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1 Importance of short-term temporal variability in soil 2 physical properties for soil water modelling under different 3 tillage practices 4

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15

16 HIGHLIGHTS:

- 17
- 18 • No-till and ploughed soil properties vary over short time with different trends
- 19 • Impacts on soil water model simulations were explored using HYDRUS 1-D
- 20 • Both natural and tillage induced changes in soil lead to differences in simulations
- 21 • Accounting for soil variations over a season is important for soil water simulations
- 22

23 ABSTRACT

24

25 Soil properties are often assumed to be static over time in hydrological studies, especially in
26 hydrological modelling. Although it is well appreciated that soil structure and its impact on
27 hydraulic properties are time-variable, particularly on cultivated land, very few studies have
28 focused on quantifying the influence of such changes on soil hydrology, especially at the short
29 term (i.e. seasonal). This study explored the value of incorporating such short-term time-
30 variable soil properties in hydrological models. It is based on soil hydraulic properties from
31 temporal field data under no-till done by direct seeding and under conventional cultivation
32 done by ploughing to 0.2 m and harrowing. It uses a controlled tillage experiment in Scotland,
33 on a soil with very good structural stability that experiences gentle rainfall in a temperate

34 oceanic climate (Köppen Cfb). Water retention data were collected from intact soil cores
35 sampled at 0.025, 0.095 and 0.275 m depth at three times between April and August 2013; (i)
36 immediately following tillage, (ii) at barley crop establishment 1 month later and (iii) after
37 harvest. Soil structure varied over time, with no-till soils gaining porosity and ploughed soils
38 losing porosity. We hypothesised that no-till soils would have less seasonal temporal
39 variability, but found it to be comparable to ploughed soils, albeit with pore structure changes
40 following different trends. These changes were reflected in Van Genuchten fitting
41 parameters, which if accounted for in 1-D HYDRUS modelling, had a marked impact on
42 modelled soil water content over time if contrasted to predictions assuming a static pore
43 structure. Using data from multiple sampling events, as opposed to one sampling event,
44 resulted in up to a 44% difference in soil water content predictions and increased the
45 temporal variability by a factor of 1.5. Hence, our results have demonstrated that it is
46 important to account for short-term temporal variability in soil physical properties in soil
47 water modelling studies, and should not be ignored as a default, particularly on cultivated
48 agricultural soils.

49 **1. Introduction**

50 Soil physical properties describing pore space and water transport in hydrological models are
51 generally assumed to be static, with little change over short time periods, such as over a
52 growing season or following extreme weather events (Ahuja et al., 2006; Alaoui et al., 2011).
53 For some environments this assumption may be appropriate, such as climax ecosystems with
54 extremely stable soil structure. However, about 40% of the global land area is now under
55 agricultural production, where human induced interventions, such as tillage, create a vastly
56 different pore structure in soil, intended to increase productivity. The pore structure
57 produced by tillage, however, can be short-lived (days), particularly in structurally unstable
58 soils depleted of organic matter (Hallett et al., 2013; Kool et al., 2019). Slumping or mellowing
59 of tilth produced by tillage can cause marked impacts to its physical structure over time
60 periods as short as a single rainfall event (Leij et al., 2002). Compaction by machinery, traffic
61 can exacerbate structural degradation (Or et al., 2021).

62
63 Overall, short-term temporal variability in soil physical behaviour and its impact on hydrology
64 have received much less research than the more dramatic impacts of spatial variability in the

65 landscape (Kreiselmeier et al., 2019; Kool et al., 2019). Parameters, such as soil water content
66 (θ), vary in space and its spatial variability can be directly and solely related to the spatial scale
67 of interest. Famiglietti et al. (2008) showed that θ variations in space increased with spatial
68 scale. Previously, Western and Blöschl (1999) developed the idea that a scale triplet,
69 comprising the spacing, the support and the extent of the measurement and modelling scales
70 of θ could be used to quantify biases in the representation of θ . However, spatial variability
71 of θ can be exceeded by temporal variability at different locations in the landscape, as
72 characterised using geostatistics (Brocca et al., 2012). It has also been observed that θ
73 exhibits temporal stability regarding the areal and temporal statistical spatial distribution of
74 characteristics such as mean and extreme values (Vachaud et al., 1985).

75

76 There are many drivers in the temporal variability of θ , including evapotranspiration,
77 precipitation, interception and overland flow, but few hydrological modelling studies have
78 also considered the impact on θ of the change with time in soil hydraulic properties, especially
79 over relatively short temporal scales (e.g. between seasons). Recently, Zarlenga et al. (2018)
80 analytically linked θ spatial patterns with soil properties, showing that from small to
81 intermediate scales, spatial variations in θ can be attributed to spatial heterogeneity of soil
82 physical properties. Alletto et al. (2015) were able to obtain better agreement with field data
83 of θ when they allowed soil physical properties, such as saturated hydraulic conductivity, bulk
84 density and soil water retention curves, to vary during the growing season of maize. This is
85 the only study we know of that has included seasonal temporal changes in soil physical
86 properties in modelling soil water content, despite a large body of experimental evidence that
87 these interactions are important, in particular in the context of tillage (e.g. Ahuja et al., 2006).
88 While efforts have been made to account for such short-term changes in soil water retention
89 curves (e.g. Ahuja et al., 1998; Alaoui et al., 2011; Kool et al., 2019), these are rarely accounted
90 for in hydrological models. Regardless of the spatial and the temporal scales of interest, in
91 most cases soil physical properties are assumed constant with time.

92

93 The extent of change in the physical properties of agricultural soils during a growing season
94 is strongly affected by soil management (Kool et al., 2019). Tillage disrupts pore continuity
95 and decreases structural strength so that the ability to sustain weathering and mechanical
96 stresses diminishes (Peng and Horn, 2008). However, results can be contradictory, suggesting

97 that the impact of tillage depends on local conditions. For example, Alletto and Coquet (2009)
98 found that over a growing season, a loamy soil under conventional tillage in south-west
99 France increased in bulk density by a factor of 1.4 and decreased in saturated hydraulic
100 conductivity by a factor of 10. A similar study by Jabro et al. (2016) in a sandy loam field from
101 North Dakota, USA reported no changes in bulk density or hydraulic conductivity over the
102 growing season. In a Brazilian subtropical soil, Moreira et al. (2016) found a marked change
103 in bulk density and hydraulic conductivity over the growing season for a no-till soil, with a
104 strong impact of the severe wetting and drying cycles typical of this climate.

105

106 No-till and ploughed soils behave differently over short time-scales of weeks to months (Or
107 et al., 2021). Under ploughing, the human engineered seedbed at the start of the growing
108 season may physically degrade over time. The reverse may occur under no-till, where the
109 post-winter soil structure at the beginning of the growing season gradually improves over
110 time as biological and weathering processes naturally restructure the soil (Meurer et al.,
111 2020). The hydrological impacts could be vast, but very few studies have collected data
112 comparing short-term changes in soil physical and hydrological properties under contrasting
113 tillage systems.

114

115 This study aimed to explore the value of taking relatively short-term time-variable soil
116 properties into account in hydrological models. We considered one-off trigger (ploughing)
117 and intra-seasonal (no-tillage) variations in soil parameters on simulations of soil water
118 dynamics in the upper 0.3 m of the soil over a growing season. We explored field-driven soil
119 physical properties obtained from a field site under arable production in Scotland where
120 controlled tillage treatments had been in place for 11 years. We selected this site as a 'best
121 case scenario', because here, endogenic and exogenic factors affecting the soil hydraulic
122 properties are relatively mild. Compared to many regions, Scotland's climate (Koppen
123 classification, Cfb) rarely experiences extremes in precipitation or temperature, and
124 agricultural soils are rich in organic matter (2-5%) and physically stable under agricultural
125 production. Using the HYDRUS 1D approach that is typical for soil hydrological modelling
126 studies (Šimůnek and van Genuchten, 1999), we then assessed the differences in soil water
127 simulations between scenarios that consider dynamic (i.e. time-variable) versus static (i.e.
128 fixed) soil physical properties.

129 **2. Material and methods**

130 **2.1. Study site and data**

131 Soil samples were collected between April and August 2013 from the Mid-Pilmore field
132 experiment of the James Hutton Institute in east Scotland, United Kingdom (56°27'N, 3°W),
133 located at an altitude of 29 m above sea level (Newton et al., 2012). The total precipitation in
134 2013, recorded 500 m east of the field experiment at the James Hutton Institute
135 meteorological station, was 790 mm. This was less than 10% above the long-term annual
136 average between 1981 and 2010 (722 mm, MetOffice, 2018). Of this total, 235 mm fell
137 between 10 April and 10 August, with a maximum daily precipitation of 15 mm. The annual
138 average temperature in 2013 was around 9 °C, in line with the long-term average. Freezing
139 temperatures were infrequent, with air temperature dropping below 0 only 50 times across
140 the whole year, and only 3 times during the study period, as is typical for this region. The soil
141 at Mid-Pilmore is a chromic eutric Cambisol (WRB, 2015) with a gentle north to south slope
142 of 4%. There is a gradual change in the vertical soil texture composition from a sandy-loam
143 down to 0.6 m to a loamy sand below 0.6 m. The particle size distribution was 68% sand, 17%
144 clay, 15% silt down to 0.3 m; 75% sand, 12% clay and 13% silt between 0.3 and 0.7 m; and
145 86% sand, 4% clay and 6% silt at 1.1 m depth. The site has been planted with barley since
146 2002.

147

148 The field experiment consisted of a range of tillage treatments, each replicated three times in
149 a randomised block design (McKenzie et al. 2017), applied for 10 years prior to our study
150 period (i.e. set up in 2003). Each tillage plot was 33 m x 33 m and within each plot barley was
151 sown (360 seeds/m²) in sub-plots of 1.55 m wide x 6.0 m long. Our study explored no-till and
152 plough tillage treatments, selected to represent different pathways in soil structure dynamics;
153 plough represents a more abrupt shift over time, whereas no-till is closer to a natural
154 condition. Ploughed soils were inverted to 0.2 m and the surface soil was broken up further
155 by harrowing at the beginning of the growing season.

156

157 For each treatment and soil depth, 9 soil cores (55 mm diameter x 40 mm height) were
158 sampled (3 replicates per plot, 3 plots of each treatment) on three different occasions in 2013:
159 (1) at sowing on 10 April, which occurred 10 days after ploughing, (2) around establishment

160 of the crop on 8 May, and (3) after the harvest on 10 August. Samples collected on different
161 dates were taken as close to earlier samples as was practical, while ensuring that they were
162 unaffected by the previous sampling. Samples were taken at three depths, including $Z_{sample1}$:
163 at or near the surface, where seeds were sown (0 – 0.05m), $Z_{sample2}$: within the cultivated or
164 main rooting depth (approx. 0.07 – 0.12m), and $Z_{sample3}$: around 0.25 – 0.30m depth (just
165 below the normal depth of ploughing). We considered that the sample depths were taken at
166 the representative nominal depths of $Z_{sample1} = 0.025$ m, $Z_{sample2} = 0.095$ m, and $Z_{sample3} =$
167 0.275 m. The two deeper depths were only sampled on 10 April and 10 August, with the 8
168 May surface sample intended to capture very temporarily dynamic settling and slumping
169 post-tillage.

170 **2.2. Spatially and temporally variable hydraulic properties**

171 Core samples were processed in the laboratory to determine bulk density (ρ) and soil water
172 content (θ). Porosity (Φ) was determined from bulk density, assuming 2.65 g/cm³ for particle
173 density. Water retention characteristics were measured by placing cores on ceramic suction
174 plates (0.01 to -50 kPa) and pressure plates (-300 and 1500 kPa) to obtain water contents at
175 -0.01, -1, -5, -20, -50, -300 and -1500 kPa. It was beyond the scope of the original study
176 reported in McKenzie et al. (2017) to measure further hydrological properties, such as
177 hydraulic conductivity, but the short-term sampling at multiple depths for a range of tillage
178 systems provided a unique dataset. Only data from one year were used because the aim was
179 to explore the impact of short-term changes on hydrological modelling, rather than explain
180 long-term tillage impacts on soil physical behaviour.

181
182 Water retention functions were fitted to the data for each sample. The most commonly used
183 van Genuchten (1980) expression has been shown to provide good fit with data across many
184 types of soils, and especially when the saturated soil water content (θ_s) value is relatively
185 high (e.g. Kébré et al., 2013); this is typical for the soil conditions at the experimental site in
186 Scotland. Therefore, we fitted the soil retention data with the van Genuchten retention
187 function (Eq. 1), using the Mualem approximation ($m = 1 - 1/n$) (Mualem, 1976):

188

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha\varphi|^n]^m} \quad (\text{Eq. 1})$$

189

190 where θ_r is the residual water content, θ_s is the saturated soil water content, both expressed
 191 in volumetric terms (m^3/m^3), φ is the matric potential (P) and n (no units), m (no units) and α
 192 ($1/\text{m}$) are pore-size related parameters.

193

194 The saturated hydraulic conductivity K_s (mm/hr) was then computed from texture using the
 195 model developed by Brakensiek et al. (1984) (Eq. 2):

196

$$\begin{aligned} K_s = 10 \exp (19.52348\Phi - 8.96847 - 0.028212c + 0.00018107s^2 \\ - 0.0094124c^2 - 8.395215\Phi^2 + 0.077718s\Phi - 0.00298s^2\Phi^2 \\ - 0.019492c^2\Phi^2 + 0.0000173s^2c + 0.02733c^2\Phi \\ + 0.001434s^2\Phi - 0.0000035c^2s) \end{aligned} \quad (\text{Eq. 2})$$

197

198 where s (g/100 g of soil) is the sand content (50 and 2000 μm), and c (g/100 g of soil) is the
 199 clay content ($<2\mu\text{m}$). Tietje and Hennings (1996) demonstrated that the Brakensiek model
 200 performs best in coarse textures, so is suited to the sandy loam of the Mid-Pilmore site. The
 201 relationship between saturated hydraulic conductivity and soil texture forms the basis of
 202 several other models (e.g. Saxton et al., 1986). K_s calculated from the Brakensiek model (Eq.
 203 2) were similar to those calculated using the Rawls model (Rawls et al., 1998; Saxton and
 204 Rawls, 2006) based on pore-size distribution parameters.

205 For each replicate (9) and for each tillage treatment (2), the fitted van Genuchten soil
 206 hydraulic properties and K_s were then interpolated linearly over depth from the original
 207 sampling depths down to the deepest depth sampled $z_{sample3}$. To allow for insights into the
 208 spatial variability, we did not group replicates to obtain a mean fit of the Van Genuchten curve
 209 for each treatment and time. We defined a depth z_{nc} (m) from which the soil properties were
 210 assumed to remain constant in depth, in space, and in time and therefore were assumed to
 211 be the same for all replicates and both tillage treatments. This was set to $z_{nc} = 0.6$ m, based
 212 on a previous (unpublished) study performed nearby the experimental plots at Mid-Pilmore.
 213 In that other study, soil physical properties below 0.6 m, such as bulk density, pore-size
 214 distribution, and saturated hydraulic conductivity, were found to be only marginally affected

215 by a strong external disturbance (tractor passes). At 0.6 m there is also a relatively sharp
 216 change in texture from sandy loam to a loamy sand. At z_{nc} and down to the bottom depth of
 217 the domain, z_{gw} (m), corresponding to the average depth of the groundwater, the soil
 218 property values were derived from theoretical values for loamy sand from the literature.
 219 These were approximated using equations 4 and 5 populated with theoretical values from
 220 Carsel and Parrish (1988). We defined a correcting factor, a (no units), which described how
 221 the soil property values ($v_{d,z_{sample3}}$) in the deepest samples in the field ($z_{sample3}$) departed
 222 from the theoretical value ($v_{t,z_{sample3}}$) given by the literature for the corresponding soil
 223 texture. The parameter (a) was derived from the spatial average of the replicates in the
 224 undisturbed no-till treatment plot, as the soil is undisturbed in the no-till plots:

$$225 \quad a = \frac{v_{d,z_{sample3}}}{v_{t,z_{sample3}}} \quad (\text{Eq. 4})$$

226
 227 We then multiplied the theoretical value ($v_{t,z_{nc}}$) corresponding to the deeper depths (below
 228 z_{nc}) to obtain the soil parameter value ($v_{s,z_{nc}}$) used in the simulations below z_{nc} , for each
 229 replicate of both tillage treatments:

$$230 \quad v_{s,z_{nc}} = a v_{t,z_{nc}} \quad (\text{Eq. 5})$$

231
 232 $v_{t,z_{sample3}}$, $v_{d,z_{sample3}}$, $v_{s,z_{nc}}$ and $v_{t,z_{nc}}$ have the units of the parameter they represent: θ_r and
 233 θ_s are expressed in volumetric terms (m^3/m^3), n (no units), α (1/m), and K_s (mm/hr).

234
 235 For each of the replicates and tillage treatments, the three vertical profiles obtained for each
 236 soil property were then linearly interpolated in time over the study period. This assumption
 237 of linearity is supported by previous work from elsewhere. For example, Onstad et al. (1984)
 238 found that the bulk density change followed a linear evolution after tillage and was a function
 239 of the cumulative precipitation. Similarly, Bodner et al (2013) observed a linear decreasing
 240 trend in median pore radius since tillage. Therefore, given the relatively evenly distributed
 241 precipitation in time, it is reasonable to assume changes to soil parameters were linear in
 242 time.

2.3. Soil water content modelling approach and set-up

Our main rationale was to use a modelling framework that represents those typically used in hydrological studies involving soil water modelling, here demonstrated in the context of the tillage of agricultural soils. The HYDRUS 1D software (Šimůnek and van Genuchten, 1999) was chosen for its explicit account of soil hydraulic properties (including the van Genuchten parameters), and the possibility to model soil water content in an unsaturated soil and at a fine vertical resolution (< 1 mm) down the soil profile in a physically meaningful way by solving Richards' equation. A given hydrological model is usually applicable within specified times, depending on the physical processes included and how they are represented (Blöschl and Sivapalan, 1995). In this study, we focus on relatively short-term time scales between one day and the growing season (123 days). These time scales allow the evaluation of the impacts of precipitation events (Laio et al., 2001) up to the intra-annual variations in the hydrological cycle, possibly also allowing the assumption of steady-state (on which simple models rely) to be tested (Destouni and Verrot, 2014). Furthermore, HYDRUS 1-D allowed for focus on the plot-scale, which is the spatial scale relevant for the representation of unsaturated flows (Blöschl and Sivapalan, 1995).

Forward modelling (modelling with zero degrees of freedom) using field-informed values of soil hydraulic parameters predicted changes in soil water content. This has been described to provide "error-free data" if the problem is not overparameterized (Romanowicz et al., 1996). Using the soil properties and the daily climatic conditions from the field, ϑ time-series for each of the nine replicates (3 plots, with 3 replicates per plot) for each of the two tillage treatments were obtained by solving Richards' equation at a daily time step in HYDRUS. The study covered the full length of the 2013 growing season in Mid-Pilmore, between April 10 and August 10 (123 days). The replicates are grouped in this analysis based on the tillage treatment they received (plough or no-till), so that the plot they originated from is not relevant. The initial soil water conditions were set to field data values, obtained from the sampling on April 10, and ran with a 1 day spin up. The spin up of 1 day was found to consistently lead to the same results as multi-day spin ups.

We then specifically assessed the difference between soil water content simulations using

274 dynamic (i.e. time-variable) or static (i.e. fixed in time) soil parameters, referred to as the D
275 and S scenarios, respectively (Table 2). For S, the parameters were either set to the measured
276 values on the first day of the simulation (i.e. 10 April, S_{early}) or the last day (i.e. 10 August S_{late}).

277

278 With only the soil physical properties varying, the general HYDRUS soil profile modelling setup
279 was the same for all the D and S scenarios. Although we focussed on the top 0.3 m of the soil
280 profile in this study, the domain had a 1.6 m depth to ensure boundary conditions at the lower
281 end of the soil profile would have minimal impact. The boundary conditions were set to the
282 soil-atmosphere interface at the top and free drainage at the bottom of the domain, as the
283 soil is freely draining. Feddes model root water uptake parameters were not available for
284 barley at Mid-Pilmore so winter wheat parameters were used (Suku et al. 2013). In HYDRUS,
285 the root water uptake parameters cannot be changed in time, so we indirectly accounted for
286 the crop growth through the soil cover fraction (SCF , no units) parameter (Eq. 6), by providing
287 the model with a daily time series of the leaf area index (LAI , no units) of spring barley, as
288 monitored in East Anglia, UK, (Baruth et al., 2013), and scaled from 133 days to our 123 days
289 period of study.

290

$$SCF = 1 - \exp(-0.463LAI) \quad (\text{Eq. 6})$$

291

292 Furthermore, HYDRUS requires the evapotranspiration separately as potential evaporation
293 and transpiration. To obtain these two variables, using data from the local meteorological
294 station, we first calculated the daily potential evapotranspiration ET_0 with the Penman-
295 Monteith relationship (Allen et al., 1998) for a daily time step. ET_0 was then partitioned into
296 potential evaporation E_0 and potential transpiration T_0 fluxes using the method suggested by
297 Šimůnek et al. (2008), following:

298

$$E_0 = ET_0(1 - SCF) \quad (\text{Eq. 7a})$$

$$T_0 = ET_0 SCF \quad (\text{Eq. 7b})$$

299

300 The calculated potential transpiration and evaporation fluxes were then used to derive the
301 actual fluxes in HYDRUS based on the reduction for transpiration with the Feddes water stress
302 model (Feddes et al., 1978) and hCritA limit for soil evaporation (Šimůnek et al., 2008) which

303 is the minimum pressure head that the soil surface can reach depending on the air relative
304 humidity and temperature.

305

306 **2.4 Statistical Analyses**

307

308 Data were analysed for tillage, depth and sampling time effects using a 3-way Analysis of
309 Variance (ANOVA) for testing the (interlinked) effects of these three factors on the mean. We
310 consistently applied this approach to the field data, Van Genuchten fitting parameters and
311 soil water content model simulations. Van Genuchten fitting parameters are interdependent
312 and may converge on multiple fits for the same dataset (Vrugt et al., 2003), so we limited
313 statistical analysis to θ_s , θ_r and $\theta_s - \theta_r$. For consistency, we performed the statistical analyses
314 on the simulated soil water content data of the same days and depths for which field data
315 were determined, to have comparable results and to avoid effects of autocorrelation in the
316 timeseries.

317 **3. Results**

318 **3.1. Variations in soil properties**

319 Bulk density (ρ) decreased over time for all depths and both tillage treatments, except at
320 $Z_{sample1}$ of the ploughed fields, where it significantly increased from April to August (Table 1).
321 Overall, the van Genuchten soil-water retention functions (Eq. 1) provided a good fit to the
322 measurements from the soil samples (Figure 1). In correspondence with the soil property field
323 data (Table 1), depth and time had a significant impact on θ_s , θ_r and $\theta_s - \theta_r$ ($p < 0.01$) and tillage
324 had a significant impact on θ_r , ($p = 0.0126$) and $\theta_s - \theta_r$ ($p = 0.0155$). There was a strong
325 interaction between tillage and depth for θ_s and θ_r , and between tillage and time for θ_s
326 ($p < 0.05$).

327

328 For $Z_{sample1}$ (at 0.025 m), we generally found most marked temporal differences in the fitted
329 hydraulic parameters between April and May (Figures 2,3). For this period, θ_r , θ_s and n
330 displayed increases in both treatments, while α decreased. $\theta_s - \theta_r$ increased for no-till and
331 decreased for the plough plots, which is reflecting the proportionally greater increase in θ_s
332 for the no-till plots. Subsequent differences in the parameters at $Z_{sample1}$ between May and

333 August were mostly smaller than between April and May (Figure 2). For the two deeper soil
334 samples (i.e. $Z_{sample2}$ and $Z_{sample3}$ at 0.095 and 0.275 m, respectively), trends were similar but
335 generally smaller than shallower depths.

336

337 Overall, the temporal variations in the fitted hydraulic parameters were greater or of the
338 same order of magnitude as differences between the tillage treatments. The differences
339 between no-till and ploughing were most marked in the shallowest soil ($Z_{sample1}$) and
340 decreased with depth as well as with time (Figure 2). Exceptions to this are n at $Z_{sample2}$ and
341 $\theta_s - \theta_r$ at $Z_{sample1}$.

342

343 The error bars in Figure 2 (and dashed lines in Figure 3) allow for an evaluation of the variation
344 in spatial variability between the nine replicates with time. The spatial variability of θ_r steadily
345 decreased at all depths over time in the ploughed plots, while it was the largest at $Z_{sample1}$ in
346 May. For θ_s , the magnitude of the spatial and temporal variabilities between April and August
347 were similar in absolute values for all depths and both tillage treatments. For α , both the
348 spatial and the temporal variabilities were relatively high. n displayed an increase in spatial
349 variability over time for all depths and both tillage treatments, except at $Z_{sample2}$ in the
350 ploughed fields; here, the spatial variability was of the same order of magnitude as the
351 temporal variability.

352 **3.2. Simulations of soil water content using static and dynamic soil properties**

353 The pattern of precipitation (Figure 4a) shows a generally even distribution during the
354 simulation period, with most of the rainy days receiving less than 10 mm. There was one main
355 event of 55mm that fell on 2nd and 3rd May (17 and 34mm respectively) and another main wet
356 period at the end of July (66mm between July 22nd and 31st). The potential evapotranspiration
357 ranged from 2 to 9 mm/day, with a slight constant increase throughout the simulation period
358 to seasonal and increased LAI driving greater potential root water uptake.

359

360 Modelled soil water contents varied with depth and time, with strong interactions, for both
361 dynamic and static simulations ($p < 0.001$). The general trends in simulated ϑ were similar for
362 all of the D and S scenarios (Figures 4b-c and 5b). Figure 4b (ploughing) and 4c (no-till) show
363 that in the top 0.3m of the soil profile, there was drying with depth, with mostly small

364 responses to precipitation. In response to the main precipitation events on 2nd and 3rd May,
365 the soil profile experienced significant wetting, followed again by drying of the soil, albeit with
366 smaller responses to subsequent precipitation. The overall drying trends across the
367 simulation period agreed with field measurements of soil water content, which were
368 observed for both of the ploughed and no-tillage D scenarios (Table 1). Although the soil
369 profile, especially towards the lower part, did get relatively dry for all simulations (minimum
370 simulated value was $0.11 \text{ m}^3 \text{ m}^{-3}$; Figure 4), the simulations never reached values below the
371 residual water content. Uncertainties around the replicate averaged simulations of Figure 5b
372 are expressed as the replicate coefficient of variation in Figure 5c. These are around 0.1 for
373 all scenarios and highest during dry conditions.

374

375 Simulated soil water content of ploughed soils was generally drier than no-till soils (Table 2,
376 Figures 4,5). Tillage only affected the model soil water content for the static 'late' simulations
377 ($p=0.0482$); for the dynamic simulation ($p=0.0682$) and static 'early' simulation ($p=0.0884$) it
378 did not have a statistically significant impact, but neither did it for the field data (Table 1). The
379 coefficient of variation in the simulations was the same for ploughed and no-till soils in the D
380 scenarios (Table 2). However, for the static scenarios, ploughing increased the coefficient of
381 variation in the static scenarios S by $\sim 10\%$ (Table 2).

382

383 Not considering the gradual changes in soil parameters overestimated and resulted in smaller
384 temporal variations of ϑ in the top 0.3m of the ploughed and no-till fields (Table 2; Figures
385 4,5). In general, during relatively wet conditions, D scenarios lead to wetter conditions than
386 the corresponding S scenarios across the soil profile, and during dry conditions D scenarios
387 were drier (Figure 5b). In other words, using static instead of dynamic parameters resulted in
388 underestimating soil moisture during wet conditions, whereas it was overestimated during
389 dry conditions. When averaged across the 0.3m soil profile, the differences between D and S
390 scenarios were most marked (16%) during the relatively drier period between June and July
391 (Figure 5b). For approximately one month after the major precipitation event in early May,
392 D_{notill} was wetter than $S_{\text{notill,late}}$ (Figure 4g).

393

394 Between different depths and time, over-estimations were up to 44% and under-estimations
395 were up to 29% in the ploughed fields (Figures 4d-g). Differences between D and S scenarios

396 were most pronounced at the two more intensive precipitation events and near the surface.
397 For example, while generating slightly wetter antecedent conditions, the static soil hydraulic
398 properties resulted in an initial underestimation of ϑ in response to the main precipitation
399 event (May 2nd-3rd). The maximum value of ϑ in the upper soil was smaller than $0.35 \text{ m}^3/\text{m}^3$
400 for all the S scenarios, while it was $0.43 \text{ m}^3 \text{ m}^{-3}$ and $0.42 \text{ m}^3\text{m}^{-3}$ for D_{plough} and D_{notill} ,
401 respectively. Deeper in the soil profile, by contrast, the wetting was generally overestimated
402 at this time. For the smaller events, the S_{early} scenarios overestimated the soil water content
403 throughout the soil profile, while the S_{late} scenarios underestimated ϑ at the shallowest
404 depths and overestimated at deeper depths.

405

406 By comparing the S_{late} with their respective S_{early} simulations, we also characterised the impact
407 of sampling date on seasonal simulations of soil water. Overall, the differences between the
408 D and S simulations were larger for S_{early} than S_{late} (Table 2, Figures 4,5). Up to 46% differences
409 were observed when comparing S_{late} with S_{early} simulations. In addition, the difference
410 between the dynamic scenarios D and their corresponding static soil property simulations
411 increased for the S_{early} scenarios and decreased for the S_{late} scenarios (Figure 5b).

412 **4. Discussion**

413 **4.1. Temporal variations of soil hydraulic properties**

414 Most soil properties varied with depth and in time (Figure 2; Table 1). Results from this study
415 also suggest that temporal variability in soil hydraulic properties was generally greater under
416 ploughing than no-till (Figure 2). Soil tillage impacts on temporal soil hydraulic properties are
417 consistent with previous studies; for example, α was larger in the ploughed fields than in the
418 no-till fields, especially during the first sampling soon after ploughing. For the ploughed fields,
419 α then decreased by almost half, converging with topsoil values for no-till fields by the end of
420 the growing season. In previous studies, α has been related to the inverse of the air entry
421 pressure used in the Brooks and Corey (1964) soil water retention model (e.g. Assouline and
422 Or, 2013). Therefore, a greater value of α in the surface soil of ploughed fields at the beginning
423 of the growing season could reflect a smaller air entry pressure and thus, a greater mean
424 pore-size in the fragmented seedbed. Bodner et al (2013) observed a factor of 10 increase of
425 the median pore radius after tillage that persisted for two months.

426

427 While n average values increased in time for all depths and both tillage treatments, absolute
428 average values were greater in the ploughed fields in the topsoil, but similar for the two lower
429 depths (Figure 2). Variations in n can be interpreted in terms of pore size distribution. n is
430 positively related to the Brooks and Corey (1964) pore-size distribution index λ (Morel-
431 Seytoux et al., 1996). This is also reflected in the inverse relationship between λ and the
432 coefficient of variation of the pore-size distribution (Assouline, 2005) and pore connectivity
433 (Assouline et al., 2016). Therefore, a high value of n denotes a narrow pore size distribution
434 and a skew of the fraction of pores network and connectivity towards a small range of pore-
435 sizes. As such, in this study, ploughing resulted in more larger pores (i.e. greater values of α
436 and θ_s) and disconnect between pores (i.e. high value of n). This was also reported by Schwen
437 et al. (2011), who found a reduction in pore connectivity due to tillage from an indirect
438 method of regression between the saturated hydraulic conductivity and the macro-porosity.
439 Over the growing season the differences in the soil hydraulic properties between the
440 ploughed fields and the no-till fields decreased, but α , θ_r and n still differed in the topsoil at
441 harvest (Figure 2). For α and n , the no-till treatments varied less over the growing season
442 than for ploughing.

443

444 The initially fragmented ploughed soil with increased macroporosity has greater capacity to
445 transmit water through the soil profile (Hill et al., 1985), that diminishes over time due to
446 slumping, as reflected in the simulations of ϑ (Figure 4). Some of the temporal changes in soil
447 hydraulic properties found in the ploughed fields are also observed in the no-till soils, but with
448 a smaller amplitude. Gradual short-term changes have observed in a number of studies. For
449 example, soil wetting and drying cycles have been shown through experiments (Bodner et al.,
450 2013; Wang et al., 2015) and modelling (Leij et al., 2002) to influence short-term (sub-
451 seasonal) soil hydraulic properties. Earthworm activity (Capowiez et al., 2012) and root
452 growth (Whalley et al., 2004) are biological processes that modify soil hydraulic properties,
453 especially pore size and structure (Meurer et al., 2020). Larger, more connected pores
454 induced by biology or weathering cause faster flow, counter-acting slumping in ploughed and
455 improving structure in no-till fields over time (Or et al., 2021).

456

4.2. Effects of temporal changes in soil hydraulic properties on simulations of soil water

While temporal changes in soil properties have been investigated in a few studies (e.g. Kreiselmeier et al., 2019; Peng and Horn, 2008; Capowicz et al., 2012), to our knowledge, there is no previous study that linked these directly to effects on simulations of ϑ dynamics. Here, we investigated such impacts related to temporal variations of soil properties due to a large initial change in pore structure through ploughing, and those naturally occurring in an undisturbed soil under no-till.

Not considering temporal variability in soil hydraulic properties could significantly increase the uncertainty of hydrological soil water modelling results. The results showed that abrupt structural changes due to ploughing and gradual, more natural changes under no-till, could greatly affect the daily to intra-seasonal variations of ϑ (Figures 4, 5). Our data were collected for a structurally stable soil in a temperate climate, so the impacts in more dramatic climates or unstable soils would be expected to be much greater. However, in extreme climates or for shrinking soils, the impact of soil volume change would need to be considered as part of the modelling. This is because soil volume changes over time will affect water redistribution. In our study, the changes over time are gradual and the soil pore space is less than half-filled with water, so we have assumed such impacts are negligible.

The daily soil vertical profiles of ϑ were slightly more heterogeneous over time and in depth when the soil hydraulic properties varied with time (Table 2, Figures 4, 5). In this study case, using only static soil properties from one sampling campaign overestimated the average soil moisture, but the direction of change was variable with time and depth. With respect to the overall depth- and time-average of ϑ , the results showed that the effects of temporal variations in soil properties were relatively small during wetter conditions, but relatively large during the drier periods (Figure 5b). This was the same for both the variations due to one-off ploughing (comparison of D_{plough} with S_{plough}) and due to natural processes in the no-till fields (comparison of D_{notill} with S_{notill}).

As hypothesized in Section 4.1, the short-term changes in time of the pore-size distribution and connectivity, particularly in the ploughed fields and in the upper soil, could lead to

488 changes in flow dynamics in the soil column, thus modifying the wetting and drying properties
489 of the soil (Bodner et al., 2013). We followed the assumption that there is no hysteresis in the
490 van Genuchten function (e.g Braddock et al., 2001), but in future work this should be explored
491 further as hysteresis may increase with organic matter (Zhuang et al., 2008) and vary with
492 tillage (Ball and Robertson, 1994). In the no-till soils, θ_s varied more in time at the beginning
493 of the study period than in the ploughed fields (Figure 2), which could also explain the
494 temporal variability of ϑ . Between treatments, ploughing, as a “one-off” trigger for changes
495 in soil hydraulic properties over short timeframes, as opposed to changes in undisturbed soils,
496 here appeared to decrease the average ϑ and increase the temporal variability (Table 2).
497 Regardless, the focus of our work was to evaluate the importance of accounting for temporal
498 variability in soil physical properties in simulation of soil water dynamics for a ploughed and
499 for a no-till system; not to evaluate the simulation differences between tillage systems. While
500 the field data allowed for a quantitative assessment of tillage effects at specific moments in
501 time, to evaluate this in terms of continuous soil water simulations would require higher
502 temporal resolution data and testing of our linear interpolation assumption.

503

504 Furthermore, our results suggested that the time of sampling for the determination of soil
505 hydraulic properties may play a crucial role in the results of hydrological modelling and should
506 be considered when designing soil sampling strategies. In our results, time of sampling
507 influenced both the magnitude and the direction of the observed changes in ϑ at a sub-
508 seasonal scale. The differences between the time-varying dynamic (D) and static (S)
509 simulations were generally greater when the hydraulic properties from the early sampling
510 campaign were used in the S scenarios as opposed to the late samples (Table 2, Figure 4). The
511 importance of sampling time was also a major finding from Zarlenga et al. (2018), who found
512 through an analytical approach that the sampling scheme and the hydraulic properties played
513 a major role in the physical averaging (in their study, spatial averaging) of ϑ values.

514

515 It was beyond the scope of this study to fully quantify the potential uncertainties arising from
516 not considering temporal variations in soil hydraulic properties in hydrological modelling of
517 soil water. Instead, we set out to characterise the effect of temporal variations from a set of
518 realistic, field-driven soil physical properties on soil water simulations using an approach that
519 is typical for hydrological modelling studies. Considering spatial variability in soil hydraulic

520 properties, and how these propagate to simulations of ϑ and other hydrological variables is a
521 more routine practice than considering temporal variability. Differences in spatial variability
522 and organization of soil properties and soil water content at the hillslope-scale has, for
523 example, recently been associated with a significant variation in landslide characteristics (Fan
524 et al., 2016). Alletto and Coquet (2009) provided another example of characterising spatial
525 variability in agricultural fields, reporting that the hydraulic conductivity of the topsoil was
526 mostly correlated with the position of the sample in the plot relative to the crop rows. Our
527 results suggest that characterising (short-term) temporal variability in soil properties and
528 using these for hydrological modelling of soil water could be equally important.

529 **4.3. Study limitations**

530 Our study has demonstrated that accounting for seasonal temporal variability in soil physical
531 properties, at least on agricultural land, is important to consider for soil water modelling
532 studies. Predicting water content with a dynamic simulation produced a greater coefficient of
533 variation (Figure 4c) and differences up to 44% compared to a static simulation. This could
534 have major implications, but there are sources of uncertainty that include extrapolating
535 laboratory measurements to the field, missing data such as in-field water content and the
536 amount of data available, both in space and time as described above. We used one of the few
537 field data-sets available exploring short-term temporal soil water retention characteristics in
538 contrasting tillage regimes over multiple depths to simulate soil water dynamics over time.
539 Measurements of field soil water content and hydraulic conductivity were outside the scope
540 of the original study that collected the data, but this would be easy to address in follow-on
541 research to give greater confidence of the absolute values of our results and their
542 extrapolation to other field conditions. Here, we used the Brakensiek et al. (1984) model to
543 compute the saturated hydraulic conductivity K_s (mm/hr) in the absence of field observations.
544 Direct measurements of K_s would remove uncertainty and may better predict the combined
545 impacts of pore structure dynamics on water retention and flow.

546

547 Going forward, the pore size distribution might be modelled more effectively with a bimodal
548 distribution to capture seasonal declines in macroporosity through slumping in the ploughed
549 soil and seasonal increases in macroporosity by biological activity in the no-till soil
550 (Kreiselmeier et al., 2019). We attempted to fit bimodal models to our water retention data

551 with limited success, likely due to only 7 steps of water potential affecting convergence.
552 While a bimodal distribution could have resulted in different absolute results, especially in
553 the extreme dry and wet ends (Haghverdi et al., 2020), there is no indication that the relative
554 differences between the scenarios and treatments would have been vastly different. It would
555 also have been more difficult to rely on the soil water retention curves and there would have
556 been more degrees of freedom and interdependencies between parameters, which in itself
557 would have increased model uncertainty.

558 **5. Conclusion**

559 Our results showed that short-term temporal variability in soil physical conditions can have a
560 marked impact on predictions of soil hydrology. This was evident for both ploughed and no-
561 till soils. Modelled water content between predictions based on one sampling event versus
562 several sampling events in the same growing season varied by up to 44%, or up to 16% when
563 averaged across the soil profile. In general, θ was drier and displayed a greater temporal
564 variability when changes in soil properties were accounted for, especially in the topsoil. This
565 difference in variability suggested that extreme values could be underestimated (i.e.
566 simulations would be more dampened) when temporal dynamics of soil properties are
567 neglected in a hydrological model. It may also lead to an inaccurate representation of rapid
568 processes, especially at the surface, such as ponding and runoff generation. Nevertheless, we
569 did find that dry periods lead to larger discrepancies than wetter conditions, but further
570 research would be required to extrapolate those results to study sites with dryer conditions
571 overall. An additional outcome of this study was that the timing of sampling also had a large
572 impact on the modelled soil water content. Predictions of water content based on a one-time
573 sampling shortly after soil cultivation were on average 7% different from predictions based
574 on a later sampling shortly after crop harvest.

575

576 In a typical hydrological modelling setup, soil properties are assumed to be stationary, while
577 it is often considered that they are highly variable in space. The results of this study suggested
578 that neglecting temporal changes in soil properties could have equally important implications
579 for simulations of soil water. Short-term time-variable soil properties should therefore not be
580 ignored as a default in hydrological modelling. This has been verified here using soils where
581 the endogenic and exogenic factors affecting the soil hydraulic properties were relatively

582 mild: the soil was structurally stable and was not inherently subject to swelling or cracking;
583 the ploughing was also a typical practice for agricultural soils; and the hydroclimate displayed
584 very mild intensity at all time scales. Even under these conditions, the results of this study
585 suggested that accounting for temporal variability in soil hydraulic properties could be
586 important for simulations of soil water content dynamics. The hydroclimate at the surface
587 could strongly affect the extent of impacts. In our study, two intense rainy days had a
588 relatively large effect on the spatial variability and on the differences between the scenarios.
589 A study setup in a more extreme climate (e.g. with marked seasonality) could provide further
590 insight.

591

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598

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740

741 **Table 1** Field data values of the porosity Φ , the bulk density ρ and the soil water content θ ,
742 for the 3 samples (respectively on April 10, May 08 and August 10 2013), 3 depths ($z_{sample1}$:
743 0.025m, $z_{sample2}$: 0.0925m and $z_{sample3}$: 0.275m) and for both tillage treatments (plough and
744 no -tillage). For each table cell, the main number is the average among the 9 replicates, and
745 the numbers in brackets are the minimum and maximum values. p-values for the 3-way
746 ANOVA test results are provided in the lower part of the table, for each factor (tillage
747 treatment, soil depth and time) and interaction between factors.
748

	Depth [m]	Φ [m ³ /m ³]			ρ [g/cm ³]			Θ [m ³ /m ³]		
		April	May	August	April	May	August	April	May	August
Plough	0.025	0.55 [0.47;0.60]	0.56 [0.53;0.58]	0.51 [0.46;0.55]	1.19 [1.06;1.40]	1.17 [1.11;1.25]	1.30 [1.19;1.42]	0.18 [0.16;0.21]	0.16 [0.13;0.19]	0.12 [0.11;0.13]
	0.095	0.50 [0.44;0.54]	/	0.51 [0.44;0.58]	1.33 [1.23;1.48]	/	1.29 [1.11;1.50]	0.17 [0.15;0.19]	/	0.13 [0.12;0.15]
	0.275	0.43 [0.38;0.49]	/	0.46 [0.41;0.52]	1.52 [1.36;1.64]	/	1.42 [1.27;1.7]	0.15 [0.13;0.16]	/	0.12 [0.11;0.14]
No-till	0.025	0.47 [0.41;0.53]	0.54 [0.47;0.60]	0.56 [0.47;0.60]	1.40 [1.24;1.55]	1.22 [1.06;1.41]	1.18 [1.04;1.40]	0.18 [0.15;0.22]	0.20 [0.17;0.23]	0.15 [0.12;0.19]
	0.095	0.49 [0.45;0.53]	/	0.54 [0.47;0.60]	1.35 [1.25;1.47]	/	1.21 [1.16;1.73]	0.16 [0.14;0.19]	/	0.15 [0.11;0.19]
	0.275	0.49 [0.44;0.60]	/	0.50 [0.45;0.56]	1.36 [1.08;1.48]	/	1.33 [0.47;0.53]	0.19 [0.15;0.32]	/	0.13 [0.09;0.16]
Tillage		0.2149			0.2149			<0.001		
Depth		<0.001			<0.001			0.1111		
Time		0.0025			0.0025			<0.001		
Tillage x Depth		0.0137			0.0137			0.2336		
Tillage x Time		0.0410			0.0410			0.0937		
Depth x Time		0.8019			0.8019			0.1720		

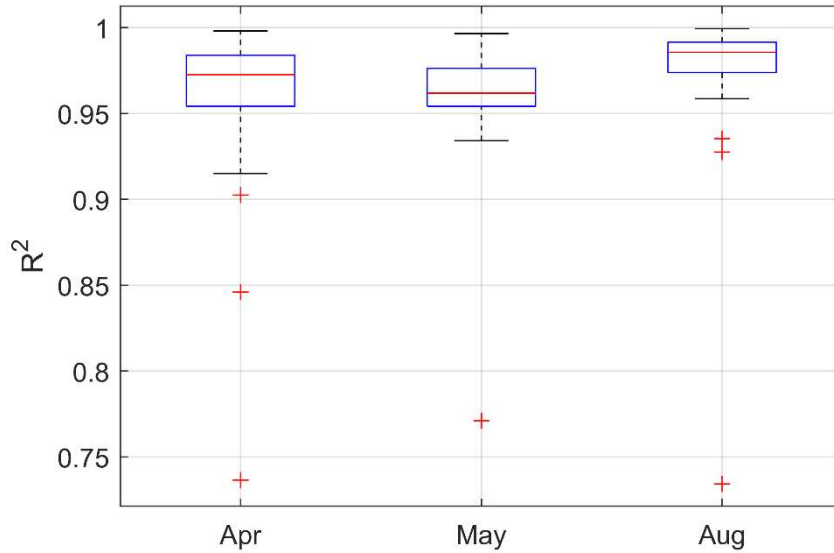
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Table 2 Overview of Hydrus 1-D simulation scenarios and summary results

Abbreviation	Tillage treatment	Soil Parameters used for simulations	Θ Simulation Summary Results		
			Number of replicate simulations	Mean across the top 0.3 m	Coefficient of variation across the top 0.3 m
D _{plough}	Plough	Dynamic	4	0.164	0.24
S _{plough,early}	Plough	Static, using April samples	9	0.180	0.21
S _{plough,late}	Plough	Static, using August samples	8	0.166	0.22
D _{notill}	No till	Dynamic	6	0.173	0.24

$S_{\text{notill,early}}$	No till	Static, using April samples	9	0.189	0.19
$S_{\text{notill,late}}$	No till	Static, using August samples	9	0.175	0.2

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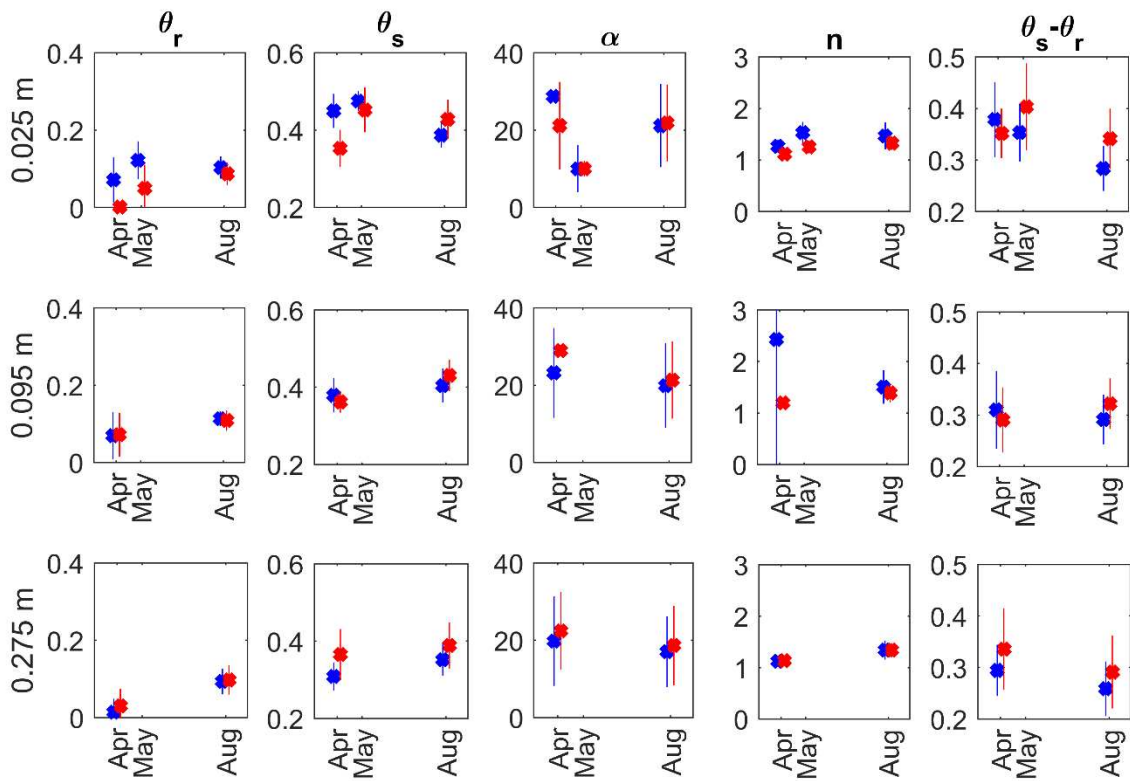
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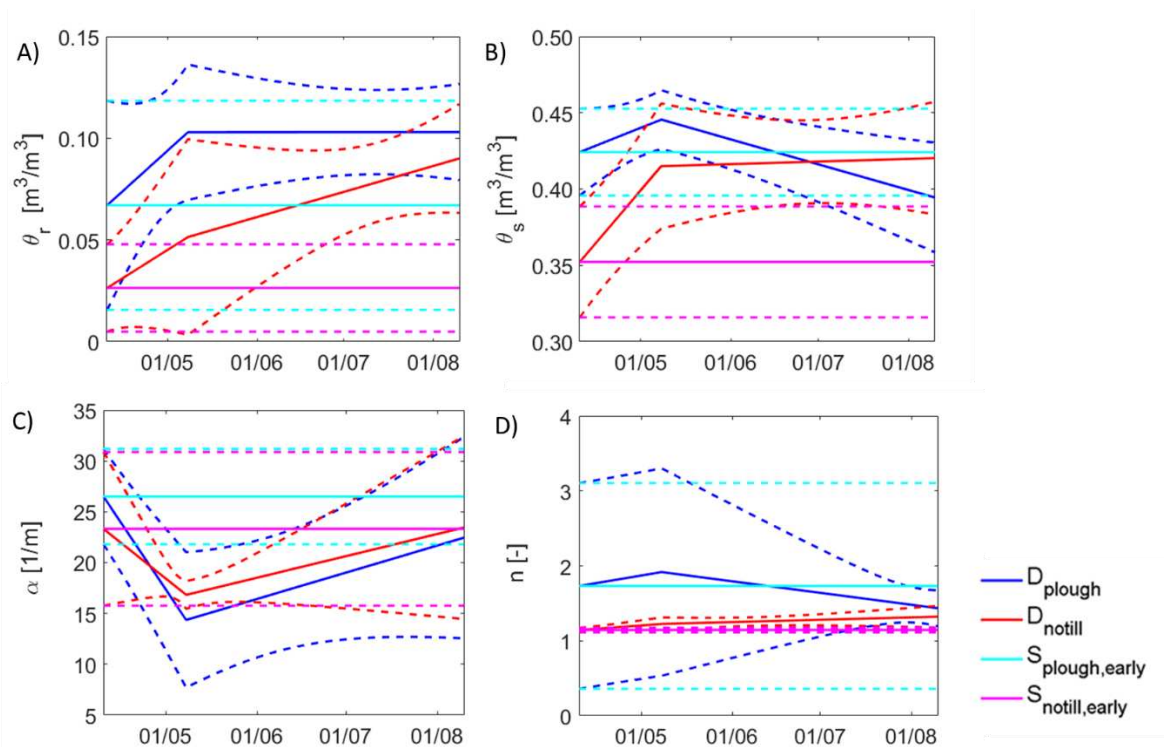
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Figure 1 R^2 values for the van Genuchten function fits to the field data of 108 soil samples, presented for each of the three sampling months. For each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points and outliers (defined as a value that is more than 1.5 times the interquartile range away from the top or bottom of the box) are plotted individually.



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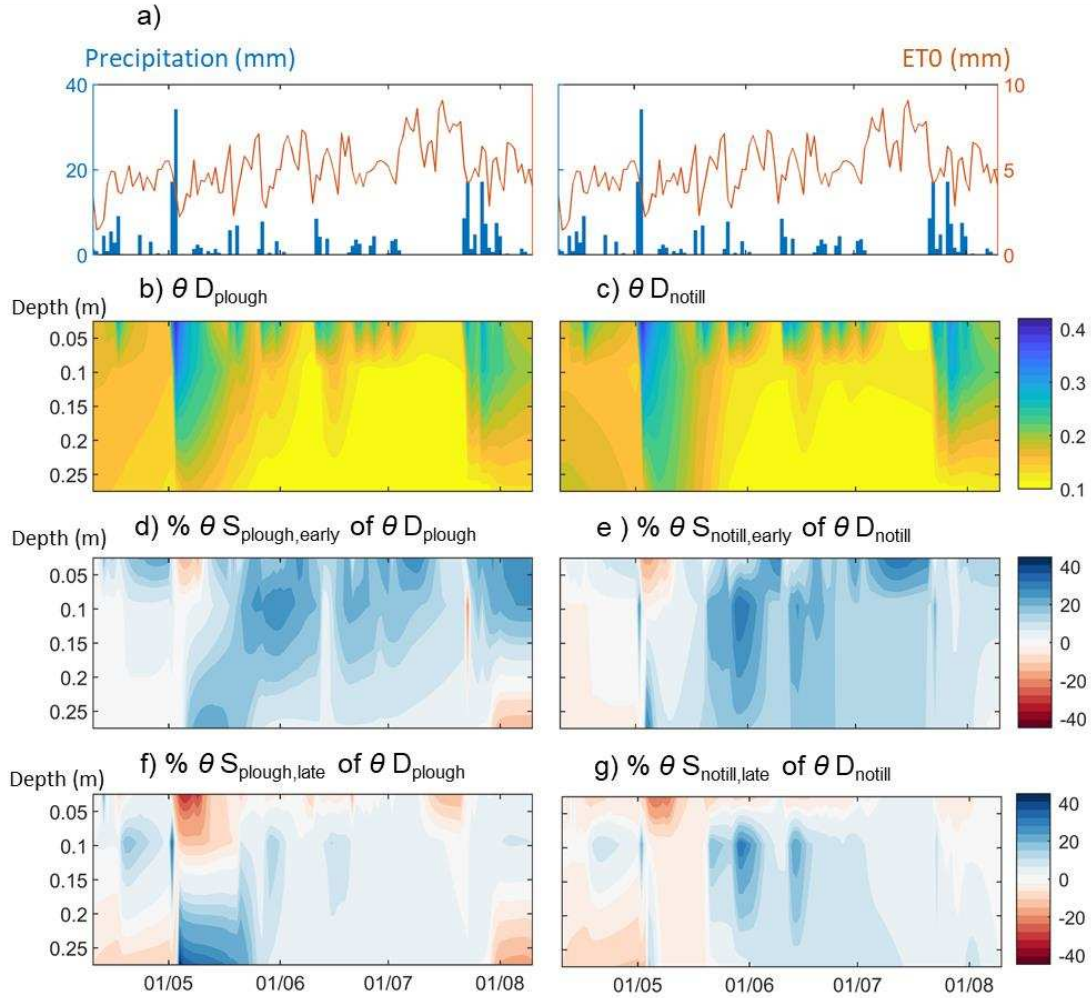
760 **Figure 2** Values of the fitted van Genuchten soil hydraulic parameters for the 3 sampling dates
 761 (Apr 10 2013, May 08 2013 and Aug 10 2013), the two tillage treatments (plough in blue, no-
 762 till in red), and the 3 sampling depths. The mean values among the 9 replicates are
 763 represented by the markers, the standard deviation around the mean by the error bars. For
 764 the error bars in the last column the error bars calculated as $\sqrt{(SD_1^2 + SD_2^2)}$, with SD_1 and
 765 SD_2 as the standard deviation of θ_s and θ_r , respectively.



766 **Figure 3** Time dynamics implemented in HYDRUS for the pore-size distribution parameters θ_r ,
 767 (a), θ_s (b), α (c), and n (d), for the upper depth ($z_{sample1} : 0.025\text{m}$) for set of dynamic scenario
 768 simulations in the ploughed fields (D_{plough} in blue) and in the no-till fields (D_{notill} in red), and in
 769 the static simulations scenario, where the temporal changes of the soil parameters were
 770 omitted. The values of the parameters in the static scenarios were based on the first sampling
 771 value in D_{plough} (S_{plough} , in light blue) and in D_{notill} (S_{notill} , in pink). The solid lines represent the
 772 average values, the dashed lines represent the ranges (minimum and maximum values)
 773 among the 9 replicate samples.

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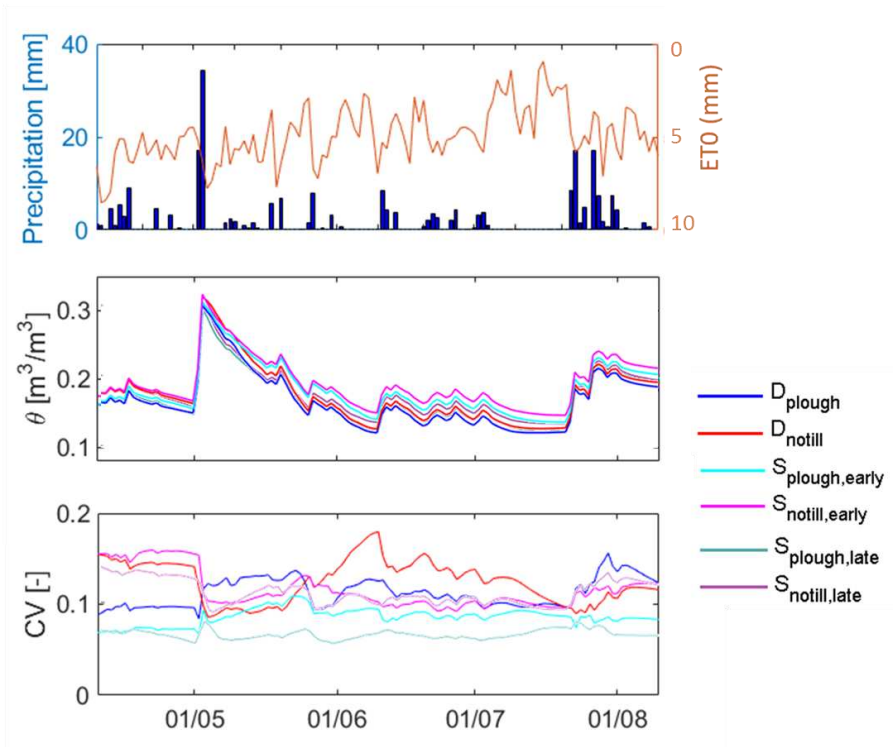
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777 **Figure 4** Daily precipitation and potential evapotranspiration (ET0) in Mid-Pilmore during
 778 the 2013 study period (a), the replicate averaged simulated volumetric water content θ
 779 down to 0.3m for the dynamic time-varying soil properties in the ploughed field, D_{plough} (b),
 780 and in the no-till field, D_{notill} (c), and the percentage differences of simulated volumetric
 781 water contents using the early (April) and late (August) static soil properties as opposed to
 782 the equivalent dynamic simulations in the ploughed field, (d and f) and in the no-till field (e
 783 and g).

784



785

786 **Figure 5** Precipitation (blue bars) and potential evapotranspiration (ET0, orange line) (a),
 787 replicate average simulated volumetric water content θ in the first 0.3m of the soil (b) and its
 788 replicate coefficient of variation CV (c). In (b) and (c), the subscripts “early” and “late”
 789 respectively refer to the results from the cases where the hydraulic properties from the first
 790 (Apr) and third (Aug) sampling values.

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