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1 **Effect of long-term irrigation and tillage practices on X-ray CT and gas transport derived**
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3

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5

6 *Karin Müller^A, Nicola Dal Ferro^{B, G}, Sheela Katuwal^C, Craig Tregurtha^D, Filippo Zanini^E, Simone*
7 *Carmignato^F, Lis Wollesen de Jonge^C, Per Moldrup^F, and Francesco Morari^B*

8

9 ^APlant & Food Research, Production Footprints, Bisley Road, Hamilton 3214, New Zealand

10 ^BDepartment of Agronomy, Food, Natural Resources, Animals and Environment, Agripolis,
11 University of Padova, Viale Dell'Università 16, 35020 Legnaro, Italy

12 ^CDepartment of Agroecology Aarhus University, Blichers Allé 20, P.O. Box 50, DK-8830 Tjele,
13 Denmark

14 ^DPlant & Food Research, Soil Water & Environment, Gerald Street, Lincoln 7608, New
15 Zealand

16 ^EDepartment of Management and Engineering, University of Padova, Stradella San Nicola,
17 36100 Vicenza, Italy

18 ^FDepartment of Civil Engineering, Aalborg University, Thomas Manns Vej 23, Aalborg Ø,
19 9200-Denmark

20

21 ^GCorresponding author. Email: nicola.dalferro@unipd.it

22

23

24 **Abstract**

25 The gas transport parameters, diffusivity and air-filled porosity are crucial for soil aeration,
26 microbial activity and greenhouse gas emission, and directly depend on soil structure. In this
27 study, we analysed the effect of long-term tillage and irrigation practices on the surface
28 structure of an arable soil in New Zealand. Our hypothesis was that topsoil structure would
29 change under intensification of arable production affecting gas exchange. Intact soil cores
30 were collected from plots under intensive tillage (IT) and direct drill (DD), irrigated or
31 rainfed. In total, 32 cores were scanned by X-ray computed tomography (CT) to derive the
32 pore network $> 30 \mu\text{m}$. The cores were then used to measure soil-gas diffusivity, air-
33 permeability and air-filled porosity of pores close to the resolution of the X-ray CT scans,
34 namely $\geq 30 \mu\text{m}$. The gas measurements allow the calculation of pore-network connectivity
35 and tortuosity parameters that were compared with the CT-derived structural
36 characteristics. Long-term irrigation had little effect on any of the parameters analysed.
37 Total porosity tended to be lower under IT than DD, while the CT-derived porosity (TP_{CCT})
38 was comparable. Both, the CT-derived mean pore diameter (MPD) and other morphological
39 parameters, as well as gas measurement-derived parameters, highlighted a less developed
40 structure under IT. The differences in the functional pore-network structure were attributed
41 to SOC-depletion and the mechanical disturbance through IT. Significant correlations
42 between CT-derived parameters and functional gas transport parameters such as tortuosity
43 and MPD were found, which suggest that X-ray CT could be useful in the prediction of gas
44 transport.

45 **Keywords:** soil organic carbon, carbon depletion, Dexter index, P-parameter, intensive
46 tillage, soil structure

47 Introduction

48 Modern agriculture associated with increased inputs of agrichemicals, irrigation and
49 intensive cultivation has led to soil compaction and erosion, which negatively affect the
50 delivery of soil ecosystem services. Concomitant are environmental problems such as
51 enhanced greenhouse gas emissions, and degradation of soil and water quality. Soil
52 degradation manifests itself in reduced soil organic matter contents and loss of soil
53 structure, and is threatening the resilience and productivity of agricultural soils.

54 It is commonly accepted that intensive tillage (IT) results in losses of soil organic carbon
55 (SOC), decreased aggregate stability, and lessivage of finer particles leading to the
56 degradation of soil structure (Pagliai et al. 2004; Puget and Lal 2005). In line with this, many
57 studies have shown that reduced tillage can change physical and chemical soil properties
58 and can confine the environmental effects of IT (Dick 1983; Tebrügge and Düring 1999;
59 Pagliai et al. 2004; D'Haene et al. 2008; Vogeler et al. 2009; Ludwig et al. 2011; González-
60 Sánchez et al. 2012).

61 Irrigation is a key management practice of modern agriculture and is indispensable for
62 today's food security, in particular, in the face of climate change. In fact, globally at least
63 33% of today's food is produced under irrigation (Siebert and Döll 2010). Less is known
64 about the long-term influence of irrigation practices on soil properties. Recently, Trost et al.
65 (2013) reviewed 14 long-term studies investigating the effect of irrigation on SOC under
66 arable production and concluded that the direction of change in SOC stocks was mainly
67 dependent on the climate and the soil's initial carbon contents. The additional water input
68 increases soil moisture, which enhances plant growth leading to higher input of organic
69 carbon, but it also promotes soil microbiological activities, which enhance microbial
70 decomposition of organic matter. It is not trivial to predict how irrigation will affect SOC

71 content, which is intrinsically linked to soil structure. Even less is known about the
72 interactions between long-term irrigation and tillage practices and their combined effect on
73 SOC and architecture. Recent research by Pareja-Sánchez et al. (2017) highlighted that
74 irrigation led to greater susceptibility to topsoil structural degradation, which in turn was
75 mitigated by adopting conservation tillage practices.

76 Understanding of gaseous flow through soils and soil air exchange with the atmosphere is
77 required for understanding many soil functions including carbon sequestration and the
78 related emission of greenhouse gases (Ball 2013). Gas transport in soil is dependent on the
79 pore-network characterized by its pore size distribution, connectivity, tortuosity and water
80 content, and as such, is influenced by soil management including tillage and irrigation.
81 Accurate prediction of air permeability and gas diffusivity requires quantifying parameters
82 describing the pore-network, in particular, tortuosity and connectivity (Ball 1981a). Previous
83 studies have used non-invasive imaging techniques including X-ray computed tomography
84 (CT) to analyse the effect of management practices on soil structure (Papadopoulos et al.
85 2009; Schlüter et al. 2011; Garbout et al. 2013; Munkholm et al. 2013; Dal Ferro et al. 2014;
86 Piccoli et al. 2017a). Only few studies have linked CT-derived morphometrical parameters to
87 functional parameters derived from gas flow measurements (Naveed et al. 2013; Katuwal et
88 al. 2015). Our hypothesis is that structural characteristics including pore size distribution,
89 connectivity and tortuosity of surface soil will change under long-term intensive arable
90 production and that these changes can compromise some pivotal soil functions, such as soil-
91 air gas flow and exchange.

92 Our main objective is therefore to assess the potential effect of long-term irrigation and IT
93 practices on soil quality and pore-network in a soil representative of arable soils in the South
94 Island, New Zealand. We analysed the pore-network architecture of a topsoil which had

95 been 14-years under different management practices using X-ray CT, air permeability and
96 gas diffusion measurements. Our specific aim was to identify structure-related soil
97 parameters that may be used as proxies to quantify soil physical quality and its functionality.

98

99 **Materials and methods**

100 *Site description*

101 The study site (-43.79 N 171.96 E, altitude 109 m) is located on a research farm of the
102 Foundation for Arable Research (FAR) in Chertsey, Canterbury, New Zealand. The warm,
103 temperate climate is characterized by long-term average annual rainfall of 699 mm and
104 annual temperature of 11.2°C. Rainfall is evenly distributed throughout the year with a
105 difference of about 20 mm between the driest and the wettest month. The shallow silt loam
106 soil is classified as Pallic Soil (Hewitt 2010), which corresponds to a Cambisol (FAO 2006).

107 The long-term cultivation and irrigation experiment was established in 2003. The crop
108 rotation at the site is typical for the Canterbury region involving wheat (*Triticum aestivum*
109 L.), peas (*Pisum sativum* L.), ryegrass (*Lolium perenne* L.) and linseed (*Linum usitatissimum* L.).

110 At the time of the soil sampling for this study, the soil was under the second year of ryegrass
111 grown for seed. The experimental design is a split-plot experiment with irrigation as main
112 plot established in duplicate and cultivation as split-plots (25 m × 12 m). The treatments are
113 a combination of two irrigation practices (non-irrigated and irrigated with a lateral travel
114 spray irrigator to a non-stress situation for the respective crop) on the four main plots with
115 six cultivation practices allocated randomly to each of the main plots. We only included the
116 two most extreme cultivation management practices in this study. These were the IT
117 treatment, which includes 20-25 cm depth ploughing, followed by two passes of a Vaderstad
118 Topdown cultivator and John Deere 750A double disc drill, and the direct drill (DD) practice

using a cross slot drill. No organic amendments were applied. The site is under conventional management.

Soil sampling

Soil samples were collected from four randomly selected locations in each split-plot at a depth of 0 to 5 cm in April 2017. At each location a disturbed bulk sample, an undisturbed soil core (5 cm I.D. × 5 cm length) and another intact core (6 cm I.D. × 3 cm length) were taken. Soil cores were excavated by slowly pushing PVC cylinders into the soil. The soil samples were kept cool until delivery to the laboratory. All soil cores were then immediately placed into a hot water bath of 0.5-m depth for three hours to dispel earthworms from the cores. All samples were stored at 4°C until further analysis.

Chemical analysis

The disturbed samples were sieved to < 2 mm. Total SOC content was determined on 0.5 g to 1.0 g sub-samples by an automated dry combustion method (Dumas) using a Leco TruMac CN analyser (Leco Corporation, MI, USA) operating at 1250°C (Blakemore et al. 1987). Hot water extractable carbon (HWC) was determined using the method developed by Ghani et al. (2003). Dissolved organic carbon in the HWC extracts was determined by high temperature catalytic combustion using a Shimadzu TOC-V CSH total organic-carbon analyser.

X-ray Computed Tomography, image processing and analysis

The intact soil cores (5 cm I.D. × 5 cm length) were air-dried for about a week prior to trimming their surfaces to exact size. Then, they were saturated from the bottom and

143 equilibrated on pressure plates to a matric potential of -150 cm to ensure uniform
144 conditions before X-ray CT scanning. The entire soil cores were scanned using a metrological
145 X-ray CT system MCT225 (Nikon Metrology, Tring, UK). A metrological X-ray CT system was
146 used to obtain more accurate 3-dimensional measurements (Khademzadeh et al. 2016;
147 Zanini and Carmignato 2017). The source was set to 210 kV and 167 μ A. A 0.1 mm copper
148 filter was used to minimize beam hardening effects. For the acquisition of bi-dimensional
149 projections (resolution of 33 μ m) the software Inspect-X Vers. XT 3.1.9 provided by Nikon
150 Metrology was used. The resulting 1500 2D-projection images in 16-bit depth were filtered
151 with a 3×3 median filter to reduce noise and reconstructed using the software CT PRO 3D
152 Vers. XT 3.1.9, provided by Nikon Metrology. The reconstructed volumes were aligned
153 using the analysis and visualization software VGStudio MAX 3.1 (Volume Graphics GmbH,
154 Heidelberg, Germany) so that the vertical axis coincided with the axis of the external PVC
155 cylinder. The reconstructed 2D images were segmented into soil pores and matrix using the
156 machine learning-based approach WEKA implemented in ImageJ (Arganda-Carreras et al.
157 2017). This plugin leverages the users' identification of object classes within a set of images,
158 and then applies the classification to the image stack, creating a fully segmented dataset.
159 Finally, a cylindrical region of interest representing the largest volume fully occupied by soil,
160 was selected for each image stack excluding the PVC cylinder. At least 1400 continuous slices
161 per soil sample were selected. Total porosity detected by CT (TP_{CT}) was calculated by dividing
162 the number of pore voxels by the total number of voxels per core volume. The pore size
163 distribution was obtained as an average of the local thickness of every voxel representing
164 pores (Ulrich et al. 1999). To facilitate the comparison of the pore size distribution, we
165 grouped pores into the following five arbitrarily chosen classes: 33-300, 300-700, 700-1,003,
166 1,003-3,000, >3,000 μ m. In addition, a set of X-ray CT-derived structural parameters were

quantified: the degree of anisotropy (DA), as an indicator of the 3D pore symmetry-asymmetry (range from 0 to 1; Harrigan and Mann 1984); the 3D fractal dimension (FD), which describes the self-similarity (scale invariance) of an object, as an indicator of surface complexity (Perret et al. 2003); the connectivity (CE), computed by dividing the connectivity calculated with the Euler-Poincaré equation (Vogel 1997) with the volume analysed; the structure model index (SMI; Hildebrand and Rügsegger 1997), that measures the pore geometry from plate-like (values close of 1) to rod-like shapes (values close to 3, cylinders, or 4, spheres); the object surface-to-volume ratio (OSVR), estimated by dividing the total pore surface by its volume, that characterizes the pore structure complexity, thickness, and roughness; the tortuosity (T), determined by relating the sum of the distances of the centroids of the pores between adjacent slices to the height of the image stack (Katuwal et al. 2015). Finally, a CT-based tortuosity-connectivity parameter (X_{CCT}) was derived following Katuwal et al. (2015).

Gas parameter measurements

The soil cores were drained to -100 cm matric potential before the gas transport measurements. The air-filled porosity (ϵ_a , $\text{cm}^3 \text{cm}^{-3}$) was obtained from the total porosity and the volumetric water content of the soil at -100 cm matric potential. The air permeability was determined using a laboratory air permeameter, the description and procedure of which are provided in Schjønning and Koppelgaard (2017). Briefly described, the convective air flow rates were measured at four pressure gradients (around 5, 2, 1 and 0.5 hPa). A second-order polynomial equation was fitted between the pressure difference (ΔP) and the air flow velocity (v) as:

$$\frac{\Delta P}{L_s} = a \times v + b \times v^2 \quad [1]$$

where L_s is the sample length (m), and a and b are fitting coefficients. The intrinsic air permeability (k_a , μm^2) was calculated as the ratio of air viscosity (η) and the fitting coefficient, a (Schjønning and Koppelgaard 2017):

$$k_a = \frac{\eta}{a} \quad [2]$$

The relative gas diffusivity (D_p/D_0) was measured using the one-chamber gas diffusion apparatus and O_2 as the diffusing gas as described in Schjønning et al. (2013). The apparatus consists of measuring chambers with O_2 sensors on the top of each chamber. The soil samples were placed in the airtight chambers with their lower end exposed to the ambient air. N_2 gas was used for flushing the closed chamber above the soil top to remove all O_2 from it. The gradient in O_2 concentration between the top and the bottom of the soil sample allowed O_2 gas to diffuse through the sample into chamber, the concentration of which was recorded every 2 min. The O_2 diffusion coefficient (D_p) was calculated using the non-steady state method described by Rolston and Moldrup (2002) as:

$$D_p = - \left(V_c \times \frac{L_s}{A_s} \right) \left[\frac{\ln \left(\frac{\Delta C_t}{\Delta C_0} \right)}{t} \right] \quad [3]$$

where ΔC_t and ΔC_0 are the differences in O_2 concentration between the two ends of the sample at time $t = t$ and $t = 0$, respectively, V_c is volume of the diffusion chamber, L_s is the sample length (m) and A_s the cross-sectional area of the soil (m^2). The relative gas diffusivity (D_p/D_0) was obtained after scaling D_p by the diffusion coefficient of O_2 gas in free air ($D_0 = 2.05 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$).

Several studies (e.g., Moldrup et al. 2001; Kawamoto et al. 2006; Chamindu Deepagoda et al. 2012) have shown that ϵ_a , k_a and D_p/D_0 in combination can be used to fingerprint the soil structure using different parameters as described below. The specific permeability was calculated as the ratio of air permeability and air-filled porosity. Specific gas diffusivity refers to the ratio of relative gas diffusivity and air-filled porosity. The gas diffusion-based tortuosity, τ , was calculated using D_p/D_0 and the air-filled porosity (ϵ_a) at -100 cm matric potential (Moldrup et al. 2001) as:

$$\tau = \sqrt{\frac{\epsilon_a}{D_p/D_0}} \quad [4]$$

The tortuosity-connectivity parameter (X) was calculated as (Chamindu Deepagoda et al. 2012):

$$X = \frac{\log(D_p/D_0)}{\log(\epsilon_a)} \quad [5]$$

The equivalent pore diameter (d , μm) was obtained following Ball (1981a):

$$d = 2 \sqrt{\frac{8k_a}{D_p/D_0}} \quad [6]$$

Air permeability was predicted from measurements of D_p/D_0 (e.g., Moldrup et al. 1998):

$$k_a = P \times D_p/D_0 \quad [7]$$

where P (μm^2) is a soil structural parameter that is dependent on the equivalent pore diameter (Katuwal et al. 2015). It was obtained as the ratio between air permeability and gas diffusivity. High P -parameter values identify a prevailing pipe-like pore-network with continuous pores enhancing convective gas exchange (Kawamoto et al. 2006).

230 *Physical analysis*

231 The soil cores were dried in the oven at 105°C for 48 h for determining the volumetric water
232 content and the bulk density following Blakemore et al. (1987). In addition, a sub-sample of
233 the soil cores was sieved to < 2 mm and dispersed in a 2% sodium hexametaphosphate
234 solution for soil textural determination by laser diffractometry using a Malver Mastersizer
235 2000 (Malvern Instruments, Malvern, UK).

236

237 *Statistical analysis*

238 To account for the split-plot design of the experiment, data were analysed with ANOVA with
239 irrigation and cultivation and their interaction as fixed effects. Data of each plot were
240 included in the analysis as a within-subplot factor. Variability associated with the modelled
241 means is provided by the Least Significant Difference (LSD) at the 5% level of significance.
242 Heterogeneity of variance was assessed and data were log-transformed if needed. These
243 statistical analyses were carried out using the statistical package GenStat (Version
244 18.2.0.18409, VSN International Ltd.). In addition, Pearson's correlation analysis and multiple
245 regression analysis were performed with Statistica (StatSoft Inc., Tulsa, USA) to estimate
246 linear relationships between the analysed variables.

247

248 **Results and discussion**

249 *General soil properties*

250 The topsoil is classified as a silt loam soil (Verheye and Ameryckx 1984). We found a
251 significant ($p < 0.05$) difference in the textural composition between the DD and IT topsoil
252 (Table 1). The higher clay (Fig. 1a) and silt contents under IT compared to those under DD
253 might be attributed to mixing of soil from deeper depth with higher clay and silt contents

254 into the topsoil through ploughing. Irrigation tended to decrease SOC concentration (-6%;
255 $p=0.124$; Fig. 1a). Tillage resulted in a significant ($p=0.01$) reduction of SOC (-19%; Fig. 1b).
256 This led to a clay-to-carbon ratio (Dexter index; Dexter 2004) < 10 in the DD topsoil and > 10
257 in the IT soil (Table 1; Fig. 1c), suggesting the potential for a more developed soil structure in
258 the DD topsoil. Crop residues and yields have been similar for the different tillage treatments
259 at the experimental site since 2003, the start of the experiment. Irrigation has led to
260 significantly higher annual yields throughout the crop rotation (data not shown). Thus we
261 attribute the observed differences in SOC to the result of physical disturbance that likely
262 produced differences in topsoil temperature and water content, and the related effects on
263 soil microbiological activities (Trost et al. 2013). Similar positive effects of reduced tillage
264 practices on SOC stocks in the topsoil have been observed in many other studies (Havlin et
265 al. 1990; Soane and Ball 1998; Al-Kaisi et al. 2005; Puget and Lal 2005). Some studies
266 cautioned that SOC increases in topsoils related to reducing tillage intensity might be the
267 consequence of redistributing carbon with depth (Baker et al. 2007; Powlson et al. 2014).
268 This suggests that SOC might be stratified differently between DD and IT, with the latter
269 showing SOC content dilution due to the mixing of topsoil and subsoil layers. In accordance
270 with our findings, irrigation had no effect on SOC content in other long-term irrigation
271 studies with arable soils under humid climate. This was explained by high mineralisation
272 (Dersch and Bohm 2001) that likely compensated increased biomass production. Mudge et
273 al. (2017) found lower SOC contents under irrigated compared to non-irrigated neighbouring
274 sites with 3 to 33 years of the respective irrigation management history. The authors
275 suggested that a combination of seasonal irrigation in temperate climates and relatively high
276 initial SOC contents were driving factors for decreasing SOC contents. These results support
277 the hypothesis of Trost et al. (2013) that the benefits of irrigation to increase SOC contents

might be restricted to arid and semi-arid ecosystems with low SOC contents. Recently, Chatterjee et al. (2018) reported further corroborating findings studying the effects of two-year irrigation of maize (*Zea mays* L.) in a semi-arid region of India: the initial low SOC content (4.2 g kg^{-1}) significantly increased with irrigation (+40.5%) accompanied by an increase in microbial biomass. However, only few studies investigated the combined effects of irrigation management and minimum tillage practices. Increased SOC stocks (Entry et al. 2004) as also found in our study, or decreased SOC stocks driven by reduced crop root growth lowering belowground carbon inputs (Scott et al. 2012), might occur. Hot water carbon (HWC), which is assumed to be closely related to total microbial biomass (Ghani et al. 2003), was significantly higher in the DD topsoil compared to the IT topsoil (Table 1). This could have been related to the generally lower SOC content in the IT topsoil or to a change in the bioavailability of SOC.

Soil structural parameters

Irrigation had little to no effect on any of the soil physical parameters analysed. Tillage practice led to higher bulk density ($p=0.06$; Table 1, Fig. 1d) and lower total porosity (TP; $p=0.09$; Table 1, Fig. 1e) under IT compared to DD. SOC was positively correlated with the total porosity for the IT soil while no such correlation was found for the DD soil (Fig. 2a). The lower SOC content of the IT soil was an important factor contributing to the higher bulk density observed under IT compared to DD (Fig. 2b). For the DD soil bulk density was more closely related to clay content (Fig. 2c). These findings confirm observations made by Dexter et al. (2008) working with French and Polish data consisting of arable soils with low carbon contents and pastoral soils with high carbon contents. In other long-term tillage studies, similarly increased topsoil bulk density under IT has been observed and attributed to stress

of heavy machinery on soil structure, which can be exacerbated by high water contents during tillage (Deen and Kataki 2003; D'Haene et al. 2008; Badalikova 2010). However, many studies under temperate climate reported the opposite due to weathering and compaction of leaving soil undisturbed (Yang and Wander 1999; Puget and Lal 2005; Dal Ferro et al. 2014; Piccoli et al. 2017b). Contrasting findings can also be attributed to different lengths of time under the respective management practice, different soil texture and SOC content.

The same intact soil cores were scanned by X-ray CT to quantify pore-network parameters. Irrigation had no effect on any of these parameters. Nor was the TP detectable by X-ray CT (TP_{CT} ; pores $> 33 \mu m$) affected by tillage (Fig. 3). The average TP_{CT} was $0.113 \text{ cm}^3 \text{ cm}^{-3}$ and ranged between 12 and 35% of the TP. Limiting the pore volume to the interconnected pore network from the top of a soil core to its bottom (TP_{CCT} ; Fig. 1f) did not change the results with respect to significance but revealed that a single pore cluster accounted for between 83 and 92% of the TP_{CT} (Table 2). In the following, we only consider this connected porosity TP_{CCT} and its related parameters.

The structural parameters DA_{CCT} , FD_{CCT} , CE_{CCT} and T_{CCT} equally showed a random pattern regardless of management (Table 2). The average degree of anisotropy DA_{CCT} was 0.21, indicating an almost symmetrical structure of the soils. The fractal dimension FD_{CCT} averaged 2.33, the average pore connectivity CE_{CCT} , quantified by the Euler number, was $-4.5 \times 10^{-10} \mu m^{-3}$, and tortuosity T_{CCT} was on average 3.2. While in our study these parameters did not differentiate management practices (Table 2), others reported structural differences due to tillage: for instance, Pagliai et al. (2004) found a higher percentage of connected pores under minimum tillage with a disk harrow compared to conventional tillage with mouldboard plough to a depth of 40 cm. In contrast, Pires et al. (2017) reported lower connectivity under DD compared to IT.

326 Nevertheless, interesting correlations between the CT-derived parameters were found in our
327 study. As suggested by Perret et al. (2003), higher values for fractal dimension can describe
328 augmented pore tortuosity or pore complexity. The significant and negative correlation
329 observed between FD_{CCT} and T_{CCT} ($r=-0.6$) highlights that more tortuous pore networks were
330 also dominated by less irregular pore volumes, which did not occupy the entire soil space.
331 Similarly, the correlations between CE_{CCT} and FD_{CCT} ($r=-0.76$) and between CE_{CCT} and T_{CCT}
332 ($r=0.39$) depict that well connected pore networks were more tortuous, in turn less
333 scattered throughout the soil matrix. Similar relationships were also reported in the past in
334 different types of soils, from sandy loam to clay (Chamindu Deepagoda et al. 2012; Katuwal
335 et al. 2015; Piccoli et al. 2017a).

336 Fractal dimension was also correlated strongly and negatively with bulk density ($r=-0.78$) and
337 positively with sand contents ($r=0.47$). Usually, FD is found to increase in soils with
338 increasing clay and fine contents (Deng et al. 2017). The mechanical effect of regular
339 ploughing overrode this relationship.

340 In contrast to the above mentioned structural parameters, IT significantly ($p=0.005$)
341 increased the mean pore diameter ($912\text{ }\mu\text{m}$) compared to DD ($770\text{ }\mu\text{m}$) (MPD_{CTT} , Table 2).
342 Object surface-to-volume ratio ($OSVR_{CTT}$) slightly significantly under IT. These results suggest
343 that IT augmented both soil disaggregation (Kay and Vanden Bygaart 2002) and pore
344 structure simplification, and agree with results on soil pore size distribution: IT showed
345 generally less steep and more variable cumulative porosity curves (Fig. 4a and 4b) than those
346 of DD (Fig. 4c and 4d), which also possessed a larger proportion of smaller pores considering
347 only those detected by the X-ray CT (Fig. 3). For all treatments the majority of pores (ca. 70%
348 of TP_{CCT}) was smaller than $1003\text{ }\mu\text{m}$ (Table 3). In particular, the absolute volumes of the pore
349 size class $300\text{-}700\text{ }\mu\text{m}$ were significantly higher ($p=0.014$) under DD than under IT. Lower

absolute volumes were observed for pores in the size class 1003-3000 μm ($p=0.032$) for DD compared to IT, leading to larger variability in the pore size distributions and reflecting more disturbed soil conditions with tillage. In contrast, large pores were often found under DD compared to IT due to earthworm activities and root growth (Wahl et al. 2004), but results depend on depth, pore size class considered, and soil type. The irrigated topsoil under IT (Fig. 4b) had the highest percentage of large pores ($>3\text{ mm}$) as well as the largest pores, albeit these did not contribute more than max 9% to the TP_{CCT} , the average contribution was 2.6% (Table 3).

Finally, the structure model index, SMI a measure for the plate- or rod-like geometry of pores (Hildebrand and Rügsegger 1997), likewise was increased ($p=0.1$), indicating that in the IT soil pores tended to be of cylindrical ($\text{SMI} = 2.3$) rather than plate-like ($\text{SMI} = 1.65$) shape. It must be noted that the X-ray CT analysis was conducted only on pores $> 30\text{ }\mu\text{m}$, which contributed about 19% to the TP in our soils, thus limiting the understanding of soil microstructural changes.

Functional structural parameters for gas exchange processes: gas diffusivity and air permeability

The air permeability of the topsoil, k_a determined at the same soil cores used for the X-ray CT scanning at a matrix potential of -100 cm was 'fast' ($101\text{-}200\text{ }\mu\text{m}^2$) to 'very fast' ($>201\text{ }\mu\text{m}^2$) according to Fish and Koppi's (1994) scoring classes reflecting the topsoil's good structure with many interaggregate pores. Air permeability is the dominant control for air exchange processes in the topsoil. Irrigation treatment had little influence on k_a , while tillage increased k_a ($p=0.15$; Table 4). In a five-year experiment, Piccoli et al. (2017) found little to no k_a differences between tilled and non-tilled silty loam soils, although characterized by

374 lower SOC content (ca. 10 g kg^{-1}) and higher BD ($> 1.45 \text{ g cm}^{-3}$) compared to the soils used in
375 our study. In contrast, Vogeler et al. (2009) found higher air permeability in conservation
376 tillage than in IT. The relative gas diffusivity (D_p/D_0) and the equivalent pore diameter (d)
377 were not affected by any of the long-term treatments (Table 4). D_p/D_0 was linearly related to
378 the air-filled porosity ϵ_a (Fig. 5a). The regression coefficients were 0.63 and 0.76 for the IT
379 and DD topsoils, respectively. Regressing k_a with ϵ_a revealed a larger scatter of the k_a
380 compared to D_p/D_0 (Fig. 5b). This was particularly the case for the IT topsoils, which
381 exhibited a non-linear relationship. The comparison of these two relationships is reflecting
382 the dependence of ϵ_a on pore sizes and continuity (Ball 1981b).

383 The average P-parameter values for the IT and DD topsoils were 9,587 and 4,538,
384 respectively. Both these values are high compared to loamy Danish soils with average P-
385 parameter values of 700 (Kawamoto et al. 2006). The extremely high P-parameter values for
386 the IT soil reflect that the IT soil was SOC-depleted as already seen in its high clay/OC ratio
387 (Table 1). It seems that crossing the previously suggested Dexter index threshold value of 10
388 (Dexter et al. 2008) resulted in a shift to a more pipe-like soil structure with an overall more
389 poorly connected pore-network, as revealed by the visual inspection of the CT-derived
390 images (Fig. 3), and also quantified in terms of MPD_{CCT} , CE_{CCT} and SMI_{CCT} (Table 2). In
391 addition, in a multiple regression analysis 66% of the total variability of the P-parameter was
392 explained by MPD_{CCT} ($\beta_1 = 0.8$), HWC ($\beta_2 = -1.9$) and SOC ($\beta_3 = 1.8$; $p < 0.0001$). Although the soils
393 had similar TP_{CCT} , the functional pore-network structure was quite different between the DD
394 and IT soil, supported by both gas transport measurements and derived structural
395 parameters and the CT-derived parameters.

396

397 *Relationships between soil quality and X-ray CT-derived structural parameters and functional*
 398 *structural parameters for soil gas exchange*

399 The laboratory measurements of the structural parameters D_p/D_0 and k_a , necessary for
 400 characterizing gas transport processes, were conducted at a matrix potential of -100 cm.
 401 According to the capillary rise equation pores with a diameter larger than 30 μm were
 402 drained at this tension. The X-ray CT scans of the intact soil cores were acquired at a matrix
 403 potential of -150 cm. The final CT image resolution was 33 μm meaning that only pores with
 404 a diameter larger than 33 μm were visible. The closeness of these two pore diameters
 405 associated with the measurements enabled us to relate their results, namely the soil pore
 406 architectural parameters derived from the X-ray CT images to the functional soil structural
 407 parameters D_p/D_0 and k_a . We used the CT scan parameters of the connected porosity, which
 408 were assumed to be more relevant than those derived from TP_{CT} . In addition, we
 409 investigated the relationships between soil quality and texture determined at bulk soil
 410 samples with D_p/D_0 , k_a , and the X-ray CT-derived structural parameters.
 411 TP_{CCT} and ϵ_a were strongly correlated ($r=0.75$) with TP_{CCT} ranging between 35 and 99% of ϵ_a
 412 with an average of 67% (Fig. 6a, Table 5) suggesting the relevance of pores between 20 μm
 413 and 33 μm for ϵ_a . Accordingly, regressing ϵ_a with TP_{CT} had a higher correlation coefficient
 414 ($r=0.83$). In our topsoil, gas diffusivity, D_p/D_0 , was mainly dependent on TP_{CCT} ($r=0.78$), bulk
 415 density ($r=-0.79$), and tortuosity, T_{CTT} ($r=-0.72$). Higher bulk density reduces ϵ_a , leading to a
 416 subsequent reduction in D_p/D_0 at the same soil water potential. Other less strong but equally
 417 significant correlations were found with the structural parameters MPD_{CTT} ($r=0.55$), FD_{CTT}
 418 ($r=0.51$) and SMI_{CTT} ($r=0.41$), highlighting pore shape and structure complexity as pivotal soil
 419 properties that affect gas transport parameters. The roughness and complexity of pores
 420 reduced gas interchange, whereas the more cylindrical and self-similar ones favoured gas

diffusion. Bulk density and soil texture were identified as governing factors for D_p/D_0 (Grable and Siemer 1968), but others have found no influence of these on D_p/D_0 (Eden et al. 2011). The functional equivalent pore diameter (d) was derived from the laboratory measurements as ratio between k_a and D_p/D_0 . The higher the value, the more continuous and interconnected is the pore network (Kawamoto et al. 2006; Katuwal et al. 2015). It ranged from 193 μm to 1076 μm and averaged 425 μm . It was significantly ($p < 0.0001$) and positively ($r = 0.74$) correlated with the mean pore diameter MPD_{CCT} determined by X-ray CT, which ranged from 425 μm to 1481 μm with an average of 841 μm (Fig. 6b). The pore classes enclosing pores from 700 to 3000 μm were equally correlated with d . It appears that MPD_{CCT} derived from CT-images could potentially be used as independently obtained parameter for predicting k_a in arable soils. Moreover, we found a positive and significant ($p < 0.001$) relationship between the tortuosity derived from the X-ray CT images T_{CCT} and the tortuosity calculated using the gas parameters determined at a matrix potential of -100 cm, D_p/D_0 and ϵ_a , with a Pearson correlation coefficient of 0.58 (Table 5). The CT-derived tortuosity ranged between 1.81 and 5.77 and was in all cases higher than the D_p/D_0 -based tortuosity, which ranged from 1.62 to 2.58 (Fig. 6c). In contrast, Katuwal et al. (2015) found consistently higher D_p/D_0 -based tortuosity than CT-derived tortuosity. In their study, however, the soils were repacked, and with the exception of one soil, had lower clay (157-197 g kg^{-1}) and SOC (0.9-2%) contents than the topsoil used in our study. A less well aggregated soil structure thus can be assumed. The D_p/D_0 -based tortuosity-connectivity parameter, X ranged between 1.45 and 2.08, which is in the range of values reported by others (e.g., Chamindu Deepagoda et al. 2012). The X_{CCT} maximum value was 2.34 and the minimum value was 1.69. But while the range was rather similar to X , the correlation between the two parameters was relatively weak ($r = 0.25$) (Table 5; Fig. 6d). The variation of the parameter is small but not negligible as

commonly assumed in D_p/D_0 power function models and recently discussed by Katuwal et al. (2015).

Conclusions

In this study we analysed the effect of long-term agricultural intensification defined as irrigation and IT on soil quality and structural parameters. Irrigation had no significant effect on any of the parameters measured. In contrast, IT increased the Dexter index of the topsoil which resulted in higher bulk density and lower TP. The Dexter index crossed the previously proposed critical threshold of 10 resulting in a more pipe-like soil structure with an overall more poorly connected pore network under IT compared to DD. This was also reflected by the CT-derived structural parameters MPD_{CCT} , CE_{CCT} and SMI_{CCT} and the functional pore-structural P-parameter. Differences in pore morphometrical parameters such as P-parameter, pore size distribution and pore shape were attributed to mechanical disturbance and SOC depletion through IT. Moreover, significant correlations between structural parameters derived with X-ray CT and air permeability and gas diffusivity measurements verified that X-ray CT parameters might be useful proxies for relevant functional parameters including equivalent pore diameter, connectivity and tortuosity required to predict gas diffusivity and air permeability. This is a first step to test this concept on soil collected as intact cores from a site under long-term arable production.

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472

473 **Conflict of interests**

474 The authors declare no conflict of interests.

475

For Review Only

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- 684

685 **Figure captions**

686 **Figure 1:** (a) Clay content (%), (b) soil organic carbon contents (%), (c) clay to carbon ratio
 687 (Dexter index), (d) bulk density (g cm^{-3}), (e) total porosity ($\text{cm}^3 \text{ cm}^{-3}$), and (f)
 688 connected total porosity detectable in the X-ray CT scans ($\text{cm}^3 \text{ cm}^{-3}$) of the
 689 topsoil (0-5 cm) under different management practices, irrigated and non-
 690 irrigated, intensive tillage (IT) and direct drill (DD).

691 **Figure 2:** Relationship between (a) total porosity and total carbon, (b) bulk density and
 692 total carbon, and (c) bulk density and clay content of the topsoil (0-5 cm) under
 693 different management practices, intensive tillage (IT) and direct drill (DD).

694 **Figure 3:** 2D sections and 3D porosity of selected topsoil cores under long-term tillage (IT,
 695 intensive tillage; DD, direct drill) and irrigation practices analysed in this study.

696 **Figure 4:** Pore size distribution of the connected pore volume (TP_{CCT}) for the topsoil (0-5
 697 cm) under (a) non-irrigated intensive tillage, (b) irrigated intensive tillage, (c)
 698 irrigated direct drill, (d) non-irrigated direct drill determined by X-ray CT. For
 699 each treatment eight intact cores were scanned.

700 **Figure 5:** Relationship between (a) gas diffusivity and air-filled porosity, and (b) air
 701 permeability and air-filled porosity.

702 **Figure 6:** Relationships between (a) total pore volume visible by CT and the air-filled
 703 porosity determined at -100 cm matrix potential, (b) tortuosity determined from
 704 X-ray CT images and a tortuosity parameter (τ) calculated based on
 705 measurements of D_p/D_0 , (c) X-ray CT-derived mean pore diameter MPD_{CTT} and
 706 the equivalent pore diameter d , and (d) the tortuosity-connectivity factor X
 707 derived by X-ray CT and based on gas measurements for topsoils under different

708 management practices (IRR, irrigated; DRY, non-irrigated; IT, intensive tillage;
709 DD, direct drill).

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Table 1: Long-term tillage and irrigation effects on soil properties of an arable soil under a crop rotation typical for Canterbury, New Zealand. The results presented are the predicted means followed by the 5% least significant difference (LSD) to compare means with different tillage and same irrigation treatments (LSD_{Till}), and means with different irrigation treatments (LSD_{Irr}). The textural parameters, total porosity and bulk density were determined at intact soil cores of 5 x 5 cm depth, and the remaining parameters at bulked soil samples collected beside the intact cores.

Treatment	Non-irrigated		Irrigated		$LSD_{0.05}$	
	DD*	IT [#]	DD	IT	LSD_{Till}	LSD_{Irr}
Clay ($kg\ kg^{-1}$)	0.247	0.278	0.251	0.281	0.025	0.058
Silt ($kg\ kg^{-1}$)	0.522	0.565	0.509	0.565	0.048	0.031
Sand ($kg\ kg^{-1}$)	0.231	0.158	0.241	0.154	0.053	0.047
Total carbon ($kg\ kg^{-1}$)	0.031	0.024	0.029	0.022	0.004	0.003
Dexter index (-)	8.02	11.46	8.54	12.65	1.98	3.20
Hot water carbon ($10^{-3}\ kg\ kg^{-1}$)	1.098	0.733	1.077	0.634	0.222	0.158
pH (-)	5.74	5.93	5.85	6.19	0.13	0.08
Bulk density ($g\ cm^{-3}$)	1.202	1.250	1.214	1.286	0.097	0.209
Total porosity ($cm^3\ cm^{-3}$)	0.54	0.53	0.54	0.51	0.036	0.077

*Direct drill; [#]Intensive tillage.

Table 2: Long-term tillage and irrigation effects on soil structural properties of the topsoil (0-5 cm) of an arable soil under a crop rotation typical for Canterbury, New Zealand. All properties were calculated for the CT-visible pores connected from the top to the bottom of a core. The results presented are the predicted means followed by the 5% least significant difference (LSD) to compare means with different tillage and same irrigation treatments (LSD_{Till}), and means with different irrigation treatments (LSD_{Irr}).

Treatment	Non-irrigated		Irrigated		$LSD_{0.05}$	
	DD*	IT [#]	DD	IT	LSD_{Till}	LSD_{Irr}
$TP_{CCT} (cm^3 cm^{-3})$	0.094	0.106	0.105	0.094	0.044	0.029
DA_{CCT}	0.21	0.20	0.25	0.17	0.28	0.19
$CE_{CCT} \times 10^{-10} (\mu m^{-3})$	-5.62	-3.50	-4.44	-4.48	7.950	5.130
FD_{CCT}	2.36	2.33	2.35	2.30	0.20	0.12
$OSVR_{CCT} (\mu m^{-1})$	0.008	0.007	0.007	0.007	0.003	0.002
$MPD_{CCT} (\mu m)$	681.46	910.43	858.17	913.18	105.99	83.10
SMI_{CCT}	1.63	2.43	1.68	2.18	2.17	1.40
T_{CCT}	3.33	3.21	3.16	3.19	2.40	1.63

*Direct drill; [#]Intensive tillage; TP_{CCT} , total porosity measured with X-ray CT; DA_{CCT} , degree of anisotropy; CE_{CCT} , connectivity; FD_{CCT} , fractal dimension; $OSVR_{CCT}$, Object surface to volume ratio; MPD_{CCT} , mean pore diameter; SMI_{CCT} , structure model index; T_{CCT} , tortuosity.

Table 3: Pore size distribution of the connected pores for the topsoil under long-term irrigation and tillage treatment analysed by X-ray CT. Presented are the predicted mean percentages followed by the 5% least significant difference (LSD) to compare means with different tillage and same irrigation treatments (LSD_{Till}), and means with different irrigation treatments (LSD_{Irr}).

Treatment	Non-irrigated		Irrigated		LSD	
	DD*	IT [#]	DD	IT	LSD_{Till}	LSD_{Irr}
30-300 μm	26.63	18.83	21.73	21.62	15.441	10.224
300-700 μm	37.28	32.09	33.98	29.43	3.566	2.075
700-1003 μm	15.29	17.00	15.39	16.52	8.480	5.247
1003-3000 μm	20.59	30.08	27.48	30.56	6.966	4.840
>3000 μm	0.21	2.00	1.43	2.60	4.437	2.585

*Direct drill; [#]Intensive tillage.

Table 4: Long-term tillage and irrigation effects on gas parameters of the topsoil (0-5 cm) of an arable soil under a crop rotation typical for Canterbury, New Zealand. Presented are the predicted mean percentages followed by the 5% least significant difference (LSD) to compare means with different tillage and same irrigation treatments (LSD_{Till}), and means with different irrigation treatments (LSD_{Irr}).

Treatment	Non-irrigated		Irrigated		LSD	
	DD*	IT [#]	DD	IT	LSD_{Till}	LSD_{Irr}
Air-filled porosity ($cm^3\ cm^{-3}$)	0.153	0.161	0.140	0.147	0.080	0.068
Air permeability* (μm^2)	114	225	115	222	4.80 ^{\$}	5.35 ^{\$}
Gas diffusivity	0.033	0.042	0.031	0.042	0.035	0.021
Equiv. pore diameter (μm)	357	482	368	495	401	366
P-parameter	3513	5666	3887	6011	3.69 ^{\$}	4.70 ^{\$}
τ -parameter	2.16	1.99	2.12	1.97	0.46	0.42
X-parameter	1.82	1.75	1.76	1.69	0.26	0.41

*removed 2 outliers with large k_a -values due to gap between soil and sleeve during measurements; ^{\$}least square ratio: smallest ratio for which the ratio between back-transformed means was significant.

Table 5: Pearson correlation coefficients (r) between the structural parameters derived with X-ray CT and the functional structural parameters for gas exchange processes based on gas measurements. Boldfaced figures indicate significant parameters at the 0.05 significance level.

	ϵ_a	D_p/D_0	k_a	τ	d	P	X
TP	0.80	0.55	0.27	0.10	0.34	0.28	0.65
TP _{CCT}	0.75	0.78	0.58	-0.33	0.63	0.59	0.3
OSVR _{CCT}	-0.03	-0.24	-0.41	0.33	-0.56	-0.49	0.23
SMI _{CCT}	0.02	0.41	0.55	-0.49	0.34	0.46	-0.39
MPD _{CCT}	0.23	0.55	0.70	-0.49	0.74	0.72	-0.23
FD _{CCT}	0.73	0.51	0.19	0.00	0.25	0.20	0.55
DA _{CCT}	0.27	-0.01	-0.18	0.28	-0.14	-0.16	0.43
CE _{CCT}	-0.46	-0.33	-0.06	-0.02	0.03	0.01	-0.35
T _{CCT}	-0.57	-0.72	-0.39	0.58	-0.45	-0.37	-0.02
X _{CCT}	-0.09	-0.33	-0.1	0.43	0.01	0.03	0.235
Class 1	0.50	0.36	0.04	-0.01	-0.02	-0.01	0.37
Class 2	0.60	0.36	0.04	0.00	0.18	0.11	0.49
Class 3	0.63	0.59	0.40	-0.27	0.59	0.48	0.29
Class 4	0.53	0.77	0.80	-0.48	0.82	0.80	0.00
Class 5	0.47	0.75	0.81	-0.44	0.71	0.75	-0.05

TP_{CCT}, total porosity measured with X-ray CT; DA_{CCT}, degree of anisotropy; CD_{CCT}, connectivity; FD_{CCT}, fractal dimension; OSVR_{CCT}, Object surface-to-volume ratio; MPD_{CCT}, mean pore diameter; SMI_{CCT}, structure model index; T_{CCT}, tortuosity; Class 1_{CCT}, TP of pores of 33-100 μm ; Class 2_{CCT}, TP of pores of 300-700 μm ; Class 3_{CCT}, TP of pores of 700-1003 μm ; Class 4_{CCT},

756 TP of pores of 1003-3000 μm ; Class 5_{CCT}, TP of pores >3000 μm ; ϵ_a , air-filled porosity; k_a , air
757 permeability; D_p/D_0 , gas diffusivity; τ , tortuosity; d , equivalent pore diameter; P , P-
758 parameter; X , X-parameter (refer to text for more information).

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