; Jensen et al. 2020b)  
111 developed on clay-with-flints over Eocene London Clay (Batcombe series), classified as  
112 Chromic Luvisol by FAO criteria (Avery and Catt, 1995; FAO, 2006; Watt and Dexter,  
113 1997). In October 2008, plots of soil managed as bare-fallow by regular tillage to remove any  
114 plants since 1952, were converted to arable and grassland managements. The conversion  
115 plots had similar soil characteristics. The conversion of the plots from bare-fallow to arable  
116 and grassland is explained in details in Hirsch et al. (2017). Arable soil was placed under  
117 continuous wheat rotation (winter wheat, *Triticum aestivum* L., c.v. 'Hereward' seed coated

118 with Redigo® Deter® combination insecticide/fungicide treatment, Bayer CropScience)  
119 receiving ammonium nitrate fertilization to provide approximately 220 kg-N ha<sup>-1</sup> y<sup>-1</sup>. For the  
120 arable and grassland plots additional fertilizers 250 kg-K ha<sup>-1</sup> and 65 kg-P ha<sup>-1</sup> was added  
121 every three years. Grassland plots were maintained as a managed sward of mixed fescue  
122 (*Festuca pratensis* L.), Timothy grass (*Phleum pratense* L.) and white clover (*Trifolium*  
123 *repens* L.) (30 kg ha<sup>-1</sup>). To remove weeds, bare-fallowed plots were maintained with regular  
124 tillage or rotavation at least four times *per* year. Arable and bare-fallowed plots were tilled to  
125 a standard depth of 23 cm. Plots have been sampled annually using cores (10 cm height and 3  
126 cm diameter) in October, except in 2018 where the plots were sampled in June. Following  
127 sampling, soil was air-dried and sieved at 2 mm before being archived at room temperature.  
128 Aggregates (< 2 mm diameter) from continuous bare fallow (bare-fallow), bare fallow  
129 converted into arable (arable) and bare fallow converted to grassland (grassland) were  
130 randomly selected from samples collected in 2008, 2010, 2012, 2015 and 2018, representing  
131 0-, 2-, 4-, 7- and 10- years *post* conversion. The replication of treatments was a total of 9  
132 scanned aggregates (< 2 mm) *per* year and *per* treatment where randomly selected from 3  
133 independent plots *per* treatment and 3 aggregates (< 2 mm) *per* plot (i.e. 3 replicates *per* plot)  
134 to be X-ray CT scanned.

135

### 136 *X-ray Computed Tomography*

137 Aggregates (< 2 mm diameter) were scanned using a Phoenix Nanotom® (GE Measurement  
138 and Control solution, Wunstorf, Germany) set at a voltage of 90 kV, a current of 65 µA and  
139 at a resolution of 1.50 µm (thus pores below this size were not considered) at the Hounsfield  
140 Facility at The University of Nottingham. A total of 1,440 projection images were taken at a  
141 500 ms period using an averaging of 3 images and skip of 2. The total scan time per sample  
142 was 60 minutes. Scanned images were reconstructed using Phoenix datos | x2 rec

143 reconstruction software. They were optimised to correct for any movement of the sample  
144 during the scan and subjected to noise reduction using the beam hardening correction  
145 algorithm, set at 8.

146

#### 147 *Image analysis*

148 Image analysis was performed using two software packages, ImageJ (Schneider et al., 2012)  
149 and QuantIm (Vogel et al., 2010) following the method from Bacq-Labreuil et al. (2018).  
150 Briefly, all the images were thresholded using the bin bi-level threshold developed by Vogel  
151 and Kretschmar (1996). QuantIm was used to output the 3D characteristics of the pore  
152 network calculated from the Minkowski functions where the total porosity (referred to as  
153 porosity from here) is the percentage of all the pores  $>1.5 \mu\text{m}$ ; pore size distribution is the  
154 proportion of each size class in the volume normalised to the total pore volume, expressed  
155 here as a cumulative value; pore connectivity was calculated from the Euler number and  
156 normalised to the total volume (the more negative the Euler number, the greater the pore-  
157 connectivity); the pore surface density represents the roughness of the surface of pores: a  
158 lower surface density means a lower roughness, i.e. less surface to be colonised by living  
159 organisms (Vogel et al., 2010). The Gini-coefficient ( $G$ ), a statistical measure of distribution,  
160 was also determined. It is commonly applied in economics research to estimate the statistical  
161 dispersion of income or wealth, and commonly used as a measurement of inequality (Bellù  
162 and Liberati, 2006). Here,  $G$  was applied to measure the distribution of pore size classes as an  
163 indicator of the equality of the pore size distribution.  $G \approx 0$  represents an equitable  
164 distribution of pores amongst all pore size classes meaning that the soil pores have a  
165 homogenous distribution of the pore sizes.  $G \approx 1$  represents a heterogeneous distribution of  
166 pores which means that a majority of pores have the same sizes.

167



168 *Statistical analysis*

169 A standard analysis of variance (ANOVA) was performed using Genstat v 17.1 (VSN  
170 International Ltd., 2014) on the porosity. A two-factor ANOVA was conducted on each  
171 Minkowski function divided by year using a split plot design with the treatment and the  
172 diameter of pores as factors. For total porosity,  $G$ , the connected porosity and pore surface  
173 area, an analysis of co-variance (ANCOVA), was also performed between the arable and  
174 grassland with years' post-conversion as a co-variate using SigmaPlot for Windows ver. 14.0  
175 (Systat Software Inc., San Jose, CA). In the case of pore surface area, pore diameter was  
176 employed as a second covariate. Parameters were tested following either square root or  $\log_{10}$   
177 transformation where necessary to conform to model assumptions of normality (tested using  
178 the Shapiro-Wilk test) and homogeneous variances (tested using Levene's test). In each case,  
179 ANCOVA was used to test for homogeneity of slopes associated with the change of total and  
180 connected porosities and  $G$  with years' post-conversion of bare fallow to either arable or  
181 grassland management. Soil managed as bare fallow throughout the experiment was used to  
182 account for temporal changes in soil parameters under continuous management. *Post hoc*  
183 pair-wise comparisons were performed employing the Copenhaver & Holland multiple  
184 comparisons procedure (Holland and Copenhaver, 1987).

185

186 **Results**

187 *Visual appraisal of soil structures*

188 Representative 2D images showed that after 1 and 3 years, all three treatments had similar  
189 pore architectures in terms of size and shape (Fig. 1a-f). After 5 years, arable and grassland  
190 started to display different pore configurations clearly manifest by a greater proportion of  
191 larger pores ( $>40 \mu\text{m}$ ; Fig. 1g-i). The evolution of the pore characteristics over time was  
192 apparent, after 7- and 10-years *post* conversion for the arable and grassland treatments

193 especially for vugh (i.e. irregular) and crack shaped pores (Fig. 1j-o). In contrast the size and  
194 distribution of pores was relatively consistent over time.

195

#### 196 *Total Porosity*

197 Before the conversion (in 2008) and after 2 and 4 years, there were no significant treatment  
198 effects on porosity ( $P > 0.05$ ; Fig. 2a-c) compared to 7- and 10-years post conversion  
199 (respectively  $P = 0.029$  and  $P = 0.002$ ; Fig. 2d, e). After 7 years, the porosity in the grassland  
200 soil was greater than in bare-fallow or arable soils which were similar (Fig. 2d). However,  
201 after 10 years, porosity increased in the presence of plants according to the ranking; bare-  
202 fallow < arable < grassland (Fig. 2e). No significant change in  $\log_{10}$  total porosity was  
203 observed in the continuous bare-fallow soil over the 10 years (slope = 0.026,  $t = 0.104$ ,  $p =$   
204 0.917) (Supplementary Fig. 1). However, total porosity in soils converted to arable (slope =  
205 0.713,  $t = 3.4$ ,  $p = 0.0014$ ) and grassland (slope = 0.41,  $t = 3.7$ ,  $p < 0.001$ ) managements  
206 increased over the same period (Fig. 1f). ANCOVA comparing the arable and grassland soils  
207 identified a significant time response in  $\log_{10}$  porosity ( $F_{1,86} = 31.0$ ,  $p < 0.001$ ) but no  
208 significant difference in the rates of change (slope) in total porosity ( $F_{1,86} = 0.8$ ,  $p = 0.36$ ).  
209 The resulting equal slopes model identified a significant difference in the adjusted mean  $\log_{10}$   
210 total porosity of each treatment ( $F_{1,87} = 23.5$ ,  $p < 0.001$ ) with grassland accumulating  
211 significantly greater  $\log_{10}$  porosity ( $0.985 \pm 0.025$ , equivalent to  $9.66 \pm 1.05\%$ , adjusted mean  
212  $\pm$  standard error of the mean) than arable soil ( $0.848 \pm 0.021$ , equivalent to  $7.05 \pm 1.05\%$ )

213

#### 214 *Pore size distribution*

215 Before the conversion (in 2008), there was no significant treatment effect on the cumulative  
216 pore size distribution ( $P > 0.05$ ; Fig. 3a). Between 2- to 10-years post conversion, there was a  
217 significant diameter by treatment interaction with respect to the cumulative pore size

218 distribution (2 and 7 years:  $P < 0.001$ ; 4 and 10 years:  $P < 0.05$ ; Fig. 3b-e). After 2 years post  
219 conversion, there was a greater proportion of smaller pores under bare-fallow and arable  
220 treatments than grassland: for bare-fallow and arable, approximately 50% of pores were  
221 smaller than  $3.56 \mu\text{m}$  and 70% of pores smaller than  $5.97 \mu\text{m}$  compared to grassland where  
222 50% of pores were smaller than  $5.97 \mu\text{m}$  and 70% smaller than  $14.9 \mu\text{m}$ . Moreover, the  
223 proportion of pores larger than  $42 \mu\text{m}$  was greater under grassland (13% of pores) than bare-  
224 fallow and arable (respectively 1% and 2% of pores; Fig. 3b). After 4 years, this trend was  
225 not apparent: the difference between grassland compared to bare-fallow and arable was less  
226 significant than after 2 years. The proportion of pores smaller than  $9.26 \mu\text{m}$  was greater under  
227 bare-fallow and arable compared to grassland but the proportion of pores larger than  $42 \mu\text{m}$   
228 was not significant between all treatments (Fig. 3c). After 7 years, the trend observed after 2  
229 years was more apparent: the proportion of pore sizes smaller than  $14.9 \mu\text{m}$  was greater  
230 ranking from bare-fallow > arable > grassland and the proportion of pore sizes over  $42 \mu\text{m}$   
231 was greater under arable and grassland (respectively 7% and 10% of pores) than bare-fallow  
232 (2% of pores; Fig. 3d). After 10 years post conversion, this trend was also observed, but only  
233 for pores smaller than  $9.26 \mu\text{m}$ , where the proportion of pores followed the ranking; bare-  
234 fallow > arable > grassland (Fig. 3e). Beyond this pore size, the proportion of pore sizes was  
235 not significantly different between bare-fallow and arable. The proportion of pore sizes  
236 greater than  $42 \mu\text{m}$  was highest under grassland (15% of pores) than bare-fallow and arable  
237 (respectively 4% and 2% of pores; Fig. 3e).

238 The general trend in all three treatments was a shift to a more even distributions of pore sizes,  
239 manifest as a decrease in  $G$  over time (Fig. 3f). ANCOVA indicated equal rates of change of  
240  $G$  between treatments ( $F_{2,129} = 0.18, p = 0.834$ ). Using an equal slopes model, there was a  
241 significant effect of land management upon  $G$  ( $F_{2,131} = 9.1, p < 0.001$ ) with grassland having  
242 a significantly lower adjusted mean  $G$  ( $0.420 \pm 0.033$ ) than either bare-fallow (adjusted mean

243  $G = 0.566 \pm 0.028$ ;  $t = 3.6$ ,  $p < 0.001$ ) or arable (adjusted mean  $G = 0.571 \pm 0.024$ ;  $t = 3.7$ ,  $p$   
244  $< 0.001$ ). There was no significant difference in adjusted mean  $G$  between arable and bare-  
245 fallow ( $t = 0.13$ ,  $p = 0.900$ ).

246

#### 247 *Pore connectivity*

248 Before the conversion (in 2008) and after 7-years post conversion, there was no significant  
249 pore diameter by treatment interaction with regards to pore connectivity ( $P = 0.05$ ; Fig. 4a, d).  
250 However, there was a significant pore diameter by treatment interaction after 2-, 4- and 10-  
251 years (with 2- and 10-years:  $P < 0.001$ ; 4-years:  $P < 0.05$ ; Fig. 4b, c, e). After 2- and 4- years,  
252 the difference was significant only for the pore sizes smaller than  $3.56 \mu\text{m}$ . After 2-years,  
253 pore connectivity was greater ranking from bare-fallow  $>$  grassland  $>$  arable (Fig. 4b) and  
254 after 4-years, pore connectivity was greater under arable and grassland than bare-fallow (Fig.  
255 4c). After 10-years post-conversion, the same trend as after 4-years was shown with a greater  
256 difference in the values (Fig. 4e). There was no significant trend in square root transformed  
257 connected porosity (Supplementary Fig. 2) in bare-fallow (slope =  $-0.00023$ ,  $t = 0.051$ ,  $p =$   
258  $0.959$ ). However, both arable (slope =  $0.017$ ,  $t = 4.0$ ,  $p = 0.0002$ ) and grassland (slope =  
259  $0.022$ ,  $t = 5.3$ ,  $p < 0.0001$ ) showed increases in connected porosity with time. ANCOVA  
260 comparing arable and grassland indicated a significant influence of time *post* conversion  
261 upon square root transformed connected porosity ( $F_{1,85} = 43.9$ ,  $p < 0.001$ ) but no significant  
262 heterogeneity of slopes ( $F_{1,85} = 0.98$ ,  $p = 0.326$ ). Using an equal slopes model, a significant  
263 effect of management was detected ( $F_{1,85} = 4.4$ ,  $p = 0.039$ ): grassland was associated with  
264 greater connected porosity ( $0.048 \pm 0.0002\%$ , adjusted mean  $\pm$  standard error) than arable  
265 ( $0.011 \pm 0.0002\%$ ).

266

#### 267 *Pore surface density*

268 Before the conversion (in 2008) and at 4- and 7-years *post* conversion, there was no  
269 significant pore diameter by treatment interaction with regards to pore surface density  
270 ( $P > 0.05$ ; Fig. 5a, c, d). There was a significant diameter by treatment interaction after 2- and  
271 10-years (respectively  $P < 0.05$  and  $P < 0.001$ ; Fig. 5b, e). After 2-years, the difference in pore  
272 surface density was greater ranking from bare-fallow > arable > grassland for the pore sizes  
273 equal to 1.86  $\mu\text{m}$ , and the difference between arable and grassland was not significant for the  
274 pore sizes equal to 3.56  $\mu\text{m}$ . Beyond this pore size, there was no significant difference  
275 between treatments (Fig. 5b). Ten years *post* conversion, pore surface density was greater  
276 ranking from grassland > arable > bare-fallow, for all pore sizes smaller than 14.9  $\mu\text{m}$ , there  
277 was no significant difference beyond this pore size (Fig. 5e). Years post-conversion and pore  
278 diameter were both used as covariates in ANCOVA analysis of pore surface area.  
279 Accounting for these two covariates, an equal slopes model identified a significant effect of  
280 land management upon pore surface area ( $F_{2,2020} = 9.1, p < 0.001$ ). *Post hoc* pair-wise  
281 comparison of adjusted means indicated that grassland supported a greater pore surface area  
282 ( $0.00784 \pm 0.000493 \mu\text{m}^2 \mu\text{m}^{-3}$ ) than either arable ( $0.00617 \pm 0.000452 \mu\text{m}^2 \mu\text{m}^{-3}$ ; difference  
283 =  $0.00167, t = 3.4, p = 0.001$ ) or bare-fallow ( $0.00593 \pm 0.000443 \mu\text{m}^2 \mu\text{m}^{-3}$ ; difference =  
284  $0.00191, t = 3.9, p < 0.001$ ). There was no significant difference in pore surface area between  
285 arable and bare-fallow (difference =  $0.000240, t = 0.495, p = 0.621$ ).

286

## 287 Discussion

288 The plots studied here were derived from long-term bare-fallow management converted to  
289 arable and grassland. A lack of a significant treatment effect on porosity until 7-years post  
290 conversion suggests that modification of micro-porosity takes several years (Fig. 2). Another  
291 study on the same soil 2 and 4 years post conversion found some recovery of meso-faunal  
292 populations after 2-years of conversion and an increase in soil organic matter and microbial

293 abundance after 4- and 2-years respectively (Hirsch et al., 2017). However, our study showed  
294 that development of micro-scale porosity apparently takes longer. This might be related to  
295 carbon cycling processes which are modified by the microbial communities and plants (*via*  
296 decomposition of organic matter and rhizodeposition). This is likely to affect soil structure at  
297 the micro-scale, but not instantaneously. Increased pore formation under grassland compared  
298 to arable is consistent with a previous study, which showed greater resistance to, and  
299 development from physical stresses of soil structure from grassland (Gregory et al., 2009).  
300 They posited that the greater proportion of organic matter enhanced the elastic recovery of  
301 soil structure (Gregory et al., 2009).

302 Pore size distributions showed a more rapid response to altered management than porosity for  
303 the grassland treatment: after only 2-years of conversion (in 2010), a greater diversity of pore  
304 sizes was observed, and this trend was also recorded in the data after 7- and 10-years (Fig. 3).  
305 The Gini-coefficient indicated that soil converted to grassland established a more even  
306 distribution of pore sizes than the other treatments, meaning that grassland treatment had a  
307 greater diversity of pores after 2-, 7- and 10-years post conversion (Supplementary Fig. 2)  
308 leading to enhanced functionality. This increase in pore size diversity might be due to the  
309 increase of presence of plants, active organisms and organic matter (Hirsch et al., 2017) as  
310 well as the absence of tillage. A study focused on the soil organic carbon on the same  
311 experiment found that the conversion of the bare-fallow soil to grassland led to an increase of  
312 soil organic carbon (+46 %) 7-years post conversion (Jensen et al. 2020a). There is no data  
313 regarding the conversion from bare-fallow to arable. Thus, the increase of organic matter in  
314 the converted soil may play a role in the more homogenous distribution of the pore sizes.  
315 Indeed, in a silty clay soil, the greater organic matter content increases the proportion of  
316 pores between 0.5 to 500  $\mu\text{m}$  (Metzger and Yaron, 1987; Watts and Dexter, 1997) leading to  
317 a more equitable distribution of pore sizes, i.e. a greater diversity of pore sizes. The greater

318 diversity of pore sizes under soil converted to grassland was consistent with a previous study  
319 describing the long-term effect of grassland management on the same field experiment  
320 (Bacq-Labreuil et al., 2018). After 4-years the pore size distribution did not follow this trend  
321 (Fig. 3c), which could be due to weather conditions prior sampling in that year. Indeed, 2008  
322 and 2012 (at the start and 4-years post conversion respectively) were the wettest years during  
323 the experimental period (Supplementary Fig. 3). In the presence of water, clay particles can  
324 swell, and the compression of entrapped air in capillary pores can disrupt the pore  
325 architecture, and affect the pore size distribution (Denef et al., 2001; Grant and Dexter,  
326 1990). Pore networks are re-structured upon re-wetting due to the nature of soil particles.  
327 Changes in pore size between 2-, 4- and 7-years post-conversion raises the question of the  
328 dynamics of this mechanism. The pore size distribution may have had a heterogeneous  
329 response over time due to the impact of the wet year 4-years post-conversion, which shows  
330 the rapid development of the pore size distribution after a sustained wet period compared to  
331 the impact of agricultural practices (Supplementary Fig. 3). For the arable treatment, this  
332 trend was not observed even 10-years post conversion, which might be due to the associated  
333 tillage practices.

334 For pore connectivity, the conversion to grassland had a small effect after 2- and 4-years  
335 compared to after 10-years post conversion (Fig. 4 b, c, e). However, pore connectivity data  
336 after 10-years post conversion, for both arable and grassland converted soils (Fig. 4e),  
337 suggested the pore network was less connected compared to Bacq-Labreuil et al., (2018).  
338 This indicated that a longer time may be required to develop the connectivity of a pore  
339 network than the overall porosity. Increased connectivity of pores promotes water, gasses and  
340 nutrient flows within the pore structure (Dexter, 1988; Tisdall and Oades, 1982). Therefore,  
341 subtle increases in pore connectivity might increase water, gas and nutrient flux within the  
342 soil. As well as the pore connectivity, the pore surface density was significantly increased in

343 the grassland and arable 10-years post-conversion (Fig. 5e). Our results are congruent with  
344 Bacq-Labreuil et al. (2018), which showed grassland managed consistently for over 200 years  
345 has an increased pore surface density compared to arable and bare-fallow soils *i.e.* the pore-  
346 solid interface which led to a greater surface of the pore where micro-organisms and plant  
347 roots can colonise and water films can develop. A greater pore surface density in the  
348 converted plot means that the grassland and the arable have a more complex structure of  
349 pores than the bare-fallow soil (Müller et al. 2019). The greater surface density for the  
350 grassland compared to the arable might be induced by the greater SOC content and the  
351 absence of tillage for this treatment (Hirsch et al. 2017; Jensen et al. 2020a). This can lead to  
352 the formation of new habitats and niches which can be beneficial for microbial community  
353 diversity (Holden, 2011). The greater pore surface area might increase water and nutrient  
354 uptake by the microbial community and plants.

355 This study suggests that conversion of degraded bare-fallow soil to grassland requires at least  
356 10-years after conversion before being effective in terms of significant development of soil  
357 structure at aggregate scale, as assessed by the overall and connected porosity. Moreover, the  
358 conversion from bare-fallow to arable had no significant effect on soil structural properties  
359 after a decade. In general, the recovery of meso-fauna and organic matter (Griffiths et al.,  
360 2000; Hirsch et al., 2017) were more rapid than the recovery of soil structure (Gregory et al.,  
361 2009). The pore size distribution was the only characteristic which was more sensitive to  
362 changes induced by wetting and drying cycles and living organisms.

363

364 Our first hypothesis was supported since porosity, pore size diversity, pore connectivity, and  
365 pore surface area density were all enhanced in grassland soil. Moreover, the conversion to  
366 arable management did not affect soil structural development significantly. The conversion to  
367 grassland increased the range of pore sizes after 2-years, consistent with our second



368 hypothesis. However, all other Minkowski functions (porosity, pore connectivity and pore  
369 surface area density) responded to change more slowly. The mechanisms behind the  
370 development of pore sizes appeared to be dynamic and possibly dependent upon weather  
371 conditions before sampling. Apart from the pore size distribution, the magnitude of the  
372 grassland effects on all other Minkowski functions was lower than the difference observed  
373 after a minimum of 50 years of management (Bacq-Labreuil et al., 2018). In this study, the  
374 effect of grassland upon porosity and pore connectivity were two-fold greater than bare-  
375 fallow management. Here, the difference was significant but not as major. Bare-fallow soil  
376 management for this long period (> 50 years) is detrimental to both physical and biological  
377 soil properties and the development of the soil structure after this requires more than 10 years  
378 after the conversion the grassland

379

### 380 **Conclusions**

381 The soil structural development of a degraded silt-clay loam soil, as quantified by micro-scale  
382 topological metrics, requires at least 10-years of a grassland management before showing any  
383 significant effects.. These observations raise the question on the application to certain  
384 managements in agricultural practices. For example, instead of applying a bare-fallow  
385 treatment in a crop rotation, it would be beneficial for the soil characteristics to apply a  
386 vegetation cover *i.e.* cover crops which increase organic matter inputs and influence soil  
387 structure, leading to a 'conditioning' of soil physical and biological characteristics for the  
388 next crop. This would prevent further degradation of soil and help its development if the soil  
389 characteristics were compromised. Moreover, the development of soil structure is apparently  
390 a long process in the context of current agricultural practices and perceived imperatives.  
391 Thus, a modification of cropping managements should be anticipated to require some time  
392 before the observation of beneficial impacts on soil structural dynamics.

393

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404

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529

530 **Figure 1:** Representative 2D X-ray attenuation images of soils subjected to different forms of  
531 management over 10-years following conversion to each treatment. Base resolution is 40  $\mu\text{m}$ ;  
532 (P) pores are the darker shades and (S) soil matrix are the lighter shades which relate to the  
533 attenuation of the X-ray (a sharpening algorithm has been passed over these images to  
534 increase contrast of features); (a, d, g, j, m) bare-fallow; (b, e, h, k, n) arable; and (c, f, i, l, o)  
535 grassland.

536

537 **Figure 2:** Porosity (based on resolution of 1.5  $\mu\text{m}$ ) in bare fallow, arable and grassland soils  
538 in the years following: (a) 0-year; (b) 2-years; (c) 4-years; (d) 7-years; (e) 10-years. Bars are  
539 means ( $n = 9$ ) expressed as the percentage of pores relative to the total volume, whiskers  
540 denote pooled standard errors. (f) Porosity evolution 0- to 10-years *post* conversion, data  
541 points represent means ( $n = 9$ ), whiskers denote pooled standard errors for clarity and trend  
542 lines are linear regressions.

543

544 **Figure 3:** Cumulative pore size normalized to the total volume in relation to bare-fallow,  
545 arable and grassland in the years following conversion: (a) 0-year; (b) 2-years; (c) 4-years;  
546 (d) 7-years; (e) 10-years. Data points indicate means ( $n=9$ ), whiskers denote pooled standard  
547 errors. (f) Gini coefficient development 0- to 10-years post conversion, data points represent  
548 means ( $n = 9$ ), whiskers denote pooled standard errors for clarity and trend lines are linear  
549 regressions.

550

551 **Figure 4:** Pore connectivity normalized to total volume in continuous bare fallow, arable and  
552 grassland soils following conversion: (a) 0-year; (b) 2-years; (c) 4-years; (d) 7-years; (e) 10-  
553 years. Data points indicate means ( $n=9$ ), whiskers denote pooled standard errors.

554



555 **Figure 5:** Pore surface density in continuous bare fallow, arable and grassland soils following  
556 conversion: (a) 0-year; (b) 2-years; (c) 4-years; (d) 7-years; (e) 10-years. Data points indicate  
557 means ( $n = 9$ ), whiskers denote pooled standard errors.

558

For Peer Review

## Appendix

### **Significant structural development of a long-term fallow soil in response to agricultural management practices requires at least 10 years after conversion**

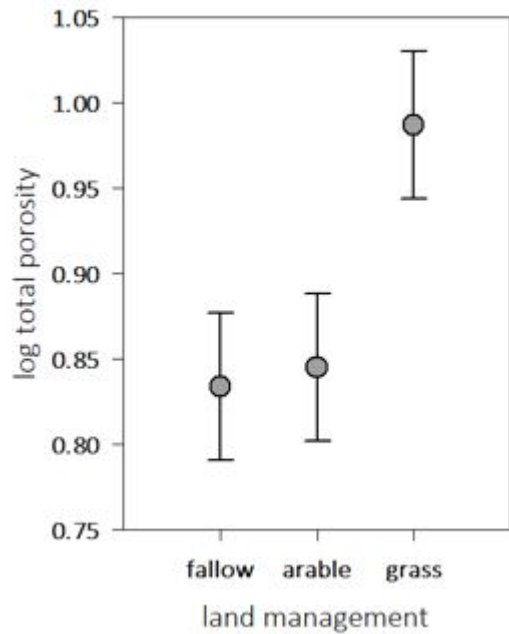
NAME(S) OF AUTHOR(S): A. BACQ-LABREUIL<sup>a§\*</sup>, A. L. NEAL<sup>b</sup>, J. CRAWFORD<sup>c†</sup>, S. J. MOONEY<sup>a</sup>, E. AKKARI<sup>c</sup>, X. ZHANG<sup>c</sup>, I. CLARK<sup>c</sup>, K. RITZ<sup>a</sup>

#### **List of figures**

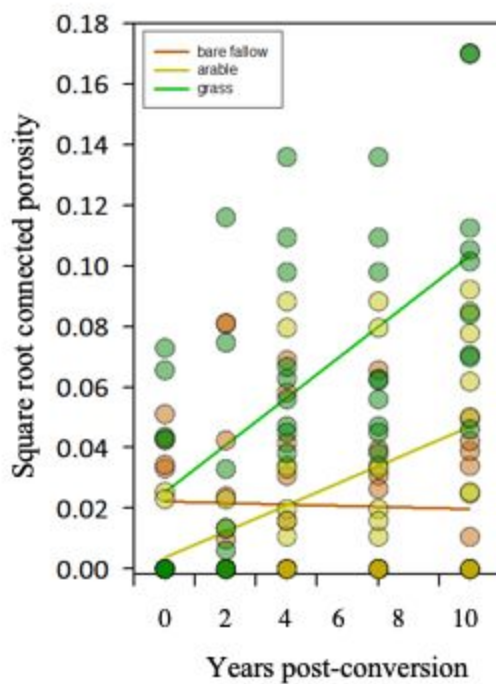
**Supplementary Figure 1:** Log<sub>10</sub> total porosity, points represent the adjusted means generated from an analysis of covariance, employing time *post* conversion (years) as the covariate. Errors represent the 95% confidence intervals associated with the adjusted means

**Supplementary Figure 2:** Square root transformed connected porosity: points represent the replicates and the lines are a linear regression for each treatment.

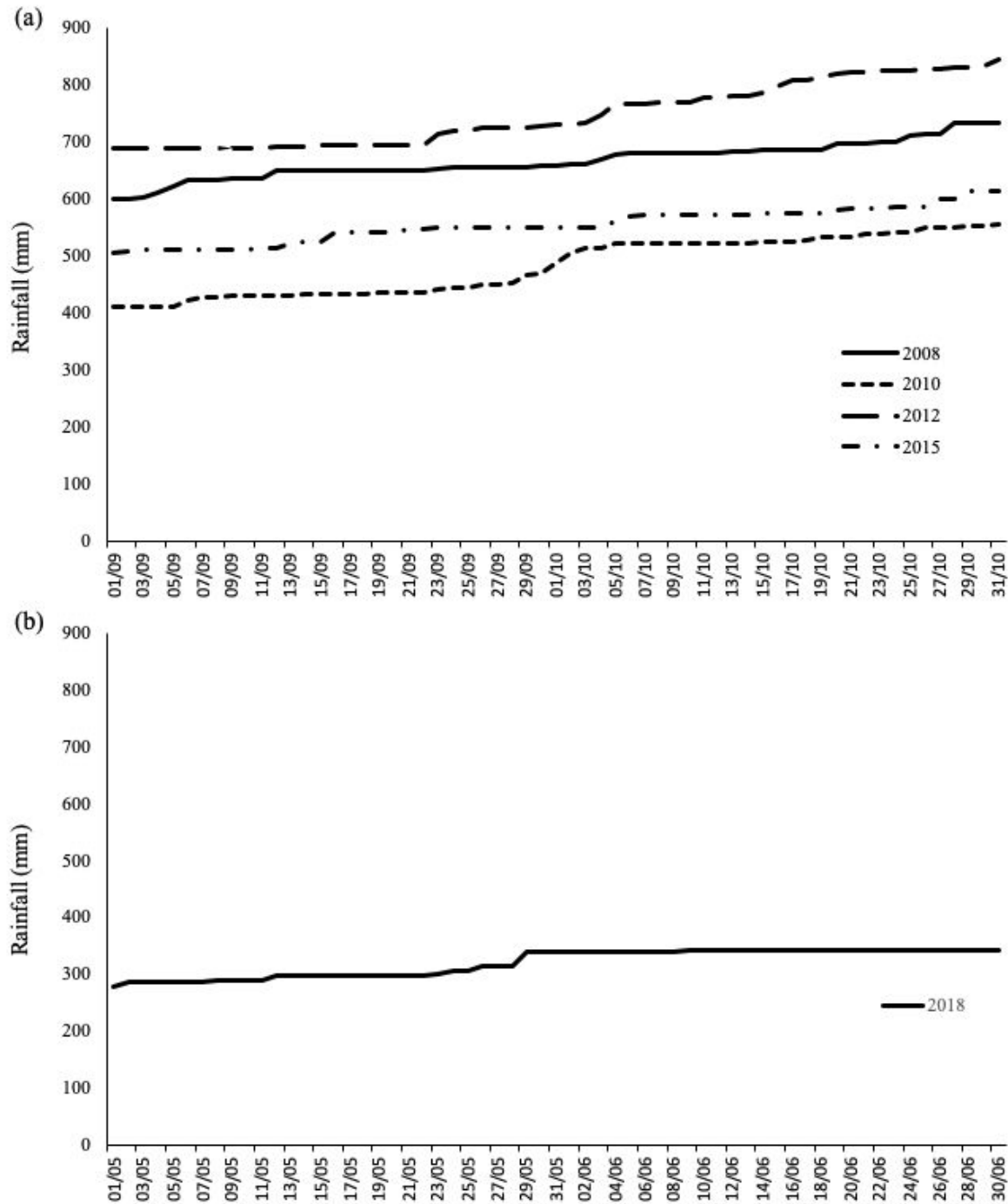
**Supplementary Figure 3:** Cumulative rainfall (mm) on the Highfield from (a) September to October for 2008 to 2015; and (b) May to June for 2018, as the sampling time were different.



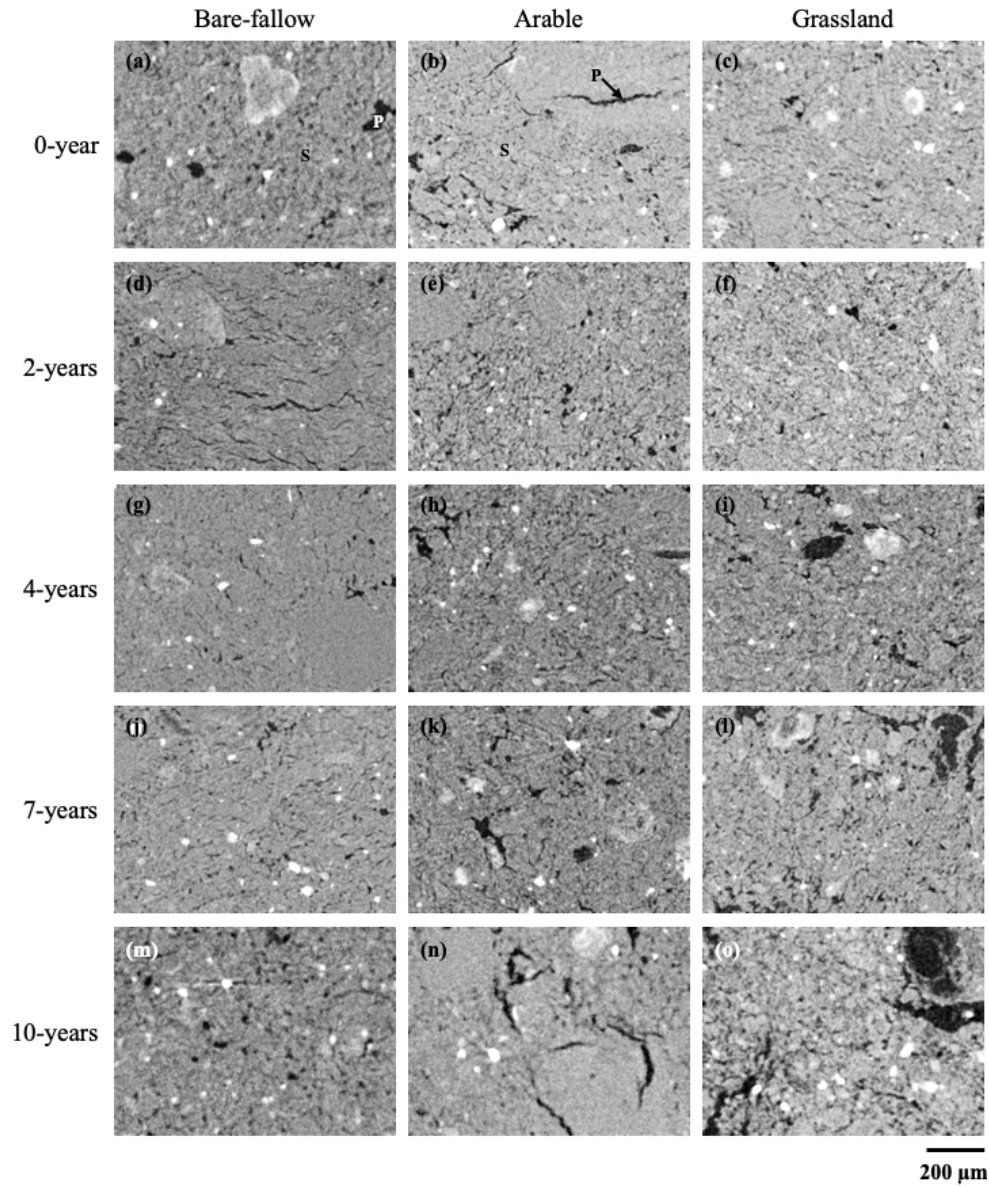
**Supplementary Figure 1:**  $\text{Log}_{10}$  total porosity, points represent the adjusted means generated from an analysis of covariance, employing time *post* conversion (years) as the covariate. Errors represent the 95% confidence intervals associated with the adjusted means



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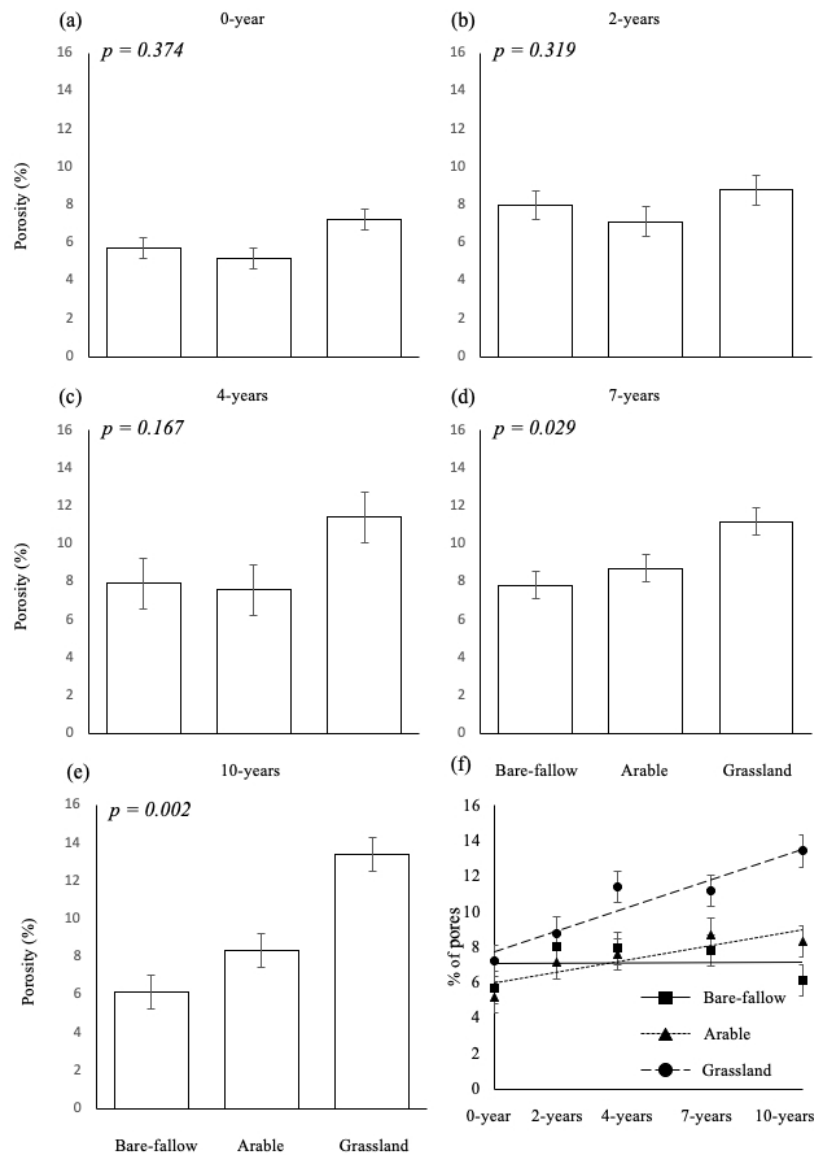


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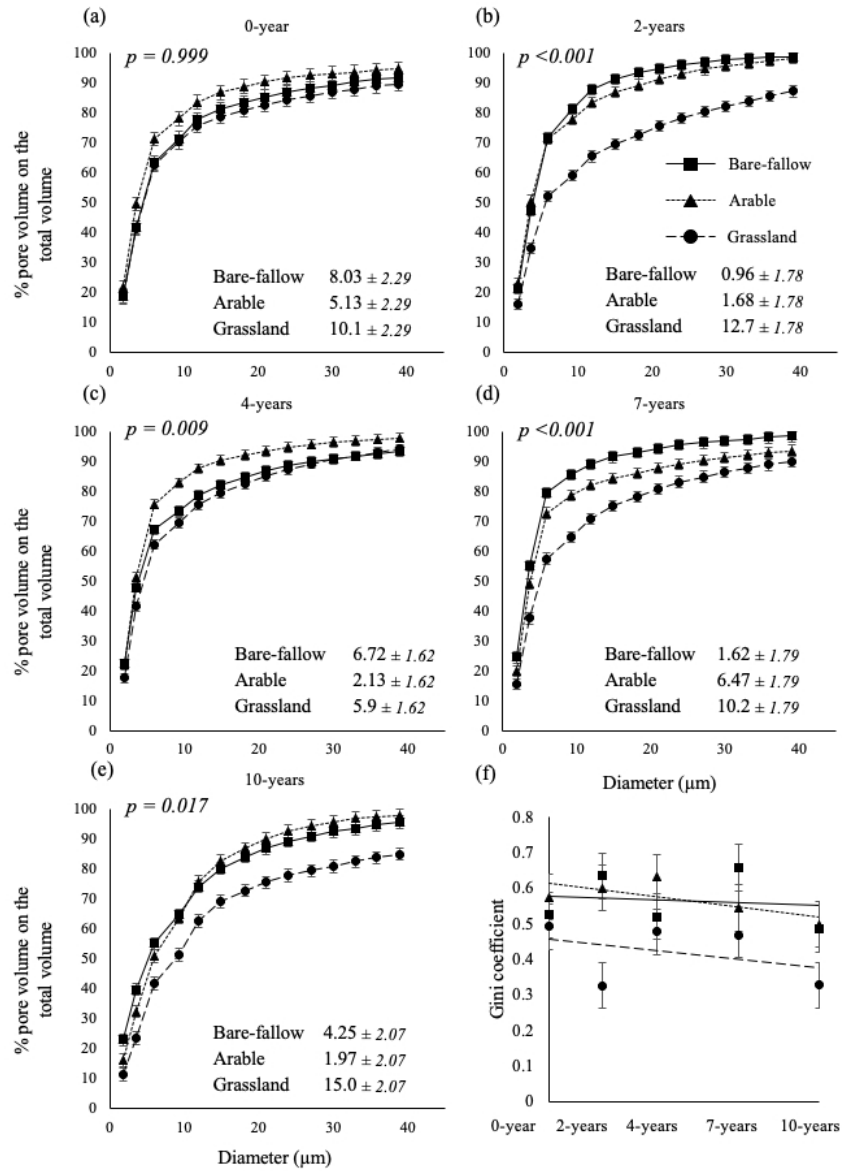
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190x234mm (96 x 96 DPI)



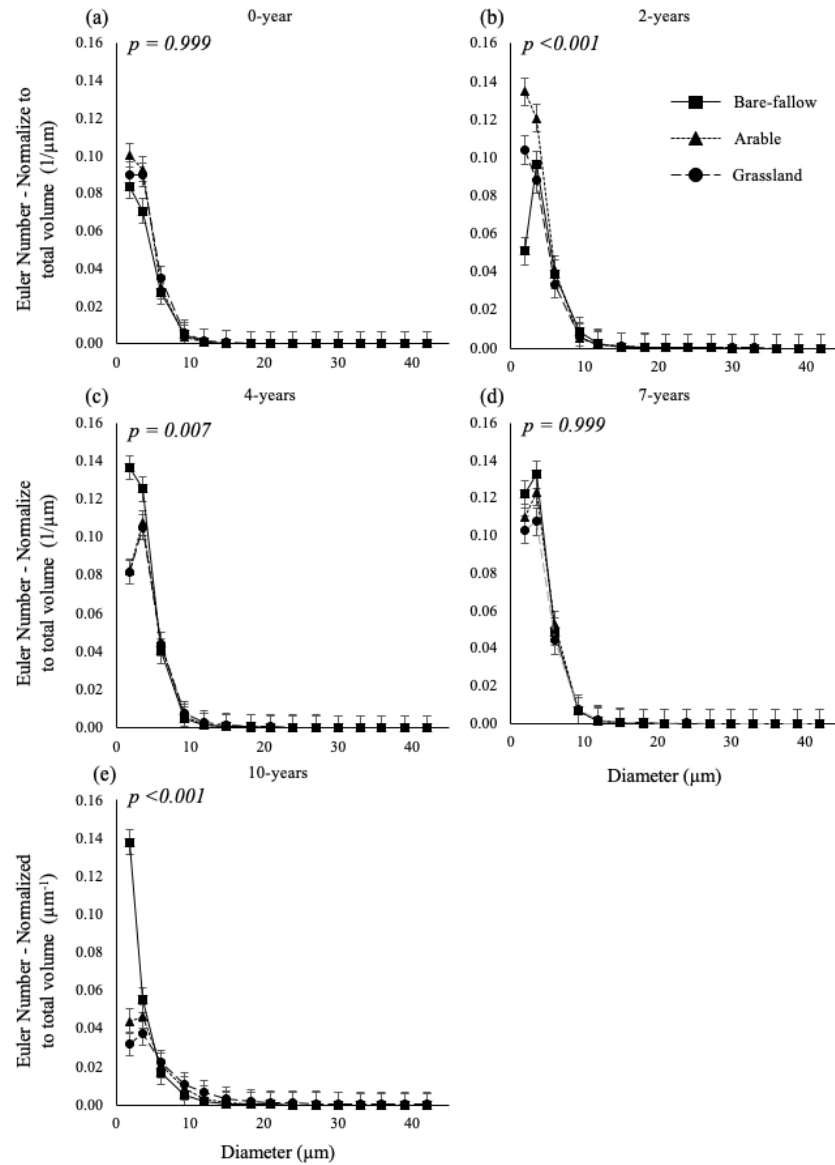
Porosity (based on resolution of 1.5  $\mu\text{m}$ ) in bare fallow, arable and grassland soils in the years following: (a) 0-year; (b) 2-years; (c) 4-years; (d) 7-years; (e) 10-years. Bars are means ( $n = 9$ ) expressed as the percentage of pores relative to the total volume, whiskers denote pooled standard errors. (f) Porosity evolution 0- to 10-years post conversion, data points represent means ( $n = 9$ ), whiskers denote pooled standard errors for clarity and trend lines are linear regressions.

179x244mm (96 x 96 DPI)



Cumulative pore size normalized to the total volume in relation to bare-fallow, arable and grassland in the years following conversion: (a) 0-year; (b) 2-years; (c) 4-years; (d) 7-years; (e) 10-years. Data points indicate means (n=9), whiskers denote pooled standard errors. (f) Gini coefficient development 0- to 10-years post conversion, data points represent means (n = 9), whiskers denote pooled standard errors for clarity and trend lines are linear regressions.

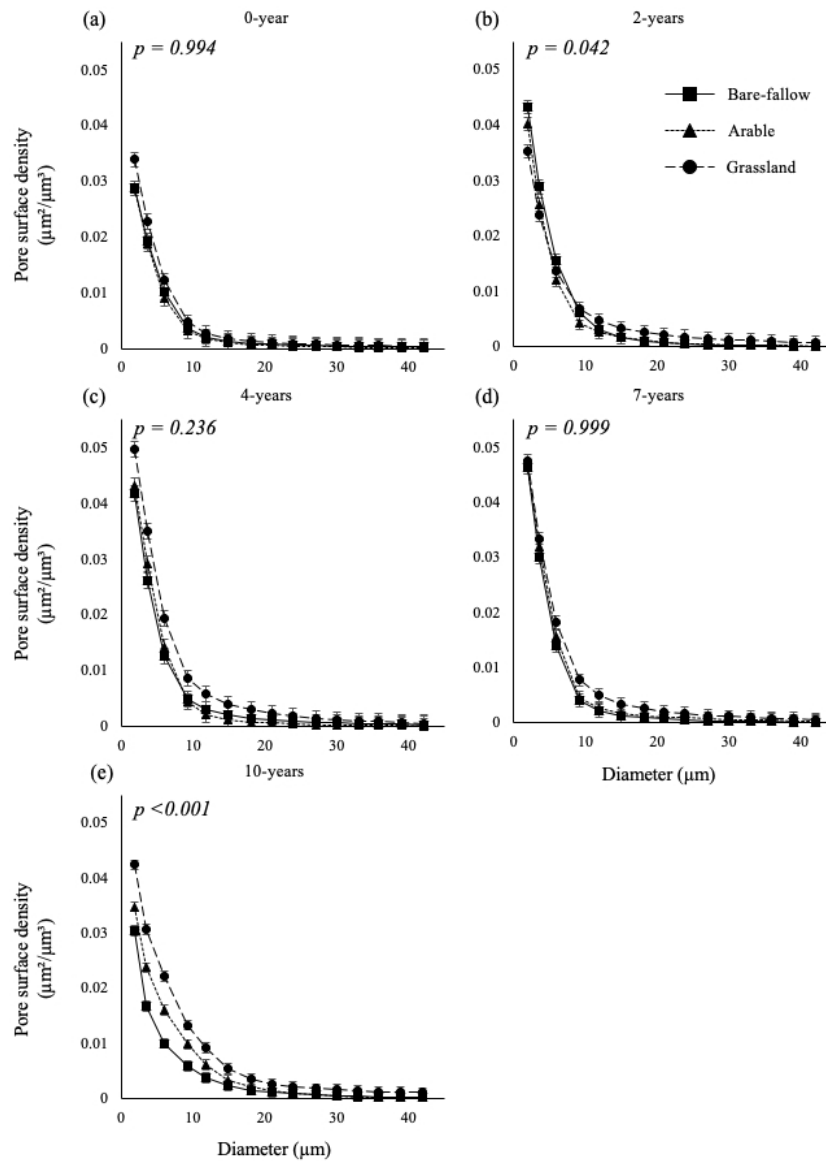
177x244mm (96 x 96 DPI)



Pore connectivity normalized to total volume in continuous bare fallow, arable and grassland soils following conversion: (a) 0-year; (b) 2-years; (c) 4-years; (d) 7-years; (e) 10-years. Data points indicate means ( $n=9$ ), whiskers denote pooled standard errors.

181x243mm (96 x 96 DPI)





Pore surface density in continuous bare fallow, arable and grassland soils following conversion: (a) 0-year; (b) 2-years; (c) 4-years; (d) 7-years; (e) 10-years. Data points indicate means ( $n = 9$ ), whiskers denote pooled standard errors.

176x244mm (96 x 96 DPI)

1 **Significant ~~S~~structural ~~recovery~~-development of a long-term fallow soil in response to**  
2 **~~annual or perennial~~agricultural management practices ~~cropping~~ requires at least 10**  
3 **years after conversion**

4  
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19

20 **Abstract (250 words, currently 23023312)**

21 Agricultural practices can have significant effects on ~~soil~~ the physical and biological ~~soil~~  
22 properties ~~of soil~~. ~~Crop rotation and modification of cropping systems can lead to marked~~  
23 ~~effects on these properties and enhance plant growth, sequestration of carbon and reorganise~~  
24 ~~soil structure~~. The aim of this study was to understand how the physical structure of a  
25 compromised soil, arising from a long-term ~~bare-bare-fallow~~ ~~period~~ ~~management~~, was  
26 modified by adopting different field management practices. ~~Soil aggregates collected on~~  
27 ~~successive years from field plots subjected to three contrasting management regimes were~~  
28 ~~studied, viz. bare fallow, bare fallow converted to arable, and bare fallow converted to~~  
29 ~~grassland~~. We hypothesised ~~that a changeing of plant inputs agricultural practices from bare-~~  
30 ~~fallow to arable and/or grassland would~~ influence the modification of pore structure *via* an  
31 increase ~~of in~~ porosity, ~~pore connectivity,~~ and a more homogenous distribution of pore  
32 ~~sizes; diversity of pore sizes and pore connectivity;~~ and ~~that~~ ~~thise~~ effect of plants ~~change~~ exerts  
33 a rapid ~~recovery-development~~ of soil structure ~~after following~~ conversion. ~~Soil aggregates (<~~  
34 ~~2 mm) collected e~~in successive years from field plots subjected to three contrasting  
35 ~~managements were studied;~~ ~~viz. bare-fallow, bare-fallow converted to arable, and bare-~~  
36 ~~fallow converted to grassland~~. Soil structure was assessed by X-ray Computed Tomography  
37 ~~of 2 mm on the~~ aggregates at 1.5  $\mu\text{m}$  resolution, ~~to captureing~~ detail relevant to ~~key~~ soil  
38 biophysical processes. ~~The greatest presence of plants, here represented by t~~The grassland  
39 system; increased ~~significantly~~ porosity, diversity of pore sizes, pore-connectivity and pore-  
40 surface density ~~significantly over the decade following conversion.~~ However, measured at  
41 this resolution, the ~~recovery-development~~ of most of these metrics of soil structure required  
42 approximately 10 years post-conversion to show a significant effect ~~of plant presence after the~~  
43 ~~conversion to grassland~~. ~~The arable system did not affect influence the soil structure al~~  
44 ~~development significantly~~. Only the pore size distribution was modified ~~in grassland in by~~

45 ~~plants in~~ a shorter time frame (2 years post-conversion). ~~Hence Full-dDevelopmentrecovery~~  
46 of the soil structural characteristics, ~~therefore~~, appears to require at least a decadal ~~time-~~  
47 ~~scale~~timescale after being converted following conversion to grassland.

48

#### 49 **Key words:**

50 Soil structure, ~~soil recovery~~, 3D pore characteristics, ~~cropping systems~~agricultural  
51 management practices, X-ray Computed Tomography, porosity

52

53

#### 54 **Highlights:**

- 55 - ~~How~~The physical structure of a compromised soil was modified by adopting  
56 different plant-based field management practices.
- 57 - ~~The presence of plants~~Conversion to grassland increased ~~the pore size~~ diversity of  
58 ~~pore sizes~~ after ~~only 2 years~~ post-conversion.
- 59 - Porosity, pore connectivity and pore surface ~~area~~ density showed ~~recovery a~~  
60 significant modification between 7 to ~~10~~ years ~~post-after~~ conversion.
- 61 - Bare fallow soil management for this extreme period (> 50 years) is detrimental to  
62 ~~both~~ physical ~~and biological~~ soil properties and the ~~recovery~~ regeneration of the soil  
63 structure requires more than 10 years after being reconverted to arable and grassland.

64

#### 65 **Introduction**

66 ~~When applied for decades to soil, a~~gricultural practices can have ~~both~~ beneficial or  
67 detrimental effects on ~~soil function~~properties; ~~when applied for decades~~, depending on the  
68 nature of such practices (Ashworth et al., 2017; Bronick and Lal, 2005; Deneff et al., 2009;  
69 Pagliai et al., 2004). Agricultural management generally aims to increase ~~---~~ or at least

70 stabilise ~~the~~ crop yield, but intensive farming can lead to soil degradation, erosion,  
71 compaction and pollution (Bronick and Lal, 2005). Conventional tillage can lead to a decline  
72 of in soil aggregation and soil structure (Watts et al., 2001), as well as a depletion of  
73 nutrients and organic carbon within soil (Coleman et al., 1997). ~~The a~~ Addition of organic  
74 matter or crop rotations can prevent soil disruption from tillage by improving soil porosity  
75 and aggregation (Abdollahi et al., 2014; Pagliai et al., 2004). In some cases, m Modification  
76 of cropping management can have beneficial impacts on soil propertiesfunctions. For  
77 example, after 50 years of continuous cultivation, a desert aeolian sandy soil was managed  
78 into a sustainable agricultural soil by increasing silt and clay content which was (a  
79 determinant for aggregate formation), soil organic matter and the content of silt and clay  
80 (caused by irrigation) leading to an increase of aggregationnutrient retention (Su et al., 2010).  
81 Moreover, soil aggregate stability is a key factor for soil fertility and physical resilience from  
82 external forces, e.g. wind and water (Abivent et al. 2009).  
83 Soil structure plays a fundamental role in the distribution of carbon, soil microorganisms,  
84 water and nutrient accessibility (Rabot et al. 2018; Smith et al. 2017). ~~The a~~ Analysis of soil  
85 structure led to suggestindicates that pore size distribution, assessed by X-ray Computed  
86 Tomography (X-ray(CT), plays an important role in aggregate stability (Menon et al. 2020).  
87 The greaterIncreased diversity of pore sizes diversity (i.e. a more homogenous distribution of  
88 pores) createsis associated with a more complex pore network. This might leads to an  
89 increase of thein the number of storage and transmission pores resulting in an increase  
90 ofgreater water and nutrient flowsflux (Kravchenko et al. 2014; 2019). The modification of  
91 the-pore size distributions appears to also play also-a key role in the decomposition of organic  
92 matter (Quigley et al. 2018; Smith et al. 2017; Toosi et al. 2017a; 2017b). For example, the  
93 presence of small (13-32 µm) and large (136-260 µm) pores decreases-the organic matter  
94 decomposition within macro-aggregates (Toosi et al. 2017b). ~~The p~~ Pore connectivity is also

95 one of the most important factors, alongside with porosity and pore size distribution, to  
96 understand soil functions (Rabot et al. 2018). The mModification of pore connectivity can  
97 have a significant effect upon the distribution and the transport of gas and water (Lucas et al.  
98 2020; Müller et al. 2019; Pires et al. 2019). Pires et al. (2017) demonstrated that pore  
99 connectivity was enhanced in zero tillage systems over conventional tillage systems,  
100 especially in the upper 10 cm.  
101 In the field, long-term  
102 Furthermore, microbial biomass—a fundamental component of soil fertility—is highly  
103 sensitive to tillage (Ashworth et al., 2017). Drijber et al. (2000) showed that on bare-fallow  
104 plots microbial biomass was reduced by approximately 30% compared to cropped plots after  
105 25 years. The composition of the bacterial communities is more closely related to soil  
106 characteristics (such as pH and soil texture) than cropping management, and the fungal  
107 community is more associated with nutrients within the soil than cropping management  
108 (Lauber et al. 2008). By contrast, a recent study showed that crop management did not have  
109 any impact on the microbial community structure, but had an effect on the distribution of  
110 genes coding for different functions (Neal et al., 2017). This study focused on phosphatase-  
111 coding genes, and showed that bare-fallowed soil contained more genes coding for  
112 extracellular and outer-membrane-associated enzymes compared to grassland and arable  
113 soils, leading to a community with greater foraging potential to access nutrients from a  
114 greater distance under the bare-fallow (Neal et al., 2017). Moreover, different  
115 mManagement practices can have a substantial impacts on soil structural dynamics (Bacq-  
116 Labreuil et al. 2018; Müller et al. 2019; Pires et al. 2019). For example, After 50-years under  
117 aof management of a typical silty clay loam soil as bare fallow treatment resulted in  
118 significant reductions of carbon and nitrogenn was markedly reduced, and in thethe  
119 abundance of biological communities was reduced (Hirsch et al. 2009) and sWith soil

120 structure ~~was also~~ severely compromised (Bacq-Labreuil et al. 2018). Conversion from bare  
121 fallow to arable or grassland increased soil organic carbon, soil nitrogen and the population  
122 of meso-fauna and fungi within 3 to 5 years ~~after following~~ conversion (Hirsch et al. 2017).  
123 ~~However although~~, soil structure modification was not assessed in this experiment.  
124 The aim of this study was to establish how the ~~micro~~-structure of a compromised ~~silt-clay~~  
125 ~~loam~~ soil is modified by altered field management over time ~~using soil aggregates (< 2 mm~~  
126 ~~diameter)~~. Three treatments were studied from the converted field of the long-term  
127 experiment: continuous ~~bare-bare-fallow~~, ~~bare-fallow~~ converted to arable, and ~~bare-bare-~~  
128 ~~fallow~~ converted to grassland. We hypothesised that: (1) plants ~~inputs~~ are an active factor in  
129 ~~the modification of soil pore structure via an increase in~~ ~~in soil~~ porosity, diversity of pore  
130 sizes and pore connectivity, and (2) structural ~~recovery development would be~~ more rapid  
131 in grassland than arable converted systems due to the greater ~~and presence of more persistent~~  
132 ~~presence of vegetation plant populations~~. The precise time for ~~recovery soil structural~~  
133 ~~development~~ is unclear *a priori*, and we aimed to determine this by measuring structural  
134 properties on several successive years after conversion.

135

## 136 **Materials and Methods**

### 137 *Soil aggregates samplings*

138 Samples were obtained from conversion plots of the long-term Highfield Ley-Arable  
139 experiment at Rothamsted Research, Harpenden, UK (LATLONG 51.8103 N, -0.3748 E).

140 The soil is a silty-clay loam (clay: 27%, silt: 58.4, sand: 14.6%; Jensen et al. 2020b)  
141 developed on clay-with-flints over Eocene London Clay (Batcombe series), classified as  
142 Chromic Luvisol by FAO criteria (Avery and Catt, 1995; FAO, 2006; Watt and Dexter,  
143 1997). In October 2007/2008, plots of soil managed as bare-fallow by regular tillage to  
144 remove any plants since 1952, were converted to arable and grassland managements. The

Commented [Ab1]: À ajouter

145 ~~conversion plots had~~ similar soil characteristics. The conversion of the plots from bare-  
146 ~~fallow to arable and grassland i~~was explained in details in Hirsh et al. (2017). ~~Arable~~ Briefly,  
147 ~~a~~Arable soil was placed under continuous wheat rotation (winter wheat, *Triticum aestivum* L.,  
148 c.v. 'Hereward' seed coated with Redigo® Deter® combination insecticide/fungicide  
149 treatment, Bayer CropScience) receiving ammonium nitrate fertilization to provide  
150 approximately 220 kg-N ha<sup>-1</sup> ~~annu~~my<sup>-1</sup>, and. For the arable and grassland plots additional  
151 ~~fertilizers~~ 250 kg-K ha<sup>-1</sup> and 65 kg-P ha<sup>-1</sup> ~~was~~ added every three years, ~~and grassland~~  
152 ~~Grassland~~ plots ~~we~~are maintained as a managed sward of mixed ~~grasses and forbs~~fescue  
153 (*Festuca pratensis* L.), ~~†~~Timothy- grass (*Phleum pratense* L.) and white clover (*Trifolium*  
154 *repens* L.) (30 kg ha<sup>-1</sup>). To remove weeds, bare-fallowed plots ~~we~~are maintained with regular  
155 ~~ploughed, tillage and~~ rotavation at least four times *per* year. Arable and bare-fallowed  
156 ~~plots we~~are tilled ~~with~~to a standard depth of 23 cm. Plots have been sampled annually ~~using~~  
157 ~~cores (10 cm height and 3 cm diameter) in October, except in 2018 where the plots were~~  
158 ~~sampled in June 2018. Following sampling, using cores (10 cm height and 3 cm diameter),~~  
159 ~~the and~~ soil ~~was~~ air-dried and sieved (~~at~~ 2 mm) before being archived ~~at room temperature.~~  
160 Aggregates (< 2 mm diameter) from continuous bare fallow (bare-fallow), bare fallow  
161 converted into arable (arable) and bare fallow converted to grassland (grassland) were  
162 ~~randomly~~ selected from ~~the years; samples collected in~~ 2008, 2010, 2012, 2015 and 2018,  
163 representing ~~10-, 32-, 54-, 8-7- and 11-10-~~years *post*-conversion. The replication of  
164 treatments was: ~~a total of 9 scanned aggregates (< 2 mm) per years and per treatments where~~  
165 ~~randomly selected from~~ 3 independent plots *per* treatments and 3 aggregates (< 2 mm) *per*  
166 ~~plots (i.e. 3 replicates per plot) were randomly selected~~ to be X-ray CT scanned, ~~therefore a~~  
167 ~~total of 9 scanned aggregates per year, per treatment were assessed by this approach.~~

168

169 *X-ray Computed Tomography*



170 Aggregates (< 2 mm diameter) were scanned using a Phoenix Nanotom<sup>®</sup> (GE Measurement  
171 and Control solution, Wunstorf, Germany) set at a voltage of 90 kV, a current of 65  $\mu$ A and  
172 at a resolution of 1.50  $\mu$ m (thus pores below this size were not considered ~~in this study~~) at the  
173 Hounsfield Facility at ~~the~~ The University Of Nottingham. A total of 1,440 projection  
174 images were taken at a 500 ms period using an averaging of 3 images and skip of 2. The total  
175 scan time per sample was 60 minutes. Scanned images were reconstructed using Phoenix  
176 datos |x2 rec reconstruction software. They were optimised to correct for any movement of  
177 the sample during the scan and subjected to noise reduction using the beam hardening  
178 correction algorithm, set at 8.

179

#### 180 *Image analysis*

181 Image analysis was performed using two software packages, ImageJ (Schneider et al., 2012)  
182 and QuantIm (Vogel et al., 2010) following the method from Bacq-Labreuil et al. (2018).

183 Briefly, all the images were thresholded using the bin bi-level threshold developed by Vogel

184 and Kretschmar (1996). QuantIm was used to output the 3D characteristics of the pore

185 network calculated from the Minkowski functions where the total porosity (~~called~~

186 ~~herereferred to as~~ porosity from here) is the percentage of all the pores >1.5  $\mu$ m; pore size

187 distribution is the proportion of each size class in the volume normalised to the total pore

188 volume, expressed here as a cumulative value; pore connectivity was calculated from the

189 Euler number and normalised to the total volume (the more negative the Euler number, the

190 greater the pore-connectivity); the pore surface density represents the roughness of the

191 surface of pores: a lower surface density means a lower roughness, i.e. less surface to be

192 colonised by living organisms (Vogel et al., 2010). The Gini-coefficient ( $G$ ), ~~is~~ a statistical

193 measure of distribution, was also determined. It is commonly applied in economics research

194 to estimate the statistical dispersion of income or wealth, and commonly used as a

195 measurement of inequality (Bellù and Liberati, 2006). Here,  $G$  was applied to measure the  
196 distribution of pore size classes as an indicator of the equality of the pore size distribution.  $G$   
197  $\approx 0$  represents an equitable distribution of the pores amongst all pore size classes meaning  
198 that the soil pores have a homogenous distribution of the pore sizes and  $G \approx 1$  represents a  
199 heterogeneous distribution of pores which means that a majority of pores have the same  
200 sizes.

201

### 202 *Statistical analysis*

203 A standard analysis of variance (ANOVA) was performed using Genstat v 17.1 (VSN  
204 International Ltd., 2014) on the porosity. A two-factor ANOVA was conducted on each  
205 Minkowski function divided by year using a split plot design with the treatment and the  
206 diameter of pores as factors. For total porosity,  $G$ , the connected porosity and pore surface  
207 area, an analysis of co-variance (ANCOVA), was also performed between the arable and  
208 grassland with years' post-conversion as a co-variate using SigmaPlot for Windows ver. 14.0  
209 (Systat Software Inc., San Jose, CA). In the case of pore surface area, pore diameter was  
210 employed as a second covariate. Parameters were tested following either square root or  $\log_{10}$   
211 transformation where necessary to conform to model assumptions of normality (tested using  
212 the Shapiro-Wilk test) and homogeneous variances (tested using Levene's test). In each case,  
213 ANCOVA was used to test for homogeneity of slopes associated with the change of total and  
214 connected porosities and  $G$  with years' post-conversion of bare fallow to either arable or  
215 grassland management. Soil managed as bare fallow throughout the experiment was used to  
216 account for temporal changes in soil parameters under continuous management. *Post hoc*  
217 pair-wise comparisons were performed employing the Copenhaver & Holland multiple  
218 comparisons procedure (Holland and Copenhaver, 1987).

219

## 220 Results

### 221 *Visual appraisal of soil structures*

222 Representative 2D images showed that after 1 and 3 years, all three treatments had similar  
223 pore architectures in terms of size and shape (Fig. 1a-f). After 5 years, arable and grassland  
224 started to display different pore configurations clearly manifest by a greater proportion of  
225 larger pores ( $>40\ \mu\text{m}$ ; Fig. 1g-i). The evolution of the pore characteristics over time was  
226 apparent, after ~~8 and 11 years~~ 8- and 10- years post-conversion for the arable and grassland  
227 treatments especially for vugh (i.e. irregular) and crack shaped pores (Fig. 1j-o). In contrast  
228 the size and distribution of pores ~~is-was~~ relatively stable-consistent over time.

### 230 *Total Porosity*

231 Before the conversion (in 2008) and after 1, 3-2 and 5-4 years, there were no significant  
232 treatment effects on porosity ( $P > 0.05$ ; Fig. 2a-c) compared to ~~8 and 11 years~~ 8- and 10-  
233 years post-conversion (respectively  $P = 0.029$  and  $P = 0.002$ ; Fig. 2d, e). After ~~8-7~~ years, the  
234 porosity ~~of in the grassland soil~~ was greater than ~~the porosity of in~~ bare-fallow ~~and-or~~ arable  
235 soils which were similar (Fig. 2d). However, after ~~11-10~~ years, porosity increased in the  
236 presence of plants according to the ranking: bare-fallow  $<$  arable  $<$  grassland (Fig. 2e). No  
237 significant change in  $\log_{10}$  total porosity was observed in the continuous bare-fallow soil over  
238 the ~~11-10~~ years (slope = 0.026,  $t = 0.104$ ,  $p = 0.917$ ) (Supplementary Fig. 1). However, total  
239 porosity in ~~both~~ soils converted to arable (slope = 0.713,  $t = 3.4$ ,  $p = 0.0014$ ) and grassland  
240 (slope = 0.4107,  $t = 3.7$ ,  $p < 0.001$ ) managements increased over the same period (Fig. 1f).  
241 ANCOVA comparing the arable and grassland soils identified a significant time response in  
242  $\log_{10}$  porosity ( $F_{1,86} = 31.0$ ,  $p < 0.001$ ) but no significant difference in the rates of change  
243 (slope) in total porosity ( $F_{1,86} = 0.8$ ,  $p = 0.364$ ). The resulting equal slopes model identified a  
244 significant difference in the adjusted mean  $\log_{10}$  total porosity of each treatment ( $F_{1,87} = 23.5$ ,

245  $p < 0.001$ ) with grassland accumulating significantly greater  $\log_{10}$  porosity ( $0.985 \pm 0.025$ ,  
246 equivalent to  $9.66 \pm 1.05\%$ , adjusted mean  $\pm$  standard error of the mean) than arable soil  
247 ( $0.848 \pm 0.021$ , equivalent to  $7.05 \pm 1.05\%$ )

248

249 *Pore size distribution*

250 ~~After 1 year~~ ~~1 year post~~ ~~Before the~~ conversion (in 2008), there was no significant treatment  
251 effect on the cumulative pore size distribution ( $P > 0.05$ ; Fig. 3a). Between ~~3-2~~ to ~~11-10~~ years  
252 post-conversion, there was a significant diameter by treatment interaction with respect to the  
253 cumulative pore size distribution (~~3-2~~ and ~~8-7~~ years:  $P < 0.001$ ; ~~4-5~~ and ~~11-10~~ years:  $P < 0.05$ ;  
254 Fig. 3b-e). After ~~3-2~~ years post-conversion, there was a greater proportion of smaller pores  
255 under bare-fallow and arable treatments than grassland: for bare-fallow and arable,  
256 approximately 50% of pores were smaller than  $3.56 \mu\text{m}$  and 70% of pores smaller than  $5.97$   
257  $\mu\text{m}$  compared to grassland where 50% of pores were smaller than  $5.97 \mu\text{m}$  and 70% smaller  
258 than  $14.9 \mu\text{m}$ . Moreover, the proportion of pores larger than  $42 \mu\text{m}$  was greater under  
259 grassland (13% of pores) than bare-fallow and arable (respectively 1% and 2% of pores; Fig.  
260 3b). After ~~5-4~~ years, this trend was not apparent: the difference between grassland compared  
261 to bare-fallow and arable was less significant than after ~~3-2~~ years. The proportion of pores  
262 smaller the  $9.26 \mu\text{m}$  was greater under bare-fallow and arable compared to grassland but the  
263 proportion of pores larger than  $42 \mu\text{m}$  was not significant between all treatments (Fig. 3c).  
264 After ~~8-7~~ years, the trend observed after ~~3-2~~ years was more apparent: the proportion of pore  
265 sizes smaller than  $14.9 \mu\text{m}$  was greater ranking from bare-fallow  $>$  arable  $>$  grassland and the  
266 proportion of pore sizes over  $42 \mu\text{m}$  was greater under arable and grassland (respectively 7%  
267 and 10% of pores) than bare-fallow (2% of pores; Fig. 3d). After ~~11-10~~ years post-  
268 conversion, this trend was also observed, but only for pores smaller than  $9.26 \mu\text{m}$ , where the  
269 proportion of pores ~~was followed the~~ ranking, ~~from~~ bare-fallow  $>$  arable  $>$  grassland (Fig.

270 3e). Beyond this pore size, the proportion of pore sizes was not significantly different  
271 between bare-fallow and arable. The proportion of pore sizes greater than 42  $\mu\text{m}$  was highest  
272 under grassland (15% of pores) than bare-fallow and arable (respectively 4% and 2% of  
273 pores; Fig. 3e).

274 The general trend in all three treatments was a shift to a more equitable even distributions of  
275 pore sizes, manifest as a decrease in  $G$  over time (Fig. 3f). ANCOVA indicated equal rates of  
276 change of  $G$  between treatments ( $F_{2,129} = 0.18, p = 0.834$ ). Using an equal slopes model,  
277 there was a significant effect of land management upon  $G$  ( $F_{2,131} = 9.1, p < 0.001$ ) with  
278 grassland having a significantly lower adjusted mean  $G$  ( $0.420 \pm 0.033$ ) than either bare-  
279 fallow (adjusted mean  $G = 0.566 \pm 0.028; t = 3.6, p < 0.001$ ) or arable (adjusted mean  $G =$   
280  $0.571 \pm 0.024; t = 3.7, p < 0.001$ ). There was no significant difference in adjusted mean  $G$   
281 between arable and bare-fallow ( $t = 0.13, p = 0.900$ ).

282

### 283 *Pore connectivity*

284 Before the conversion (in 2008) and after 1 and 8 years post-conversion,  
285 there was no significant pore diameter by treatment interaction with regards to pore  
286 connectivity ( $P = 0.05$ ; Fig. 4a, d). However, there was a significant pore diameter by  
287 treatment interaction after 3, 5 and 11 years (with 3- and 11-years:  $P < 0.001$ ; 5  
288 years:  $P < 0.05$ ; Fig. 4b, c, e). After 3- and 5- years, the difference was significant only  
289 for the pore sizes smaller than 3.56  $\mu\text{m}$ . After 3-years, pore connectivity was greater  
290 ranking from bare-fallow > grassland > arable (Fig. 4b) and after 5-years, pore connectivity  
291 was greater under arable and grassland than bare-fallow (Fig. 4c). After 11-years post-  
292 conversion, the same trend as after 5-years was shown with a greater difference in the  
293 values (Fig. 4e). There was no significant trend in square root transformed connected porosity  
294 (Supplementary Fig. 2) in bare-fallow (slope =  $-0.00023, t = 0.051, p = 0.959$ ). However,

295 both arable (slope = 0.017,  $t = 4.0$ ,  $p = 0.0002$ ) and grassland (slope = 0.022,  $t = 5.3$ ,  $p <$   
296 0.0001) showed increases in connected porosity with time. ANCOVA comparing arable and  
297 grassland indicated a significant influence of time *post*-conversion upon square root  
298 transformed connected porosity ( $F_{1,85} = 43.9$ ,  $p < 0.001$ ) but no significant heterogeneity of  
299 slopes ( $F_{1,85} = 0.98$ ,  $p = 0.326$ ). Using an equal slopes model, a significant effect of  
300 management was detected ( $F_{1,85} = 4.4$ ,  $p = 0.039$ ): grassland was associated with greater  
301 connected porosity ( $0.048 \pm 0.0002\%$ , adjusted mean  $\pm$  standard error) than arable ( $0.011 \pm$   
302  $0.0002\%$ ).

303

#### 304 *Pore surface density*

305 Before the conversion (in 2008) and After 4-, 5 and 8 years and 54- and 87-years *post*-  
306 conversion, there was no significant pore diameter by treatment interaction with respect  
307 regards to pore surface density ( $P > 0.05$ ; Fig. 5a, c, d). There was a significant diameter by  
308 treatment interaction after 3-2- and 11-10- years (respectively  $P < 0.05$  and  $P < 0.001$ ; Fig. 5b,  
309 e). After 3-2- years, the difference in pore surface density was greater ranking from bare-  
310 fallow > arable > grassland for the pore sizes equal to 1.86  $\mu\text{m}$ , and the difference between  
311 arable and grassland was not significant for the pore sizes equal to 3.56  $\mu\text{m}$ . Beyond this pore  
312 size, there was no significant difference between treatments (Fig. 5b). After 11-10- years  
313 *post*-conversion, pore surface density was greater ranking from grassland > arable >  
314 bare-fallow, for all pore sizes smaller than 14.9  $\mu\text{m}$ , there was no significant difference  
315 beyond this pore size (Fig. 5e). Years *post*-conversion and pore diameter were both used as  
316 covariates in ANCOVA analysis of pore surface area. Accounting for these two covariates,  
317 an equal slopes model identified a significant effect of land management upon pore surface  
318 area ( $F_{2,2020} = 9.1$ ,  $p < 0.001$ ). *Post hoc* pair-wise comparison of adjusted means indicated  
319 that grassland supported a greater pore surface area ( $0.00784 \pm 0.000493 \mu\text{m}^2 \mu\text{m}^{-3}$ ) than

320 either arable ( $0.00617 \pm 0.000452 \mu\text{m}^2 \mu\text{m}^{-3}$ ; difference = 0.00167,  $t = 3.4$ ,  $p = 0.001$ ) or  
321 bare-fallow ( $0.00593 \pm 0.000443 \mu\text{m}^2 \mu\text{m}^{-3}$ ; difference = 0.00191,  $t = 3.9$ ,  $p < 0.001$ ). There  
322 was no significant difference in pore surface area between arable and bare-fallow (difference  
323 = 0.000240,  $t = 0.495$ ,  $p = 0.621$ ).

324

### 325 Discussion

326 The ~~conversion~~ plots studied here were derived from long-term bare-fallow management  
327 converted to arable and grassland. ~~A~~ Lack of a significant treatment effect on porosity until 8  
328 7-years post-conversion suggests that modification of micro-porosity ~~at this scale~~ takes  
329 several years (Fig. 2). ~~Despite~~ Another study on the same soil realised after 2 and 4 years post  
330 conversion found that ~~the~~ some recovery of meso-faunal populations after 3-2-years of  
331 conversion and an increase ~~of~~ in soil organic matter and microbial abundance after 5-4- and 3  
332 2-years respectively (Hirsch et al., 2017). ~~However, our study showed that; recovery~~  
333 ~~development~~ of micro-scale porosity apparently takes longer ~~changes more slowly~~. This  
334 might be related to carbon cycling processes which are modified by the microbial  
335 communities and plants (*via* decomposition of organic matter and rhizodeposition). This is  
336 likely to affect soil structure at the micro-scale, but not instantaneously. ~~Greater~~ Increased  
337 pore formation under grassland compared to arable is consistent with a previous study, which  
338 showed greater resistance to, and ~~recovery~~ development from physical stresses of soil  
339 structure from grassland (Gregory et al., 2009). They posited that the greater proportion of  
340 organic matter enhanced the elastic recovery of ~~the~~ soil structure (Gregory et al., 2009).  
341 Pore size distributions showed a more rapid response to altered management than ~~total~~  
342 porosity ~~for the grassland treatment~~: after only 3-2-years of conversion (in 2010), a greater  
343 diversity of pore sizes was observed ~~under the grassland treatment~~, and this trend was also  
344 recorded in the data after 8-7- and 11-10-years (Fig. 3). ~~The~~ Gini-coefficient indicated that

345 soil converted to grassland established a more ~~equitable-even~~ distribution of pore sizes than  
346 the other treatments, meaning that grassland treatment had a greater diversity of pores after  
347 ~~32-, 8-7- and 11-10-~~years post-conversion (Supplementary Fig. 2) leading to enhanced  
348 functionality. This increase in pore size diversity might be due to the increase of presence of  
349 plants, active organisms and organic matter (Hirsch et al., 2017) as well as the ~~cessation~~  
350 ~~absence~~ of tillage. ~~A study looking at~~A study focused on the soil organic carbon on the same  
351 ~~experiment plot~~ found that the conversion of the bare-fallow soil to grassland led to an  
352 increase of soil organic carbon (+46 %) after 7-years post conversion (Jensen et al. 2020a).  
353 There is no data regarding the conversion from bare-fallow to arable. Thus, the increase of  
354 organic matter in the converted soil might have ~~may~~ play a role in the more homogenous  
355 distribution of the pore sizes. Plants increase aggregation through root action and exudation  
356 (Chan and Heenan, 1996; Haynes and Beare, 1997) and they can also break down aggregates  
357 (Chan and Heenan, 1996; Materechera et al., 1994) by growing through existing pores in the  
358 aggregates and disrupting them. However, plants enmesh soil particles forming large  
359 aggregates (Tisdall and Oades, 1982), and release mucilage that binds soil particles with  
360 organic matter which in turn stabilises new aggregates and pores (Broniek and Lal, 2005;  
361 Chenu et al., 2000). Indeed, in a silty clay soil, The addition of organic matter can increase the  
362 number of “transmission” (50–500 µm) and “storage” (0.5–50 µm) pores and decrease the  
363 prevalence of macro-pores (> 500 µm) increasing overall functionality. Thus the action of  
364 plants and the increase-greater of organic matter content increases the proportion of pores  
365 between 0.5 to 500 µm (Metzger and Yaron, 1987; Watts and Dexter, 1997) leading to a  
366 more equitable distribution of pore sizes, i.e. a greater diversity of pore sizes. The greater  
367 diversity of pore sizes under soil converted to grassland was consistent with a previous study  
368 describing the long-term effect of grassland management on the same field experiment  
369 (Bacq-Labreuil et al., 2018). After ~~5-4-~~years ~~post-conversion,~~ the pore size distribution did



370 not follow this trend (Fig. 3c), which could be due to ~~the~~ weather conditions prior sampling in  
371 that year. Indeed, 2008 and 2012 (~~1-at the start~~ and ~~5-4~~-years post- conversion respectively)  
372 were the wettest years during the experimental period (Supplementary Fig. 3). In the presence  
373 of water, clay particles can swell, and the compression of entrapped air in capillary pores can  
374 disrupt ~~the~~ pore architecture, ~~and in turn, aggregation which might and affect the pore size~~  
375 ~~distribution~~ (Denef et al., 2001; Grant and Dexter, 1990). ~~Therefore, the pP~~ore networks  
376 ~~become-are~~ re-structured upon re-wetting due to the nature of soil particles. Changes in pore  
377 size between ~~3-2~~, ~~5-4~~ and ~~8-7~~-years post-conversion raises the question of the dynamics of  
378 this mechanism. The pore size distribution may have had a heterogeneous response over time  
379 due to the impact of the wet year ~~5-4~~-years post-conversion, which shows the rapid ~~recovery~~  
380 ~~regenerationdevelopment~~ of the pore size distribution after a sustained wet period compared  
381 to the impact of ~~plant growth~~ agricultural practices (Supplementary Fig. 3). ~~For the plot~~  
382 ~~converted to arable treatment, this trend was not observed even after 10-years post-~~  
383 ~~conversion, which might be due to the associated tillage practices on the arable plots.~~  
384 For pore connectivity, the ~~magnitude of the plant conversion to grassland effect after 3 and 5~~  
385 ~~years was had a small effect after 2- and 4-years~~ compared to after ~~1-10~~-years post-  
386 conversion (Fig. 4 b, c, e). However, pore connectivity data after ~~1-10~~-years post-  
387 conversion, for both arable and grassland converted soils (Fig. 4e), suggested the pore  
388 network was less connected compared to ~~a previous study~~ (Bacq-Labreuil et al., (2018), ~~This~~  
389 ~~indicating-indicated~~ that a longer time may be required to ~~reover-develop~~ ~~the~~ connectivity of  
390 a pore network than ~~total-the overall~~ porosity. Increased connectivity of pores promotes  
391 water, gasses and nutrient flows within the pore structure (Dexter, 1988; Tisdall and Oades,  
392 1982). Therefore, ~~the~~ subtle increases in ~~the~~ pore connectivity might increase ~~the~~ water, gas  
393 and nutrient ~~movement-flux~~ within the soil. As well as the pore connectivity, the pore surface  
394 density was significantly ~~influenced by the presence of plants~~ ~~increased in the grassland and~~

395 arable 4-10-years post-conversion (Fig. 5e). Our results are congruent with Bacq-Labreuil et  
396 al. (2018), which showed plants-grassland managed consistently for over 200 years has an  
397 increased pore surface density compared to arable and bare-fallow soils; i.e. the pore-solid  
398 interface which led to a greater surface of the pore where micro-organisms and plant roots  
399 can colonise and water films can develop. A greater pore surface density in the converted plot  
400 means that the grassland and the arable have a more complex structure of pores than the  
401 bare-fallow soil (Müller et al. 2019). The greater surface density for the grassland compared  
402 to the arable might be induced by the greater SOC content and the absence of tillage for this  
403 treatment (Hirsch et al. 2017; Jensen et al. 2020a). This can lead to the formation of new  
404 habitats and niches which can be beneficial for microbial community diversity (Holden,  
405 2011). The greater pore surface area might increase water and nutrient uptake by the  
406 microbial community and plants.

407 This study suggests that the overall impact of the conversion from degraded bare-fallow soil  
408 to presence of plants-grassland -requires at least 4-10-years after conversion before being  
409 effective in terms of significant recovery-development of soil structure at aggregate scale, as  
410 assessed by total-the overall and connected porosity. Moreover, the conversion from bare-  
411 fallow to arable had no significant effect on soil structural properties after a decade. In  
412 general, the recovery of meso-fauna and organic matter (Griffiths et al., 2000; Hirsch et al.,  
413 2017) were more rapid than the recovery of soil structure (Gregory et al., 2009). The pore  
414 size distribution was the only characteristic which was more sensitive to changes-changes  
415 induced by such as wetting and drying cycles and -living organisms.

416  
417 Our first hypothesis was supported since porosity, pore size diversity, pore connectivity, and  
418 pore surface area density were all enhanced in grassland soil. Moreover, the conversion to  
419 arable management did not affect soil structural development significantly. The conversion to

420 grassland increased the range of pore sizes after 2--years, consistent with our second  
421 hypothesis. However, all other Minkowski functions (porosity, pore connectivity and pore  
422 surface area density) responded to change more slowly. The mechanisms behind the  
423 development of pore sizes appeared to be dynamic and possibly dependent upon weather  
424 conditions before sampling. Apart from the pore size distribution, the magnitude of the  
425 grassland effects on all other Minkowski functions was lower than the difference observed  
426 after a minimum of 50 years of management (Bacq-Labreuil et al., 2018). In this study, the  
427 effect of grassland upon porosity and pore connectivity were two-fold greater than bare--  
428 fallow management. Here, the difference was significant but not as major. Bare--fallow soil  
429 management for this long period (> 50 years) is detrimental to both physical and biological  
430 soil properties and the development of the soil structure after this requires more than 10 years  
431 after the conversion the grassland

### 433 **Conclusions**

434 The Ssoil structural recovery development of the a compromised degraded silt-clay loam soil,  
435 as quantified by micro-scale topological metrics related to detail capture at 1.5  $\mu$ m resolution,  
436 requires at least 10-10-years of a new-grassland management before showing any significant  
437 effects of the presence of plants. Our first hypothesis was supported since porosity, pore  
438 size the diversity of pore sizes, pore connectivity, and pore surface area density were all  
439 enhanced by the presence of plants in the grassland soil. Moreover, the conversion to arable  
440 management did not affect the soil soil structural development significantly. The presence of  
441 plants The conversion to grassland increased the range of pore sizes after only 2 years, post-  
442 conversion consistent with our second hypothesis. However, all other Minkowski functions  
443 (such as porosity, pore connectivity and pore surface area density) showed recovery an  
444 increase 7 to 11 years post conversion to grassland responded to change more slowly. The

445 mechanisms behind the recovery development of pore sizes appeared to be dynamic and  
446 possibly dependent upon weather conditions before sampling. Apart from the pore size  
447 distribution, the magnitude of the plant the grassland effects on all other Minkowski functions  
448 was lower than the difference observed after a minimum of 50 years of management (Baeq-  
449 Labreuil et al., 2018). In this study, the effect of grassland upon porosity and pore  
450 connectivity were two-fold greater than bare fallow management. Here, the difference was  
451 significant but not as major, which means that soil structure requires more time to  
452 completely establish micro-structure after being converted to grassland or arable.  
453 Demonstrably, Bare fallow soil management for this extreme long period (> 50 years) is  
454 detrimental to both physical and biological soil properties and the recovery development of  
455 the soil structure after this requires more than 10 years after the conversion the grassland.  
456 These observations raises the question on the application to certain managements in  
457 agricultural practices. For example, instead of applying a bare-fallow treatment in a crop  
458 rotation, it would be beneficial for the soil characteristics to apply a vegetation cover *i.e.*  
459 cover crops which increases the organic matter inputs and impact influence on soil structure,  
460 leading to a 'conditioning' of soil physical and biological characteristics for the next crop.  
461 This would prevent the further degradation of the soil and also help for its recovery  
462 development if the soil characteristics were compromised. Moreover, the recovery  
463 development of the soil structure is apparently a long process in the context of  
464 current agricultural practices and perceived imperatives. thus Thus, a modification of  
465 cropping managements might should be anticipated to require some time before the  
466 observation of beneficial impacts on soil structural dynamics. Therefore, this should be  
467 accounted for the future research and conclusions.

468

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481

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630 **Figure 1:** Representative 2D X-ray attenuation images of soils subjected to different forms of  
631 management over 10-10-years after post-following conversion to these each treatments. Base  
632 resolution is 40  $\mu\text{m}$ ; (P) pores are the darker shades and (S) soil matrix are the lighter shades  
633 which relate to the attenuation of the X-ray (a sharpening algorithm has been passed over  
634 these images to increase contrast of features); (a, d, g, j, m) bare-fallow; (b, e, h, k, n) arable;  
635 and (c, f, i, l, o) grassland.

636  
637 **Figure 2:** Porosity (based on resolution of 1.5  $\mu\text{m}$ ) in relation to bare fallow, arable and  
638 grassland soils in regards to in the years post-conversion following: (a) 1-0-year; (b) 3-2-years;  
639 (c) 5-4-years; (d) 8-7-years; (e) 11-10-years. Bar charts were are means ( $n = 9$ ) expressed as  
640 the percentage of pores relative to the total volume, whiskers denote pooled standard errors.  
641 (f) Porosity evolution from 1-0- to 11-10-years post-conversion, with the points were data  
642 points represent means ( $n = 9$ ), whiskers denote pooled standard errors for clarity and trend  
643 lines were are linear regressions.

644  
645 **Figure 3:** Cumulative pore size normalized to the total pore-volume in relation to bare-  
646 fallow, arable and grassland in regards to the years post-following conversion: (a) 1-0-year;  
647 (b) 3-2-years; (c) 5-4-years; (d) 8-7-years; (e) 11-10-years. Data Ppoints indicate means ( $n=9$ ),  
648 whiskers denote pooled standard errors. (f) Gini coefficient evolution-development from 1-0-  
649 to 11-10-years post-conversion, with the data points were represent means ( $n = 9$ ), whiskers  
650 denote pooled standard errors for clarity and trend lines were are linear regressions.

651  
652 **Figure 4:** Pore connectivity normalized to total volume in continuous bare fallow, arable and  
653 grassland soils in regards to the years post-following conversion: (a) 1-0-year; (b) 3-2-years;

654 (c) 5-4-years; (d) 8-7-years; (e) 11-10-years. ~~Points~~ Data points indicate means ( $n=9$ ),  
655 whiskers denote pooled standard errors.

656

657 **Figure 5:** ~~Pore S~~ surface density in ~~relation to~~ continuous bare fallow, arable and grassland  
658 ~~soils in regards to the years post-following~~ conversion: (a) 1-0-year; (b) 3-2-years; (c) 5-4-  
659 years; (d) 8-7-years; (e) 11-10-years. ~~Data P~~ points indicate means ( $n = 9$ ), whiskers denote  
660 pooled standard errors.

661

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