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ORIGINAL ARTICLE

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

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Abstract

Agricultural practices can have significant effects on the physical and biological properties of soil. The aim of this study was to understand how the physical structure of a compromised soil, arising from long-term bare-fallow management, was modified by adopting different field management practices. We hypothesized that changing agricultural practices from bare-fallow to arable or grassland would influence the modification of pore structure via an increase in porosity and pore connectivity, and a more homogenous distribution of pore sizes, and that this change exerts a rapid evolution of soil structure following conversion. Soil aggregates (<2 mm) collected in successive years from field plots subjected to three contrasting managements were studied: bare-fallow, bare-fallow converted to arable, and bare-fallow converted to grassland. Soil structure was assessed by X-ray computed tomography on the aggregates at 1.5 μm resolution, capturing detail relevant to soil biophysical processes. The grassland system increased porosity, diversity of pore sizes, pore connectivity and pore-surface density significantly over the decade following conversion. However, measured at this resolution, the evolution of most of these metrics of soil structure required approximately 10 years post-conversion to show a significant effect. The arable system did not influence soil structural evolution significantly. Only pore size distribution was modified in grassland in a shorter time frame (2 years post-conversion). Hence, evolution of soil structural characteristics appears to require at least a decadal timescale following conversion to grassland.

Highlights

- The physical structure of a compromised soil was modified by adopting plant-based field management practices.
- Conversion to grassland increased pore size diversity after 2 years.
- Porosity, pore connectivity and pore surface density showed a significant modification between 7 and 10 years after conversion.

1 | INTRODUCTION

Agricultural practices can have beneficial or detrimental effects on soil functions when applied for decades, depending on the nature of such practices (Ashworth, DeBruyn, Allen, Radosevich, & Owens, 2017; Bronick & Lal, 2005; Denef, Roobroeck, Manimel Wadu, Lootens, & Boeckx, 2009; Pagliai, Vignozzi, & Pellegrini, 2004). Agricultural management generally aims to increase - or at least stabilize - crop yield, but intensive farming can lead to soil degradation, erosion, compaction and pollution (Bronick & Lal, 2005). Conventional tillage can lead to a decline in soil aggregation and soil structure (Watts et al., 2001), as well as depletion of nutrients and organic carbon within soil (Coleman et al., 1997). Addition of organic matter or crop rotations can prevent soil disruption from tillage by improving soil porosity and aggregation (Abdollahi, Munkholm, & Garbout, 2014; Pagliai et al., 2004). In some cases, modification of crop management can have beneficial impacts on soil functions. For example, after 50 years of continuous cultivation, a desert aeolian sandy soil was converted into a sustainable agricultural soil by increasing the silt and clay content (a determinant for aggregate formation), soil organic matter and nutrient retention (Su, Yang, Liu, & Wang, 2010). Moreover, soil aggregate stability is a key factor for soil fertility and physical resilience to external forces (e.g., wind and water) (Abiven, Menasseri, & Chenu, 2009).

Soil structure plays a fundamental role in the distribution of carbon, soil microorganisms, water and nutrient accessibility (Rabot, Wiesmeier, Schlüter, & Vogel, 2018; Smith et al., 2017). Analysis of soil structure indicates that pore size distribution, assessed by X-ray computed tomography (CT), plays an important role in aggregate stability (Menon et al., 2020). Increased diversity of pore sizes (i.e. a more homogenous distribution of pore sizes) is associated with a more complex pore network. This leads to an increase in the number of storage and transmission pores,

resulting in greater water and nutrient flux (Kravchenko et al., 2014, 2019). The modification of pore size distributions appears to also play a key role in the decomposition of organic matter (Quigley, Negassa, Guber, Rivers, & Kravchenko, 2018; Smith et al., 2017; Toosi, Kravchenko, Guber, & Rivers, 2017; Toosi, Kravchenko, Mao, Quigley, & Rivers, 2017). For example, the presence of small (13–32 μm) and large (136–260 μm) pores decreases organic matter decomposition within macroaggregates (Toosi, Kravchenko, Mao, et al., 2017). Pore connectivity is also one of the most important factors, alongside porosity and pore size distribution, in understanding soil functions (Rabot et al., 2018). Modification of pore connectivity can have a significant effect upon the distribution and the transport of gas and water (Lucas, Vetterlein, Vogel, & Schlütter, 2020; Müller et al., 2019; Pires, Roque, Rosa, & Mooney, 2019). Pires et al. (2017) demonstrated that pore connectivity was enhanced in zero tillage systems over conventional tillage systems, especially in the upper 10 cm.

In the field, long-term management practices can have substantial impacts on soil structural dynamics (Bacq-Labreuil et al., 2018; Müller et al., 2019; Pires et al., 2019). For example, 50 years of management of a typical silty clay loam soil as bare-fallow resulted in significant reductions of carbon and nitrogen, and in the abundance of biological communities (Hirsch et al., 2017), with soil structure also severely compromised (Bacq-Labreuil et al., 2018). Conversion from bare-fallow to arable or grassland increased soil organic carbon, soil nitrogen and the population of mesofauna and fungi within 3 to 5 years following conversion (Hirsch et al., 2017), although soil structure modification was not assessed in this experiment.

The aim of this study was to establish how the microstructure of a compromised silt-clay loam soil is modified by altered field management over time using soil aggregates (<2 mm diameter). Three treatments were studied from the converted field of a long-term experiment: continuous bare-fallow, bare-fallow converted to arable, and

bare-fallow converted to grassland. We hypothesized that: (a) re-introduction of plants increases soil porosity, diversity of pore sizes and pore connectivity, and (b) structural evolution is more rapid in grassland than arable converted systems due to the greater and more persistent presence of vegetation and less disturbance of soil (due to tillage practices in the arable management). The precise time for soil structural evolution is unclear *a priori*, and we aimed to determine this by measuring structural properties in several successive years after conversion.

2 | MATERIALS AND METHODS

2.1 | Soil aggregate sampling

Samples were obtained from conversion plots of the long-term Highfield Ley-Arable experiment at Rothamsted Research, Harpenden, UK (LATLONG 51.8103 N, −0.3748 E). The soil is a silty-clay loam (clay, 27%; silt, 58.4%; sand, 14.6%; Jensen, Schjønning, Watts, Christensen, & Munkholm, 2020) developed on clay-with-flints over Eocene London Clay (Batcombe series), classified as Chromic Luvisol by FAO criteria (Avery & Catt, 1995; FAO, 2006; Watts & Dexter, 1997). In October 2008, plots of soil managed as bare-fallow by regular tillage to remove any plants since 1952 were converted to arable and grassland managements. The conversion plots had similar soil characteristics. The conversion of the plots from bare-fallow to arable and grassland is explained in detail in Hirsch et al. (2017). Arable soil was placed under continuous wheat rotation (winter wheat, *Triticum aestivum* L., *c.v.* "Hereward" seed coated with Redigo® Deter® combination insecticide/fungicide treatment, Bayer CropScience, UK), receiving ammonium nitrate fertilization to provide approximately 220 kg-N ha^{-1} year^{-1}. For the arable and grassland plots, additional fertilizers (250 kg-K ha^{-1} and 65 kg-P ha^{-1}) were added every 3 years. Grassland plots were maintained as a managed sward of mixed fescue (*Festuca pratensis* L.), Timothy grass (*Phleum pratense* L.) and white clover (*Trifolium repens* L.) (30 kg ha^{-1}). To remove weeds, bare-fallow plots were maintained with regular tillage or rotavation at least four times per year. Arable and bare-fallow plots were tilled to a standard depth of 23 cm. Plots have been sampled annually using cores (10 cm height and 3 cm diameter) in October, except in 2018 when the plots were sampled in June. Following sampling, soil was air-dried and sieved at 2 mm before being archived at room temperature. Aggregates (<2 mm diameter) from continuous bare-fallow (bare-fallow), bare-fallow converted to arable (arable) and bare-fallow converted to grassland (grassland) were randomly selected from samples collected in 2008, 2010, 2012, 2015 and 2018, representing 0, 2, 4, 7 and 10 years post-conversion. The replication of treatments was a total of nine scanned aggregates (<2 mm) per year and per treatment randomly selected from three independent plots per treatment and three aggregates (<2 mm) per plot (i.e. three replicates per plot) to be X-ray CT scanned.

2.2 | X-ray computed tomography

Aggregates (<2 mm diameter) were scanned using a Phoenix Nanotom® (GE Measurement and Control solution, Wunstorf, Germany) set at a voltage of 90 kV, a current of 65 μA and a resolution of 1.50 μm (thus pores below this size were not considered) at the Hounsfield Facility at The University of Nottingham. A total of 1,440 projection images were taken in a 500-ms period using an average of three images and skip of two. The total scan time per sample was 60 min. Scanned images were reconstructed using Phoenix datos|x2 rec reconstruction software. They were optimized to correct for any movement of the sample during the scan and subjected to noise reduction using the beam hardening correction algorithm, set at eight.

2.3 | Image analysis

Image analysis was performed using two software packages, ImageJ (Schneider, Rasband, & Eliceiri, 2012) and QuantIm (Vogel, Weller, & Schlüter, 2010), following the method from Bacq-Labreuil et al. (2018). Briefly, all the images were thresholded using the bin bilevel threshold developed by Vogel and Kretzschmar (1996). QuantIm was used to output the 3D characteristics of the pore network calculated from the Minkowski functions, where the total porosity (referred to as porosity from here) is the percentage of all the pores >1.5 μm; pore size distribution is the proportion of each size class in the volume normalized to the total pore volume, expressed here as a cumulative value; pore connectivity was calculated from the Euler number and normalized to the total volume (the more negative the Euler number, the greater the pore connectivity); the pore surface density represents the roughness of the surface of pores (a lower surface density means a lower roughness; i.e., less surface to be colonized by living organisms) (Vogel et al., 2010). The Gini-coefficient (*G*), a statistical measure of distribution, was also determined. It is commonly applied in economics research to estimate the statistical dispersion of income or wealth, and commonly used as a measurement of inequality (Bellù & Liberati, 2006). Here, *G* was applied to measure the distribution of pore size classes as an

indicator of the equality of the pore size distribution. $G \approx 0$ represents an equitable distribution of pores amongst all pore size classes, meaning that the soil pores have a homogenous distribution of the pore sizes. $G \approx 1$ represents a heterogeneous distribution of pores, which means that a majority of pores have the same size.

2.4 | Statistical analysis

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

3 | RESULTS

3.1 | Visual appraisal of soil structures

Representative 2D images of aggregates (with a diameter smaller than 2 mm) showed that after 1 and 3 years, all three treatments had similar pore architectures in terms of size and shape (Figure 1a–f). After 5 years, arable land and grassland started to display different pore configurations, clearly manifest by a greater proportion of larger pores (>40 μm; Figure 1g–i). The evolution of the pore characteristics over time was apparent, after 7 and 10 years post-conversion for the arable and grassland treatments, especially for vugh (i.e., irregular) and crack-shaped pores (Figure 1j–o). In contrast, the size

and distribution of pores were relatively consistent over time.

3.2 | Total porosity

Before the conversion (in 2008) and after 2 and 4 years, there were no significant treatment effects on porosity ($p > .05$; Figure 2a–c) compared to 7 and 10 years post-conversion (respectively, $p = .029$ and $p = .002$; Figure 2d,e). After 7 years, the porosity in the grassland soil was greater than in bare-fallow or arable soils, which were similar (Figure 2d). However, after 10 years, porosity increased in the grassland and arable treatments according to the ranking bare-fallow < arable < grassland (Figure 2e). No significant change in $\log_{10}$ total porosity was observed in the continuous bare-fallow soil over the 10 years (slope $= 0.026$, $t = 0.104$, $p = .917$) (Figure S1). However, total porosity in soils converted to arable (slope $= 0.713$, $t = 3.4$, $p = .0014$) and grassland (slope $= 0.41$, $t = 3.7$, $p < .001$) managements increased over the same period (Figure 1f). ANCOVA comparing the arable and grassland soils identified a significant time response in $\log_{10}$ porosity ($F_{1,86} = 31.0$, $p < .001$) but no significant difference in the rates of change (slope) in total porosity ($F_{1,86} = 0.8$, $p = .36$). The resulting equal slopes model identified a significant difference in the adjusted mean $\log_{10}$ total porosity of each treatment ($F_{1,87} = 23.5$, $p < .001$), with grassland accumulating significantly greater $\log_{10}$ porosity (0.985 ± 0.025, equivalent to $9.66 \pm 1.05\%$, adjusted mean $\pm$ standard error of the mean) than arable soil (0.848 ± 0.021, equivalent to $7.05 \pm 1.05\%$).

3.3 | Pore size distribution

Before the conversion (in 2008) there was no significant treatment effect on the cumulative pore size distribution ($P > .05$; Figure 3a). Between 2 and 10 years post-conversion, there was a significant diameter by treatment interaction with respect to the cumulative pore size distribution (2 and 7 years, $p < .001$; 4 and 10 years, $p < .05$; Figure 3b–e). After 2 years post-conversion, there was a greater proportion of smaller pores under bare-fallow and arable treatments than grassland: for bare-fallow and arable land, approximately 50% of pores were smaller than 3.56 μm and 70% of pores smaller than 5.97 μm compared to grassland, where 50% of pores were smaller than 5.97 μm and 70% smaller than 14.9 μm. Moreover, the proportion of pores larger than 42 μm was greater under grassland (13% of pores) than bare-fallow and arable land (respectively, 1 and 2% of pores; Figure 3b). After 4 years,

FIGURE 1 Representative 2D X-ray attenuation images of soils subjected to different forms of management over 10 years following conversion to each treatment. Base resolution is 40 μm; pores (P) are the darker shades and the soil matrix (S) is the lighter shades, which relate to the attenuation of the X-ray (a sharpening algorithm has been passed over these images to increase contrast of features); (a, d, g, j, m) bare-fallow; (b, e, h, k, n) arable; and (c, f, i, l, o) grassland
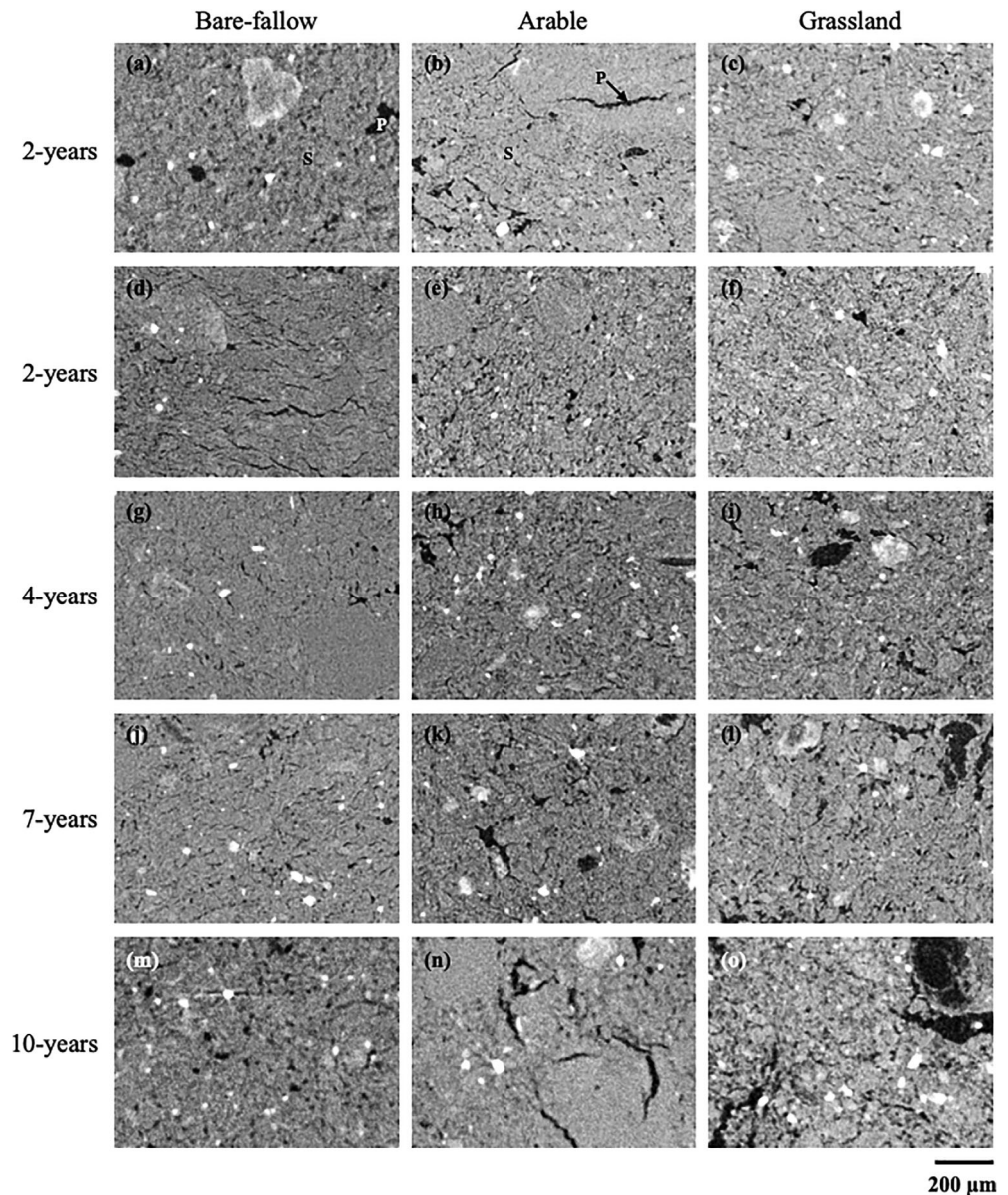
this trend was not apparent: the difference between grassland compared to bare-fallow and arable land was less significant than after 2 years. The proportion of pores smaller than 9.26 μm was greater under bare-fallow and arable land compared to grassland but the proportion of pores larger than 42 μm was not significant between all treatments (Figure 3c). After 7 years, the trend observed after 2 years was more apparent: the proportion of pore sizes smaller than 14.9 μm was greater in rank under bare-fallow > arable > grassland, and the proportion of pore sizes over 42 μm was greater under arable and grassland (respectively, 7 and 10% of pores) than bare-fallow (2% of pores; Figure 3d). After 10 years post-conversion, this trend was also observed, but only for pores smaller than 9.26 μm, where the proportion of pores followed the ranking bare-fallow > arable > grassland (Figure 3e). Beyond this pore size, the proportion of pore sizes was not

significantly different between bare-fallow and arable. The proportion of pore sizes greater than 42 μm was higher under grassland (15% of pores) than bare-fallow and arable land (respectively, 4 and 2% of pores; Figure 3e).

The general trend in all three treatments was a shift to a more even distribution of pore sizes, manifest as a decrease in G over time (Figure 3f). ANCOVA indicated equal rates of change of G between treatments ($F_{2,129} = 0.18$, $p = .834$). Using an equal slopes model, there was a significant effect of land management upon G ($F_{2,131} = 9.1$, $p < .001$), with grassland having a significantly lower adjusted mean G (0.420 ± 0.033) than either bare-fallow (adjusted mean $G = 0.566 \pm 0.028$; $t = 3.6$, $p < .001$) or arable land (adjusted mean $G = 0.571 \pm 0.024$; $t = 3.7$, $p < .001$). There was no significant difference in adjusted mean G between arable and bare-fallow land ($t = 0.13$, $p = .900$).
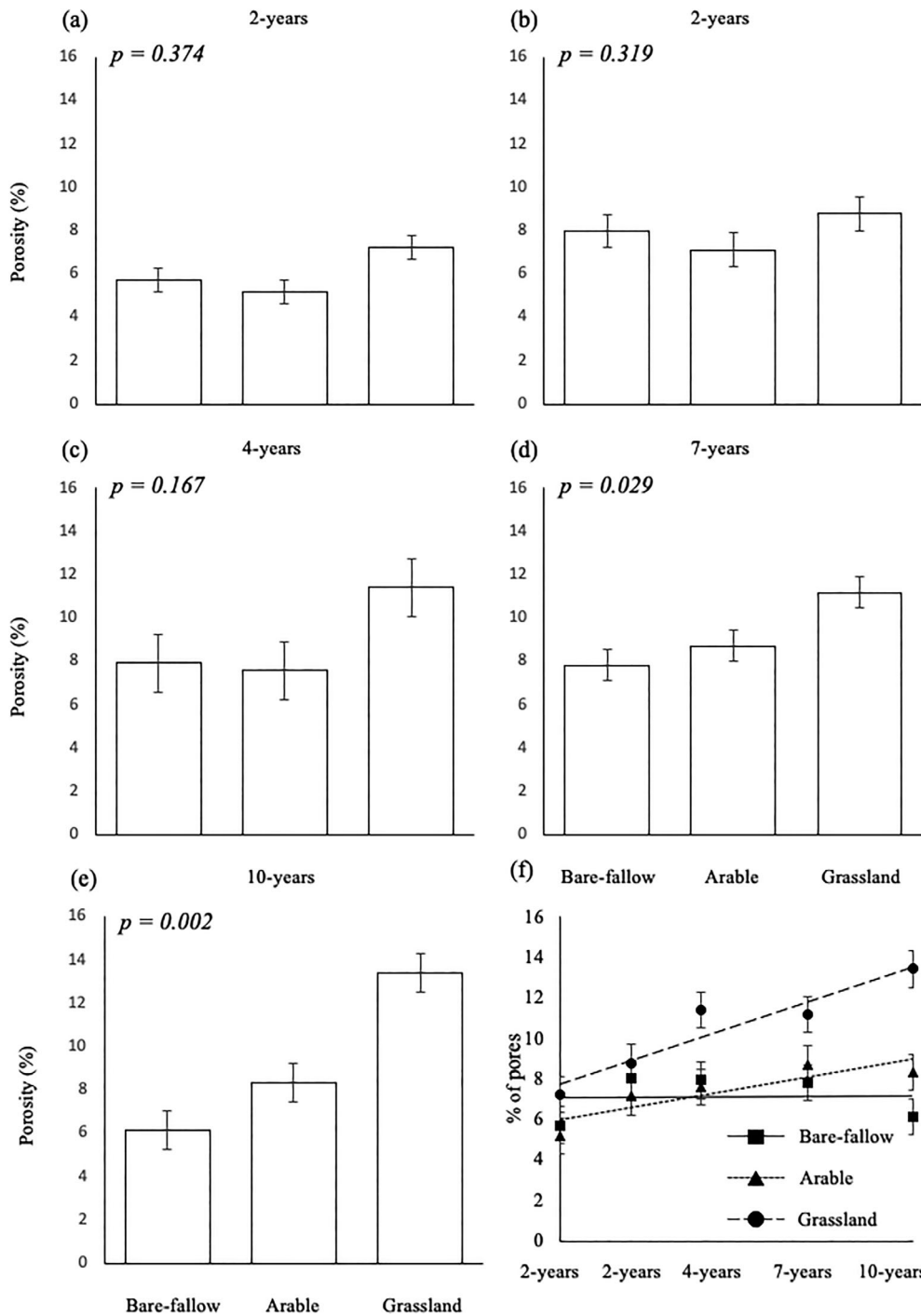
FIGURE 2 Porosity (based on resolution of 1.5 μm) in bare-fallow, arable and grassland soils in the years following conversion: (a) 0 years; (b) 2 years; (c) 4 years; (d) 7 years; (e) 10 years. Bars are means ($n = 9$) expressed as the percentage of pores relative to the total volume; whiskers denote 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

3.4 | Pore connectivity

Before the conversion (in 2008) and after 7 years post-conversion, there was no significant pore diameter by treatment interaction with regard to pore connectivity ($p = .05$; Figure 4a,d). However, there was a significant pore diameter by treatment interaction after 2, 4 and 10 years (with 2 and 10 years, $p < .001$; 4 years, $p < .05$; Figure 4b,c,e). After 2 and 4 years, the difference was significant only for the pore sizes smaller than 3.56 μm.

After 2 years, pore connectivity was greater, ranking bare-fallow > grassland > arable (Figure 4b), and after 4 years, pore connectivity was greater under arable and grassland than bare-fallow (Figure 4c). After 10 years post-conversion, the same trend as after 4 years was shown with a greater difference in the values (Figure 4e). There was no significant trend in square root transformed connected porosity (Figure S2) in bare-fallow (slope $= -0.00023$, $t = 0.051$, $p = .959$). However, both arable land (slope $= 0.017$, $t = 4.0$, $p = .0002$) and

FIGURE 3 Cumulative pore size normalized to the total volume in relation to bare-fallow, arable and grassland in the years following conversion: (a) 0 years; (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
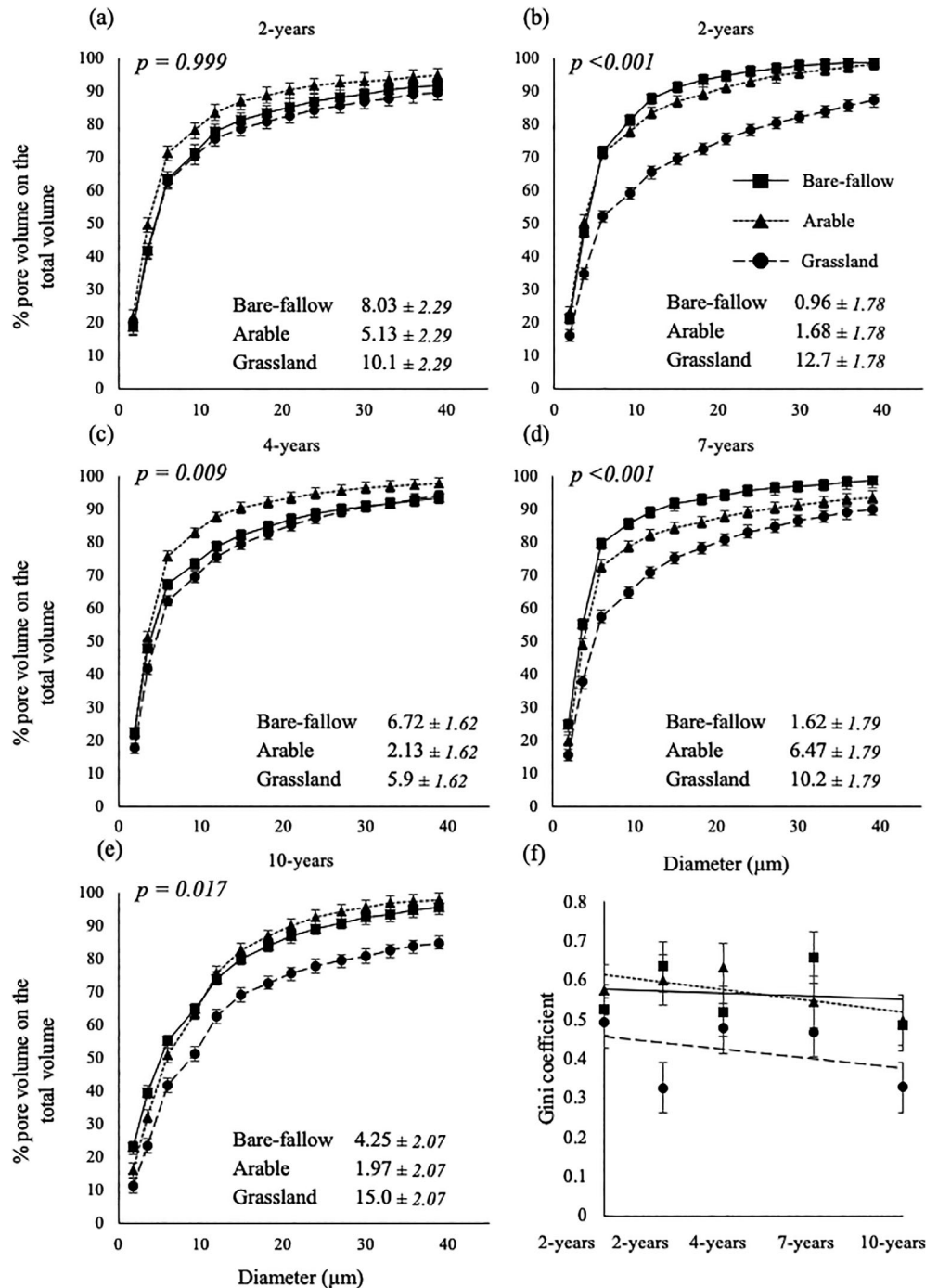
grassland (slope $= 0.022$, $t = 5.3$, $p < .0001$) showed increases in connected porosity with time. ANCOVA comparing arable and grassland indicated a significant influence of time post-conversion on square root transformed connected porosity ($F_{1,85} = 43.9$, $p < .001$) but no significant heterogeneity of slopes ($F_{1,85} = 0.98$, $p = .326$). Using an equal slopes model, a significant effect of management was detected ($F_{1,85} = 4.4$, $p = .039$): grassland was associated with greater connected porosity ($0.048 \pm 0.0002\%$, adjusted mean $\pm$ standard error) than arable land ($0.011 \pm 0.0002\%$).

3.5 | Pore surface density

Before the conversion (in 2008) and at 4 and 7 years post-conversion, there was no significant pore diameter by treatment interaction with regards to pore surface density ($p > .05$; Figure 5a,c,d). There was a significant diameter by treatment interaction after 2 and 10 years (respectively, $p < .05$ and $p < .001$; Figure 5b,e). After 2 years, the difference in pore surface density was greater, ranking from bare-fallow > arable > grassland for the pore sizes equal to $1.86 \ \mu m$, and the difference between arable
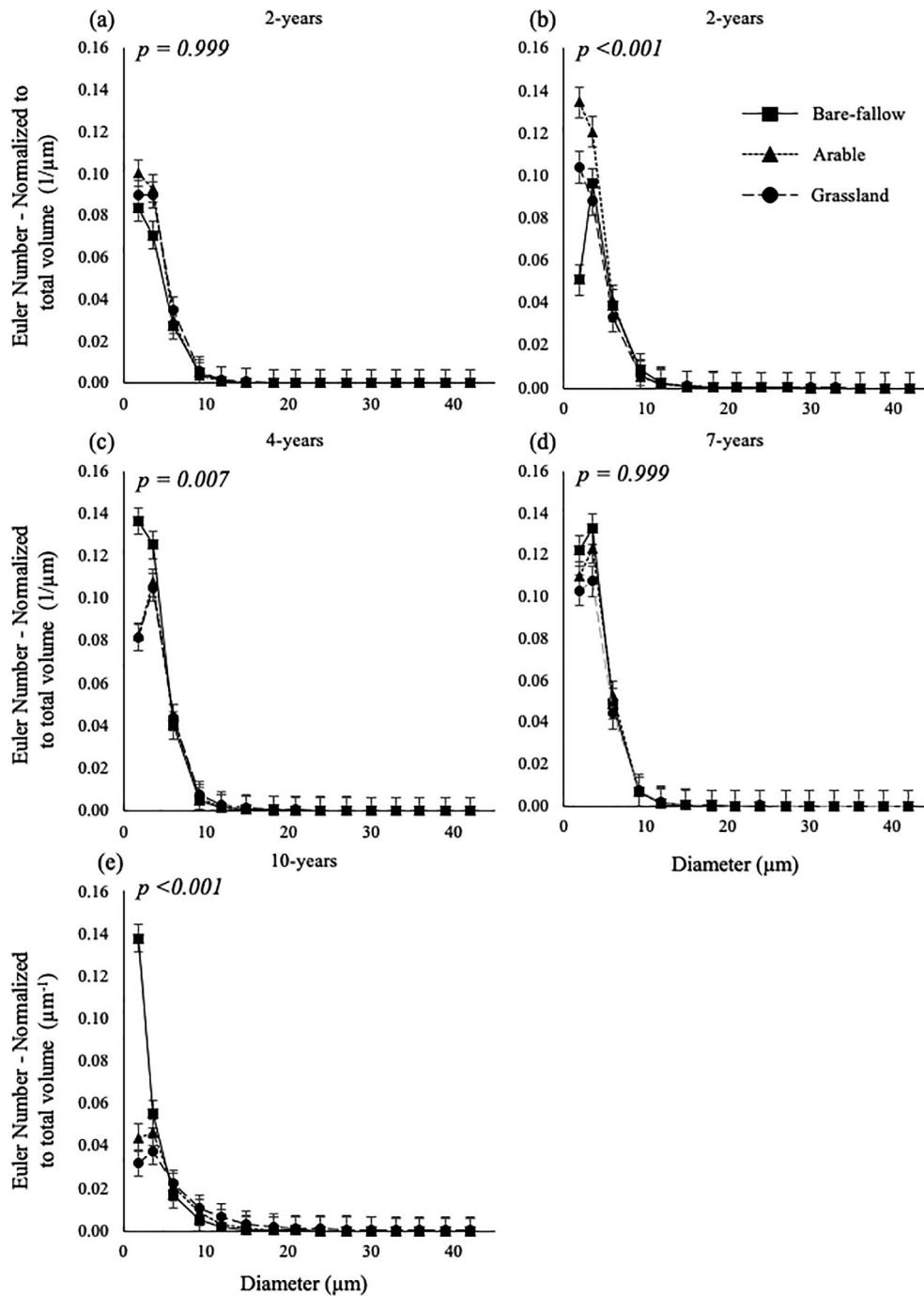
FIGURE 4 Pore connectivity normalized to total volume in continuous bare fallow, arable and grassland soils following conversion: (a) 0 years; (b) 2 years; (c) 4 years; (d) 7 years; (e) 10 years. Data points indicate means ($n = 9$); whiskers denote pooled standard errors

and grassland was not significant for the pore sizes equal to 3.56 μm. Beyond this pore size, there was no significant difference between treatments (Figure 5b). Ten years post-conversion, pore surface density was greater, ranking from grassland > arable > bare-fallow, for all pore sizes smaller than 14.9 μm; there was no significant difference beyond this pore size (Figure 5e). Years post-conversion and pore diameter were both used as covariates in ANCOVA analysis of pore surface area. Accounting for these two covariates, an equal slopes model identified a

significant effect of land management upon pore surface area ($F_{2,2020} = 9.1$, $p < .001$). Post hoc pairwise comparison of adjusted means indicated that grassland supported a greater pore surface area (0.00784 ± 0.000493 μm^2 μm^{-3}) than either arable land (0.00617 ± 0.000452 μm^2 μm^{-3}; difference $= 0.00167$, $t = 3.4$, $p = .001$) or bare-fallow (0.00593 ± 0.000443 μm^2 μm^{-3}; difference $= 0.00191$, $t = 3.9$, $p < .001$). There was no significant difference in pore surface area between arable land and bare-fallow (difference $= 0.000240$, $t = 0.495$, $p = .621$).

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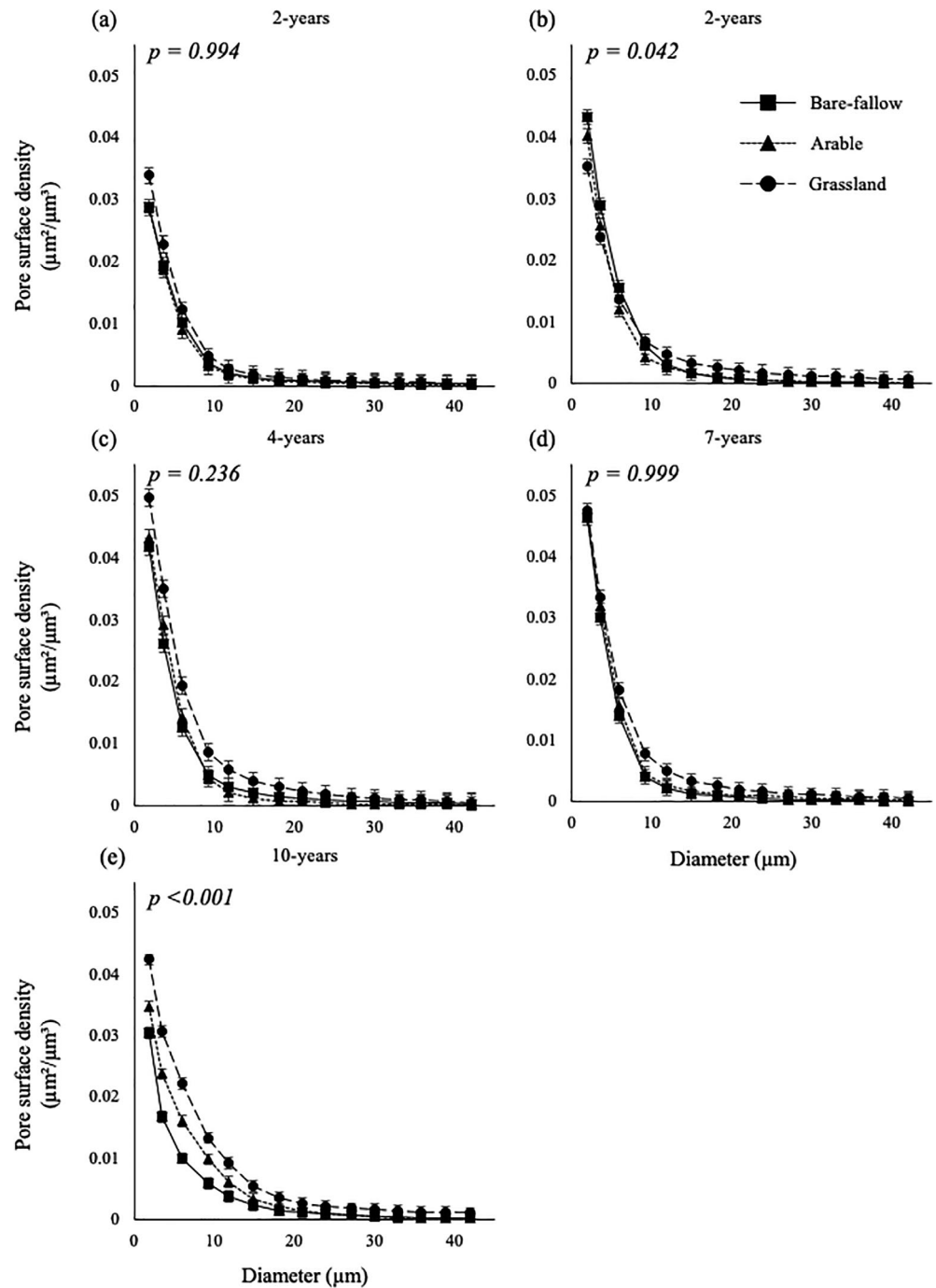
4 | DISCUSSION

The plots studied here were derived from long-term bare-fallow management converted to arable and grassland and the soil structure was measured on soil aggregates (<2 mm diameter). A lack of a significant treatment effect on porosity until 7 years post-conversion suggests that modification of microporosity takes several years (Figure 2). Another study on the same soil 2 and 4 years post-conversion found some recovery of mesofaunal populations after 2 years of conversion and an increase in

soil organic matter and microbial abundance after 4 and 2 years, respectively (Hirsch et al., 2017). However, our study showed that evolution of microscale porosity apparently takes longer. This might be related to carbon cycling processes, which are modified by the microbial communities and plants (via decomposition of organic matter and rhizodeposition). This is likely to affect soil structure at the microscale, but not instantaneously. Increased pore formation under grassland compared to arable land is consistent with a previous study, which showed greater resistance to and evolution from physical

stresses of soil structure from grassland (Gregory et al., 2009). They posited that the greater proportion of organic matter enhanced the elastic recovery of soil structure (Gregory et al., 2009).

Pore size distributions showed a more rapid response to altered management than porosity for the grassland treatment: after only 2 years of conversion (in 2010), a greater diversity of pore sizes was observed, and this trend was also recorded in the data after 7 and 10 years (Figure 3). The Gini-coefficient indicated that soil converted to grassland established a more even distribution of pore sizes than the other treatments, meaning that grassland treatment had a greater diversity of pores after 2, 7 and 10 years post-conversion (Figure S2), leading to enhanced functionality. This increase in pore size diversity might be due to the increase in the presence of plants, active organisms and organic matter (Hirsch et al., 2017) as well as the absence of tillage. A study focusing on the soil organic carbon in the same experiment found that the conversion of the bare-fallow soil to grassland led to an increase of soil organic carbon (+46%) 7 years post-conversion (Jensen et al., 2020). There are no data regarding the conversion from bare-fallow to arable. Thus, the increase of organic matter in the converted soil may play a role in the more homogenous distribution of the pore sizes. Indeed, in a silty clay soil, the greater organic matter content increases the proportion of pores between 0.5 and 500 μm (Metzger & Yaron, 1987; Watts & Dexter, 1997), leading to a more equitable distribution of pore sizes (i.e., a greater diversity of pore sizes). The greater diversity of pore sizes under soil converted to grassland was consistent with a previous study describing the long-term effect of grassland management in the same field experiment (Bacq-Labreuil et al., 2018). After 4 years the pore size distribution did not follow this trend (Figure 3c), which could be due to weather conditions prior to sampling in that year. Indeed, 2008 and 2012 (at the start and 4 years post-conversion, respectively) were the wettest years during the experimental period, with around 650 and 750 mm of rainfall on average in mid-October, respectively (Figure S3). In the presence of water, clay particles can swell, and the compression of entrapped air in capillary pores can disrupt the pore architecture and affect the pore size distribution (Denef et al., 2001; Grant & Dexter, 1990). Pore networks are restructured upon rewetting due to the nature of soil particles. Therefore, the climatic conditions might have impacted the pore size distribution of the soil due to its inherent nature, as the soil texture is silty-clay loam. Changes in pore size between 2, 4 and 7 years post-conversion raise the question of the dynamics of this mechanism. The pore size distribution may have had a heterogeneous response over time due to the impact of

the wet year 4 years post-conversion, which shows the rapid evolution of the pore size distribution after a sustained wet period compared to the impact of agricultural practices (Figure S3). For the arable treatment, this trend was not observed even 10 years post-conversion, which might be due to the associated tillage practices.

For pore connectivity, the conversion to grassland had a small effect after 2 and 4 years compared to after 10 years post-conversion (Figure 4b,c,e). However, pore connectivity data after 10 years post-conversion, for both arable and grassland converted soils (Figure 4e), suggested the pore network was less connected compared to Bacq-Labreuil et al. (2018). This indicated that a longer time may be required to develop the connectivity of a pore network than the overall porosity. Increased connectivity of pores promotes water, gasses and nutrient flows within the pore structure (Dexter, 1988; Tisdall & Oades, 1982). Therefore, subtle increases in pore connectivity might increase water, gas and nutrient flux within the soil. As well as the pore connectivity, the pore surface density was significantly increased in the grassland and arable land 10 years post-conversion (Figure 5e). Our results are congruent with Bacq-Labreuil et al. (2018), who showed grassland managed consistently for over 200 years has an increased pore surface density compared to arable and bare-fallow soils (i.e., the pore-solid interface, which led to a greater surface of the pore where microorganisms and plant roots can colonize and water films can develop). A greater pore surface density in the converted plot means that the grassland and the arable land have a more complex structure of pores than the bare-fallow soil (Müller et al., 2019). The greater surface density for the grassland compared to the arable land might be induced by the greater soil organic carbon content and the absence of tillage for this treatment (Hirsch et al., 2017; Jensen, Schjønning, Watts, Christensen, Obour, & Munkholm, 2020). This can lead to the formation of new habitats and niches, which can be beneficial for microbial community diversity (Holden, 2011). The greater pore surface area might increase water and nutrient uptake by the microbial community and plants.

This study suggests that conversion of degraded bare-fallow soil to grassland requires at least 10 years after conversion before being effective in terms of significant evolution of soil structure at the aggregate scale, as assessed by the overall and connected porosity. Moreover, the conversion from bare-fallow to arable land had no significant effect on soil structural properties after a decade. In general, the recovery of mesofauna and organic matter (Griffiths et al., 2000; Hirsch et al., 2017) was more rapid than the recovery of soil structure (Gregory et al., 2009). The pore size distribution was the only characteristic that

was more sensitive to changes induced by wetting and drying cycles and living organisms.

Our first hypothesis was supported because porosity, pore size diversity, pore connectivity and pore surface area density were all enhanced in grassland soil. Moreover, the conversion to arable management did not affect soil structural evolution significantly. The conversion to grassland increased the range of pore sizes after 2 years, consistent with our second hypothesis. However, all other Minkowski functions (porosity, pore connectivity and pore surface area density) responded to change more slowly. The mechanisms behind the evolution of pore sizes appeared to be dynamic and possibly dependent upon weather conditions before sampling. Apart from the pore size distribution, the magnitude of the grassland effects on all other Minkowski functions was lower than the difference observed after a minimum of 50 years of management (Bacq-Labreuil et al., 2018). In this study, the effect of grassland upon porosity and pore connectivity was twofold greater than bare-fallow management. Here, the difference was significant but not as major. Bare-fallow soil management for this long period (> 50 years) is detrimental to both physical and biological soil properties and the evolution of the soil structure after this requires more than 10 years after the conversion to grassland.

5 | CONCLUSIONS

The soil structural evolution of a degraded silt-clay loam soil, as quantified by microscale topological metrics (i.e., within aggregates with a diameter smaller than 2 mm), requires at least 10 years of a grassland management before showing any significant effects. Moreover, the evolution of the structure under grassland does not seem to have reached a new equilibrium 10 years post-conversion. These observations raise a question over the application of certain managements in agricultural practices. For example, instead of applying a bare-fallow treatment in a crop rotation, it would be beneficial for the soil characteristics to apply a vegetation cover (i.e., cover crops that increase organic matter inputs and influence soil structure), leading to a "conditioning" of soil physical and biological characteristics for the next crop. This would prevent further degradation of soil and help its evolution if the soil characteristics were compromised. Moreover, the evolution of soil structure is apparently a long process in the context of current agricultural practices and perceived imperatives. Thus, a modification of cropping managements should be anticipated to require some time before the observation of beneficial impacts on soil structural dynamics. Therefore, this should be accounted for in future research and conclusions.

AUTHOR CONTRIBUTIONS
A.B.L. led and conducted the experimental work, analysed the experimental results, drafted the manuscript and coordinated the revisions. K.R., S.J.M. and A.N. contributed advice on the analyses. All authors contributed to the revision of the manuscript. K.R. and S.J.M. supervised the overall project. All authors gave final approval for publication.

DATA AVAILABILITY
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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