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

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HIGHLIGHTS:

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

ABSTRACT

Soil properties are often assumed to be static over time in hydrological studies, especially in hydrological modelling. Although it is well appreciated that soil structure and its impact on hydraulic properties are time-variable, particularly on cultivated land, very few studies have focused on quantifying the influence of such changes on soil hydrology, especially at the short term (i.e. seasonal). This study explored the value of incorporating such short-term time-variable soil properties in hydrological models. It is based on soil hydraulic properties from temporal field data under no-till done by direct seeding and under conventional cultivation done by ploughing to 0.2 m and harrowing. It uses a controlled tillage experiment in Scotland, on a soil with very good structural stability that experiences gentle rainfall in a temperate oceanic climate (Köppen Cfb). Water retention data were collected from intact soil cores sampled at 0.025, 0.095 and 0.275 m depth at three times between April and August 2013; (i) immediately following tillage, (ii) at barley crop establishment 1 month later and (iii) after harvest. Soil structure varied over time, with no-till soils gaining porosity and ploughed soils losing porosity. We hypothesised that no-till soils would have less seasonal temporal variability, but found it to be comparable to ploughed soils, albeit with pore structure changes following different trends. These changes were reflected in Van Genuchten fitting parameters, which if accounted for in 1-D HYDRUS modelling, had a marked impact on modelled soil water content over time if contrasted to predictions assuming a static pore structure. Using data from multiple sampling events, as opposed to one sampling event, resulted in up to a 44% difference in soil water content predictions and increased the temporal variability by a factor of 1.5. Hence, our results have demonstrated that it is important to account for short-term temporal variability in soil physical properties in soil water modelling studies, and should not be ignored as a default, particularly on cultivated agricultural soils.

1. Introduction

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

Overall, short-term temporal variability in soil physical behaviour and its impact on hydrology have received much less research than the more dramatic impacts of spatial variability in the landscape (Kreiselmeier et al., 2019; Kool et al., 2019). Parameters, such as soil water content (ϑ), vary in space and its spatial variability can be directly and solely related to the spatial scale of interest. Famiglietti et al. (2008) showed that ϑ variations in space increased with spatial scale. Previously, Western and Blöschl (1999) developed the idea that a scale triplet, comprising the spacing, the support and the extent of the measurement and modelling scales of ϑ could be used to quantify biases in the representation of ϑ. However, spatial variability of ϑ can be exceeded by temporal variability at different locations in the landscape, as characterised using geostatistics (Brocca et al., 2012). It has also been observed that ϑ exhibits temporal stability regarding the areal and temporal statistical spatial distribution of characteristics such as mean and extreme values (Vachaud et al., 1985).

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

The extent of change in the physical properties of agricultural soils during a growing season is strongly affected by soil management (Kool et al., 2019). Tillage disrupts pore continuity and decreases structural strength so that the ability to sustain weathering and mechanical stresses diminishes (Peng and Horn, 2008). However, results can be contradictory, suggesting that the impact of tillage depends on local conditions. For example, Alletto and Coquet (2009) found that over a growing season, a loamy soil under conventional tillage in south-west France increased in bulk density by a factor of 1.4 and decreased in saturated hydraulic conductivity by a factor of 10. A similar study by Jabro et al. (2016) in a sandy loam field from North Dakota, USA reported no changes in bulk density or hydraulic conductivity over the growing season. In a Brazilian subtropical soil, Moreira et al. (2016) found a marked changed in bulk density and hydraulic conductivity over the growing season for a no-till soil, with a strong impact of the severe wetting and drying cycles typical of this climate.

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

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

2. Material and methods

2.1. Study site and data

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

The field experiment consisted of a range of tillage treatments, each replicated three times in a randomised block design (McKenzie et al. 2017), applied for 10 years prior to our study period (i.e. set up in 2003). Each tillage plot was 33 m x 33 m and within each plot barley was sown (360 seeds/m^2) in sub-plots of 1.55 m wide x 6.0 m long. Our study explored no-till and plough tillage treatments, selected to represent different pathways in soil structure dynamics; plough represents a more abrupt shift over time, whereas no-till is closer to a natural condition. Ploughed soils were inverted to 0.2 m and the surface soil was broken up further by harrowing at the beginning of the growing season.

For each treatment and soil depth, 9 soil cores (55 mm diameter x 40 mm height) were sampled (3 replicates per plot, 3 plots of each treatment) on three different occasions in 2013: (1) at sowing on 10 April, which occurred 10 days after ploughing, (2) around establishment of the crop on 8 May, and (3) after the harvest on 10 August. Samples collected on different dates were taken as close to earlier samples as was practical, while ensuring that they were unaffected by the previous sampling. Samples were taken at three depths, including $z_{sample1}$: at or near the surface, where seeds were sown (0 – 0.05m), $z_{sample2}$: within the cultivated or main rooting depth (approx. 0.07 – 0.12m), and $z_{sample3}$: around 0.25 – 0.30m depth (just below the normal depth of ploughing). We considered that the sample depths were taken at the representative nominal depths of $z_{sample1}$ = 0.025 m, $z_{sample2}$ = 0.095 m, and $z_{sample3}$ = 0.275 m. The two deeper depths were only sampled on 10 April and 10 August, with the 8 May surface sample intended to capture very temporarily dynamic settling and slumping post-tillage.

2.2. Spatially and temporally variable hydraulic properties

Core samples were processed in the laboratory to determine bulk density (ρ) and soil water content (ϑ). Porosity (Φ) was determined from bulk density, assuming 2.65 g/cm^3 for particle density. Water retention characteristics were measured by placing cores on ceramic suction plates (0.01 to -50 kPa) and pressure plates (-300 and 1500 kPa) to obtain water contents at -0.01, -1, -5, -20, -50, -300 and -1500 kPa. It was beyond the scope of the original study reported in McKenzie et al. (2017) to measure further hydrological properties, such as hydraulic conductivity, but the short-term sampling at multiple depths for a range of tillage systems provided a unique dataset. Only data from one year were used because the aim was to explore the impact of short-term changes on hydrological modelling, rather than explain long-term tillage impacts on soil physical behaviour.

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

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

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

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

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

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

For each replicate (9) and for each tillage treatment (2), the fitted van Genuchten soil hydraulic properties and K_s were then interpolated linearly over depth from the original sampling depths down to the deepest depth sampled $z_{sample3}$. To allow for insights into the spatial variability, we did not group replicates to obtain a mean fit of the Van Genuchten curve for each treatment and time. We defined a depth z_{nc} (m) from which the soil properties were assumed to remain constant in depth, in space, and in time and therefore were assumed to be the same for all replicates and both tillage treatments. This was set to $z_{nc} = 0.6$ m, based on a previous (unpublished) study performed nearby the experimental plots at Mid-Pilmore. In that other study, soil physical properties below 0.6 m, such as bulk density, pore-size distribution, and saturated hydraulic conductivity, were found to be only marginally affected by a strong external disturbance (tractor passes). At 0.6 m there is also a relatively sharp change in texture from sandy loam to a loamy sand. At z_{nc} and down to the bottom depth of the domain, z_{gw} (m), corresponding to the average depth of the groundwater, the soil property values were derived from theoretical values for loamy sand from the literature. These were approximated using equations 4 and 5 populated with theoretical values from Carsel and Parrish (1988). We defined a correcting factor, *a* (no units), which described how the soil property values ($v_{d,z_{sample3}}$) in the deepest samples in the field ($z_{sample3}$) departed from the theoretical value ($v_{t,z_{sample3}}$) given by the literature for the corresponding soil texture. The parameter (*a*) was derived from the spatial average of the replicates in the undisturbed no-till treatment plot, as the soil is undisturbed in the no-till plots:

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

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

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

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

For each of the replicates and tillage treatments, the three vertical profiles obtained for each soil property were then linearly interpolated in time over the study period. This assumption of linearity is supported by previous work from elsewhere. For example, Onstad et al. (1984) found that the bulk density change followed a linear evolution after tillage and was a function of the cumulative precipitation. Similarly, Bodner et al (2013) observed a linear decreasing trend in median pore radius since tillage. Therefore, given the relatively evenly distributed precipitation in time, it is reasonable to assume changes to soil parameters were linear in 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 dynamic (i.e. time-variable) or static (i.e. fixed in time) soil parameters, referred to as the D and S scenarios, respectively (Table 2). For S, the parameters were either set to the measured values on the first day of the simulation (i.e. 10 April, S_{early}) or the last day (i.e. 10 August S_{late}).

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

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

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

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

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

The calculated potential transpiration and evaporation fluxes were then used to derive the actual fluxes in HYDRUS based on the reduction for transpiration with the Feddes water stress model (Feddes et al., 1978) and hCritA limit for soil evaporation (Šimůnek et al., 2008) which is the minimum pressure head that the soil surface can reach depending on the air relative humidity and temperature.

2.4 Statistical Analyses

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

3. Results

3.1. Variations in soil properties

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

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

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

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

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

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

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

Modelled soil water contents varied with depth and time, with strong interactions, for both dynamic and static simulations (p<0.001). The general trends in simulated ϑ were similar for all of the D and S scenarios (Figures 4b-c and 5b). Figure 4b (ploughing) and 4c (no-till) show that in the top 0.3m of the soil profile, there was drying with depth, with mostly small responses to precipitation. In response to the main precipitation events on 2nd and 3rd May, the soil profile experienced significant wetting, followed again by drying of the soil, albeit with smaller responses to subsequent precipitation. The overall drying trends across the simulation period agreed with field measurements of soil water content, which were observed for both of the ploughed and no-tillage D scenarios (Table 1). Although the soil profile, especially towards the lower part, did get relatively dry for all simulations (minimum simulated value was 0.11 $m^3 m^{-3}$; Figure 4), the simulations never reached values below the residual water content. Uncertainties around the replicate averaged simulations of Figure 5b are expressed as the replicate coefficient of variation in Figure 5c. These are around 0.1 for all scenarios and highest during dry conditions.

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

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

Between different depths and time, over-estimations were up to 44% and under-estimations were up to 29% in the ploughed fields (Figures 4d-g). Differences between D and S scenarios were most pronounced at the two more intensive precipitation events and near the surface. For example, while generating slightly wetter antecedent conditions, the static soil hydraulic properties resulted in an initial underestimation of ϑ in response to the main precipitation event (May 2nd-3rd). The maximum value of ϑ in the upper soil was smaller than 0.35 m^3/m^3 for all the S scenarios, while it was 0.43 m^3 m^{-3} and 0.42 m^3m^{-3} for D_{plough} and D_{notill}, respectively. Deeper in the soil profile, by contrast, the wetting was generally overestimated at this time. For the smaller events, the S_{early} scenarios overestimated the soil water content throughout the soil profile, while the S_{late} scenarios underestimated ϑ at the shallowest depths and overestimated at deeper depths.

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

4. Discussion

4.1. Temporal variations of soil hydraulic properties

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

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

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

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

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

It was beyond the scope of this study to fully quantify the potential uncertainties arising from not considering temporal variations in soil hydraulic properties in hydrological modelling of soil water. Instead, we set out to characterise the effect of temporal variations from a set of realistic, field-driven soil physical properties on soil water simulations using an approach that is typical for hydrological modelling studies. Considering spatial variability in soil hydraulic properties, and how these propagate to simulations of ϑ and other hydrological variables is a more routine practice than considering temporal variability. Differences in spatial variability and organization of soil properties and soil water content at the hillslope-scale has, for example, recently been associated with a significant variation in landslide characteristics (Fan et al., 2016). Alletto and Coquet (2009) provided another example of characterising spatial variability in agricultural fields, reporting that the hydraulic conductivity of the topsoil was mostly correlated with the position of the sample in the plot relative to the crop rows. Our results suggest that characterising (short-term) temporal variability in soil properties and using these for hydrological modelling of soil water could be equally important.

4.3. Study limitations

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

Going forward, the pore size distribution might be modelled more effectively with a bimodal distribution to capture seasonal declines in macroporosity through slumping in the ploughed soil and seasonal increases in macroporosity by biological activity in the no-till soil (Kreiselmeier et al., 2019). We attempted to fit bimodal models to our water retention data with limited success, likely due to only 7 steps of water potential affecting convergence. While a bimodal distribution could have resulted in different absolute results, especially in the extreme dry and wet ends (Haghverdi et al., 2020), there is no indication that the relative differences between the scenarios and treatments would have been vastly different. It would also have been more difficult to rely on the soil water retention curves and there would have been more degrees of freedom and interdependencies between parameters, which in itself would have increased model uncertainty.

5. Conclusion

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

In a typical hydrological modelling setup, soil properties are assumed to be stationary, while it is often considered that they are highly variable in space. The results of this study suggested that neglecting temporal changes in soil properties could have equally important implications for simulations of soil water. Short-term time-variable soil properties should therefore not be ignored as a default in hydrological modelling. This has been verified here using soils where the endogenic and exogenic factors affecting the soil hydraulic properties were relatively mild: the soil was structurally stable and was not inherently subject to swelling or cracking; the ploughing was also a typical practice for agricultural soils; and the hydroclimate displayed very mild intensity at all time scales. Even under these conditions, the results of this study suggested that accounting for temporal variability in soil hydraulic properties could be important for simulations of soil water content dynamics. The hydroclimate at the surface could strongly affect the extent of impacts. In our study, two intense rainy days had a relatively large effect on the spatial variability and on the differences between the scenarios. A study setup in a more extreme climate (e.g. with marked seasonality) could provide further insight.

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

	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		

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

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

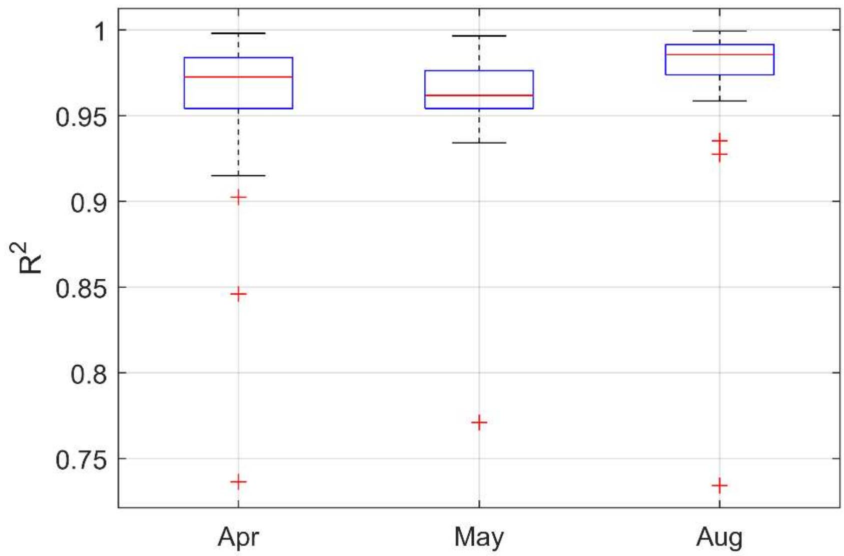

Figure 1 R^2 values for the van Genuchten function fits to the field data of 108 soil samples, presented for each of the three sampling months. For each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points and 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.

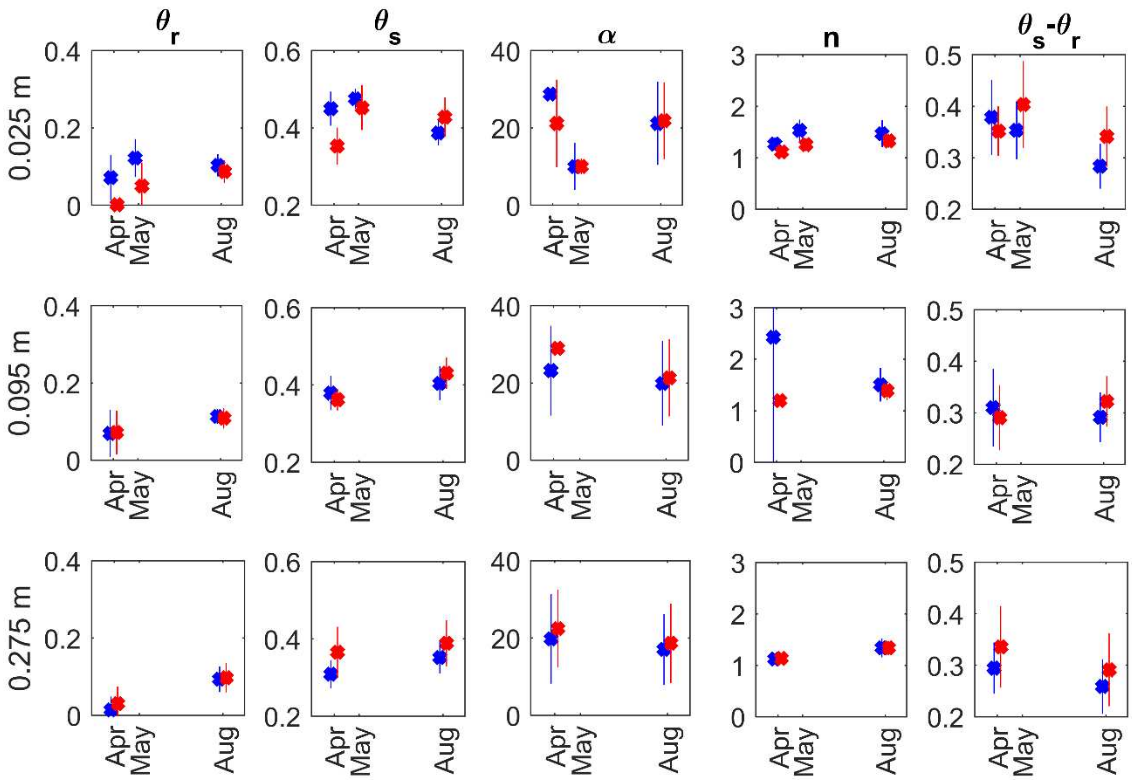

Figure 2 Values of the fitted van Genuchten soil hydraulic parameters for the 3 sampling dates (Apr 10 2013, May 08 2013 and Aug 10 2013), the two tillage treatments (plough in blue, no-till in red), and the 3 sampling depths. The mean values among the 9 replicates are represented by the markers, the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

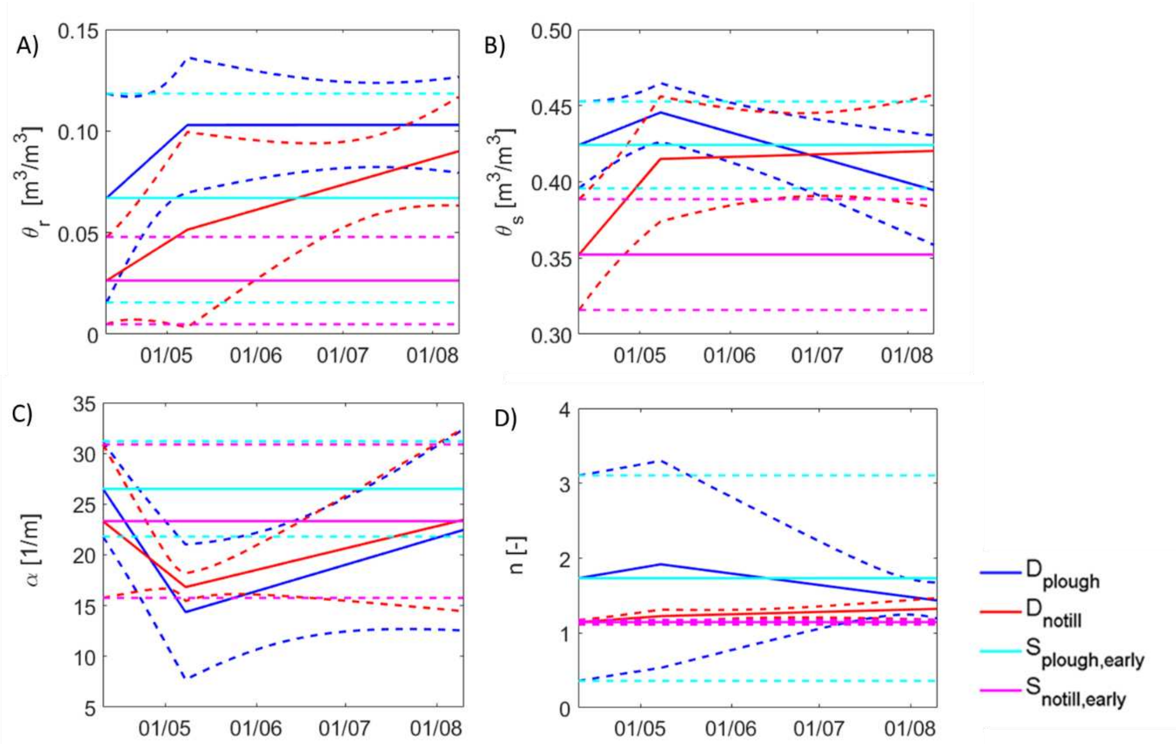

Figure 3 Time dynamics implemented in HYDRUS for the pore-size distribution parameters θ_r (a), θ_s(b), α (c), and *n* (d), for the upper depth ($z_{sample1}$: 0.025m) for set of dynamic scenario simulations in the ploughed fields (D_{plough} in blue) and in the no-till fields (D_{notill} in red), and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

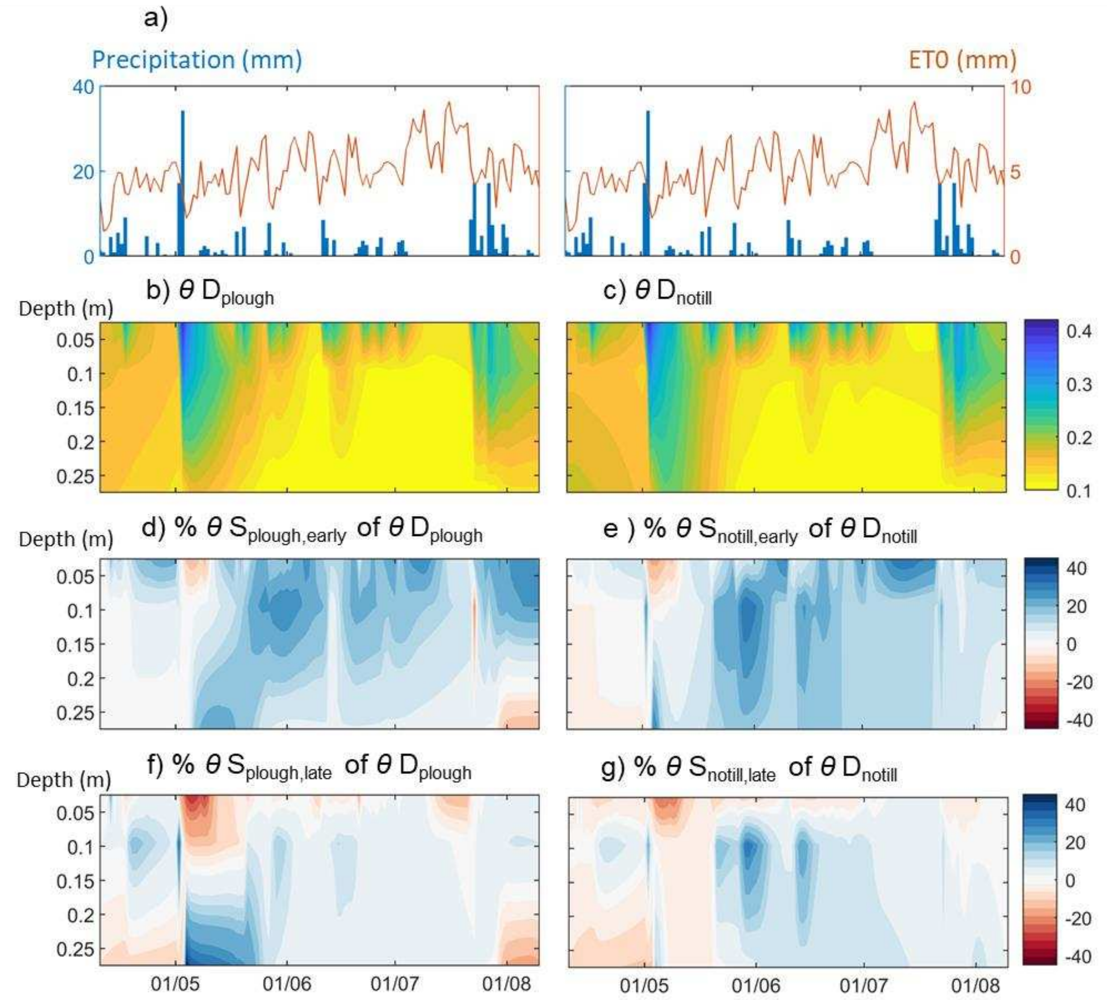

Figure 4 Daily precipitation and potential evapotranspiration (ET0) in Mid-Pilmore during the 2013 study period (a), the replicate averaged simulated volumetric water content θ down to 0.3m for the dynamic time-varying soil properties in the ploughed field, D_{plough} (b), and in the no-till field, D_{notill}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

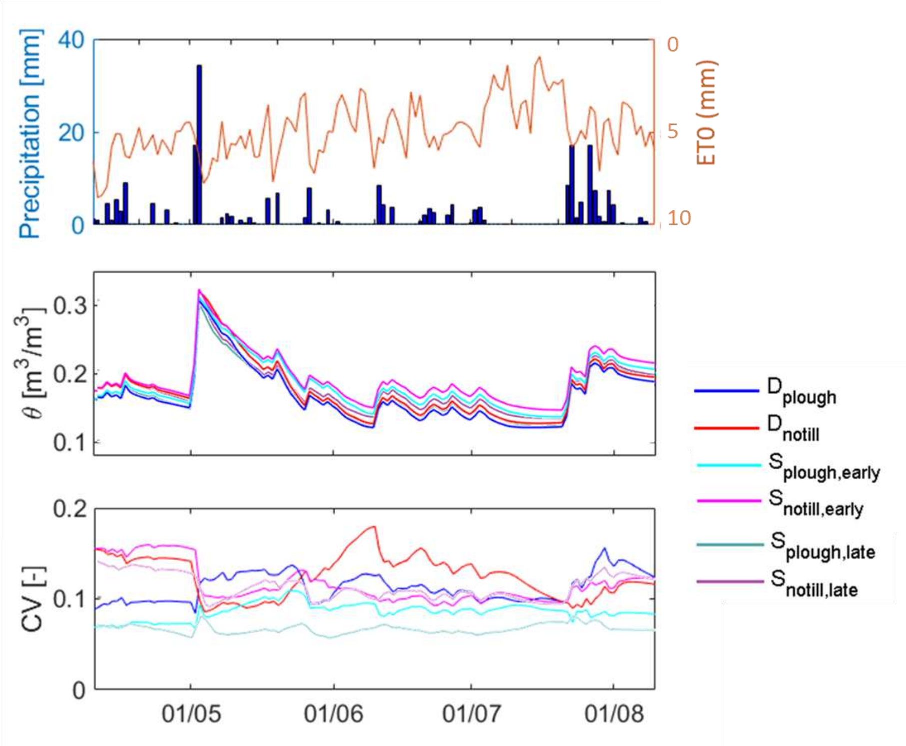

Figure 5 Precipitation (blue bars) and potential evapotranspiration (ET0, orange line) (a), replicate average simulated volumetric water content θ in the first 0.3m of the soil (b) and its replicate coefficient of variation CV (c). In (b) and (c), the subscripts "early" and "late" respectively refer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