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Impact of no-tillage on water purification and retention functions of soil

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Abstract:

There are still uncertainties regarding the long-term impact of no-tillage farming practices on separate soil functions in the United Kingdom. This paper aimed to evaluate the chemical and physical processes in two different agricultural soils under no-tillage and conventional management practices to determine their impact on water related soil functions at field scale in the United Kingdom. The field-scale monitoring compares two neighbouring farms with similar soil and topographic characteristics; one of the farms implemented no-tillage practices in 2013, while the second farm is under conventional soil management with mouldboard ploughing. Two soil types were evaluated under each farming practice: (1) a free-draining porous limestone, and (2) a lime-rich loamy soil with high silt and clay content. Field monitoring was undertaken over a 2-year period and included nutrient analysis of surface and sub-surface soil samples, bulk density, soil moisture, infiltration capacity, surface runoff and analysis of Phosphorous and suspended solids in watercourses in close proximity to the test fields. The conversion to no-tillage changed the soil structure, leading to a higher bulk density and soil organic matter content and thereby increasing the soil moisture levels. These changes impacted the denitrification rates, reducing the soil Nitrate levels. The increased plant material cover under no-tillage increased the levels of soil

Phosphate and Phosphate leaching. The extent to which soil functions were altered by farming practice was influenced by the soil type, with the free-draining porous limestone providing greater benefits under no-tillage in this study. The importance of including soils of different characteristics, texture and mineralogy in the assessment and monitoring of farming practice is emphasised, and additionally the between field and in-field spatial variability (both across the field and with depth), highlighted the importance of a robust sampling strategy that encompasses a large enough sample to effectively reveal the impact of the farming practice.

Keywords:

monitoring scale–no-tillage–soil functions–soil structure–water purification–water retention

Farmers are reliant on soil health to maintain and improve their productivity, they are therefore constantly looking to develop and improve their practice to suit the local conditions and to increase yield. This constant evolving of farming practices to changing conditions (Cock et al. 2011; Scoones and Thompson 1994) has formed the basis of farming innovation that is led by the farmers themselves (Cock et al. 2011), but formal information from research also has an important role in improving and developing aspects of the agricultural landscape (Hall 2005). Intensive farming practices such as conventional tillage (CT) farming with moldboard ploughing is beneficial for weed supression and plant growth, as loosening and inverting the soil causes a higher degree of oxidation and mineralization transitioning nutrients to plant available forms. These processes can, however, lead to an exelerated breakdown of organic compounds (Balesdent et al., 2000) and make the soil more vulnerable to erosion, also as it is left bare and unprotected by plant material (Lundekvam, 2007, Vogel et al., 2016). This has led to an increase in the uptake of alternative and less intensive farming practices to reduce the frequency of soil disturbance to avoid long term soil degradation by erosion and soil organic matter (SOM) losses, and to maintain soil fertility and the environmental functions of the soil (Reicosky 2015). Soil resources are multi-functional and have an important role in providing a wide range of regulating and production functions crucial to ecosystems (Greiner et al. 2017). These soil-based ecosystem services are often referred to as ‘soil functions’ (Schulte et al. 2014; Dominati et al. 2010) and are multi functional; the soils’ ability to deliver these different functions vary with variables such as soil properties, climate and management practices. The dynamics between them are complex and farming practices can have a positive effect on some soil functions, while negatively impacting others (Valujeva et al. 2016).

No-tillage (NT), also referred to as “zero tillage” or “direct drilling”, is a low disturbance farming practice without soil inversion (Townsend et al. 2016), and is often carried out in combination with other management practices such as crop residues, cover crops and different crop rotations (Brooker et al. 2015; Döring et al. 2005; De Baets et al. 2011; Skaalsveen et al. 2019; Sharma et al. 2018; Unger and Vigil 1998). NT practices are becoming more widely used in farming and are often considered to enhance soil functions and soil structure (Skaalsveen et al. 2019; Bertrand et al. 2015; Crotty et al. 2016). Studies indicate that NT has a particularly positive effect on the soil water purification and water retention function as the accumulation of SOM in the topsoil improves the aggregate stability of the soil (Teasdale 2007); which is an important soil structure variable, impacting the resistance to erosion and compaction (Urbanek et al. 2014) and reducing soil and nutrient losses from agricultural fields to water bodies by soil erosion (Schoumans et al. 2014; Mhazo et al. 2016). However, supporting evidence from sites within north western Europe is still limited and more research is required to fully understand the relationships (Skaalsveen et al. 2019; Soane et al. 2012). In particular, knowledge about the effect of soil management practices on separate soil functions is necessary to understand potential trade-offs between functions (Valujeva et al. 2016) and to what extent, and under what conditions, NT farming can be seen as a sustainable soil management option.

Soil type and climate are two of the most important factors influencing farmers’ decisions relating to the type of tillage practice implemented. Alskaf et al. (2020) and Powlson et al. (2012) found that the principal reason for the lower conversion to NT across north western Europe than in the Americas and Australia, where the practice is more widespread, is the build-up of grass weeds, crop disease problems and soil compaction that seems to occur with more temperate climates. NT is primarily practiced in areas with calcareous clay soils in the United Kingdom (UK) because they self-mulch as a result of wet-dry and freeze-thaw cycles which produces good tilth in a way that does not occur with other soil types (Powlson et al. 2012). Additionally, these soils tend to be associated with good drainage and naturally stable structure that is most suited for reduced tillage (Davies and Finney 2012). In drier areas of the UK clays are more suited for reduced tillage practices as free draining loams tend to over-compact (Carter 1987; Davies and Finney 2012), the latter are suitable soils in wetter areas of the UK resulting from higher SOM contents that provide higher soil stability (Davies and Finney 2012).

When evaluating the impact of a change in farming practice timescale has to be considered; both in terms of frequency of data collection and ensuring that enough time has occurred since the implementation to allow process change to occur. Peukert et al. (2013) suggested a time lag of at least five years from starting an experiment to seeing the outcome; this is somewhat problematic as scientific projects often have a shorter life span. The spatial scale that monitoring is undertaken at is also an important consideration. Operational on-farm experiments are important as factorial experiments might not predict the performance of the whole system and lead to incorrect conclusions. The on-farm approach has the advantage of studying systems that are realistic in terms of scale, management practice and constraints faced by the farmer (Drinkwater 2002). Depending on the characteristics of an area the impact of change can vary between farms and therefore when evaluating changes to farming practice care must be taken when applying results from one farm to another (Maillard et al. 2017; Pribyl 2010).

There are several factors that need to be taken into account when considering scale related to the farm management (e.g. historical management of the farm), human factors (i.e. different farming ‘styles’ and timings of different farmers), abiotic factors (local weather and topography), underlying geology, soil type (texture, organic content, particle fraction size and soil depth) that affect the properties (soil structure, hydraulic conductivity, water retention, water infiltration and soil erodibility) and the vegetation cover. Additionally, within field variations in soil properties can also be significant and often poorly understood (Paukert et al. 2013). The spatial variation on a field level is normally explained by a single factor such as soil characteristics or local pest outbreaks, while factors like management and weather conditions are constant over the whole field and more important when comparing between management units (Cook et al. 2011).

This paper aims to evaluate the chemical and physical processes in two different agricultural soils under different management practices (NT and CT) to determine their impact on water related soil functions at field scale. In our study we focus on the slow response variable of soil structure, and therefore an operational research method makes sense in this context as we benefit from collecting samples from well-established farms which have practiced the same system for a long enough time period to reach a steady-state condition that is more comparable (Drinkwater 2002), while starting up a new experiment would be challenging and affect the reliability of the results with a data collection period of only a couple of years.

The objectives are as follows:

(1) To compare soil physical and chemical variables and the water infiltration and retention functions of soils under different farm management practices (NT and CT);

(2) To determine the influence of different soil types on the benefits and drawbacks of the different farm management practices on soil functionality;

(3) To compare the spatial and vertical variability of soil physical and chemical variables in fields of different soil types and management to determine the in-field variability.

Methods and Materials

Study Site

The research was undertaken at Bredon Hill (52°03’37” N, 2°03’46” W) in Worcestershire in the UK (figure 1). The area is an outlier of the Cotswold escarpment and has a maximum elevation of 299 m (981 ft), average annual temperature of 9.7°C (49.5°F) and annual precipitation of 660 mm^{-1} (25.9 in^{-1}) (Climate-data 2019). The upper elevations are formed of the Birdlip Limestone Formation, associated with Cotswold Brash soils (Calcaric Endoleptic Cambisols (Cranfield University, 2020; IUSS, 2007)) typified by its high content of free-draining porous limestone (up to 50% of the soil volume) and shallow depth, while the lower elevations consist of the Charmouth Mudstone Formation, associated with lime-rich loamy soils (Calcaric Stagnic Vertic Cambisols (Cranfield University, 2020; IUSS, 2007)) with a medium to high silt content and the presence of calcareous Jurassic clays which have low permeability and are exposed to water logging (British Geological Survey 2018).

Experimental Fields

The monitoring was undertaken at two neighbouring commercial farms that had similar soil types (one field of Cotswold Brash and one field of lime-rich loamy soil assessed at each farm) and topographic conditions; one that used CT and the other converted to NT with direct drilling in 2013. Measurements were carried out from 2018 to 2019, with detailed

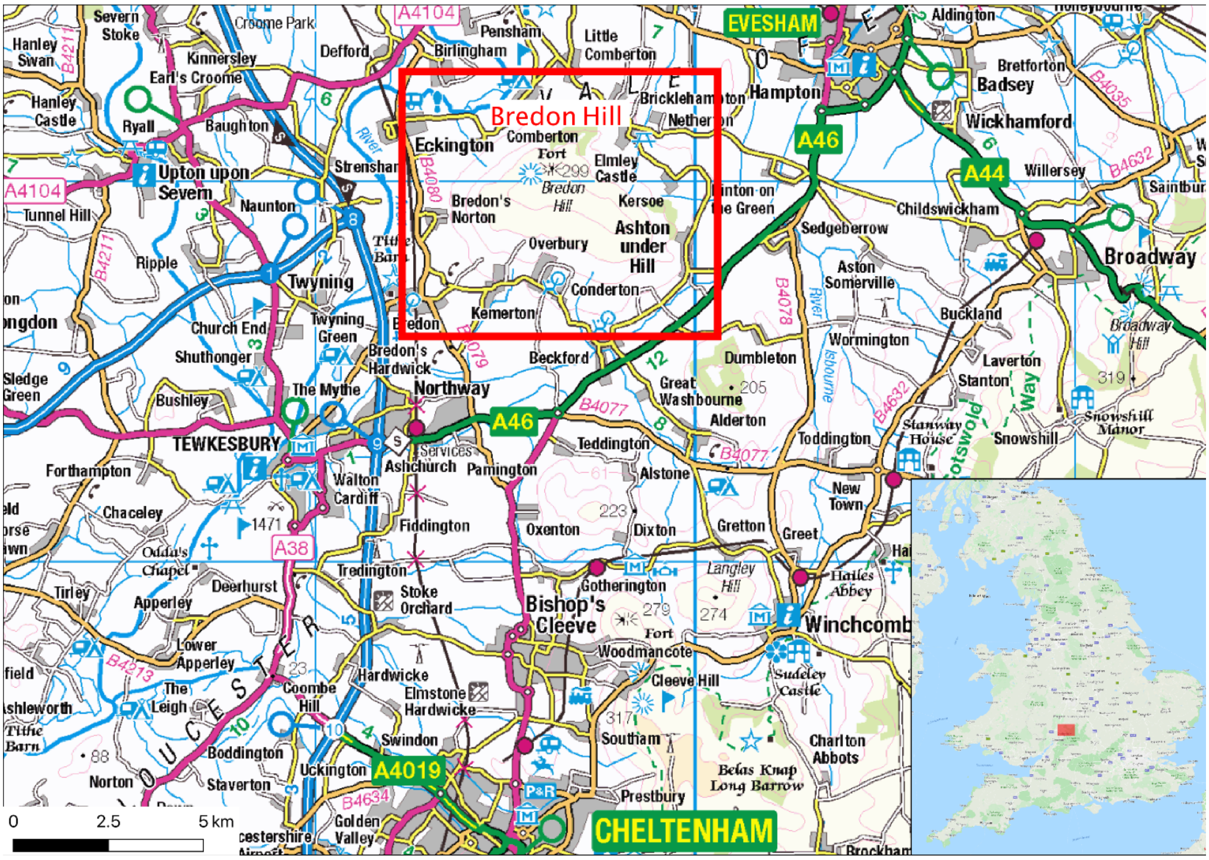

Figure 1 Study site location in Bredon Hill, Worcestershire, UK (outlined by red box).

sampling undertaken in Spring (April and May) and Autumn (September and October) of 2018 and the Spring (April and May) of 2019 to coincide with periods of crop changeover on the two farms. To account for the distinctive soil boundary in this area, the sampling strategy consisted of four fields with one field of each soil type at each of the farms. A comprehensive grain size distribution analysis was carried out with nine samples from each field consisting of soils from 0 to 50 cm (0 to 19.7 in) depth that were analysed by a Malvern Mastersizer range particle size analyser.

Tillage Treatments

The NT farm implemented direct drilling in 2013 after a transition period of reduced tillage from 2004, these practices included crop protection by crop residue management and cover crops (occasionally grazed off by sheep). The CT farm cultivates the soil by mouldboard ploughing but transitioned to minimum tillage in 2017 in the lime-rich loamy field (CT-C).

The four monitoring sites were as follows:

1) NT-S: NT farming practices on Cotswold Brash (10 to 13% clay (<0.002 mm), 26 to 36% silt (0.002 – 0.063 mm), 3 to 13% sand (0.063 – 2 mm) and approximately 50% coarse fragments (>2 mm)) with pH = 8.1. Farming practices included: direct drilling, cover crops and soil cover by crop residue with wheat and oil seed rape rotation (forage turnips grazed by sheep Autumn 2017). Average slope: 6.1%. Aspect: Southeast facing slope.
2) NT-C: NT farming practices on lime-rich loamy soils (27 to 33% clay (<0.002 mm), 50 to 65% silt (0.002 – 0.063 mm), 7 to 22% sand (0.063 – 2 mm) and no coarse fragments (>2 mm)) with pH = 6.9. Farming practices included: direct drilling, cover crops and soil cover by crop residue with wheat and peas rotation. Average slope: 0.6%. Aspect: South facing slope.
3) CT-S: CT farming practices on Cotswold Brash (11 to 14% clay (<0.002 mm), 25 to 30% silt (0.002 – 0.063 mm), 8 to 14% sand (0.063 – 2 mm) and approximately 50% coarse fragments (>2 mm)) with pH = 8.1. Farming practices included: Mouldboard ploughing with spring barely rotation (forage turnips grazed by sheep Autumn 2018). Average slope: 12.8%. Aspect: Southwest facing slope.
4) CT-C: CT farming practices on lime-rich loamy soils (26 to 31% clay (<0.002 mm), 56 to 64% silt (0.002 – 0.063 mm), 7 to 13% sand (0.063 – 2 mm) and no coarse fragments (>2 mm)) with pH = 8.1. Farming practices included: Mouldboard

ploughing with recent transition to minimum tillage with wheat, oil seed rape, wheat and beans rotation. Average slope: 5.7%. Aspect: Southwest facing slope.

Field and Laboratory Methods

The following variables were measured during the monitoring period. All measurements are recorded in metric units, where 10 cm is equal to 3.9 in.

Water Infiltration

The infiltration rate (i.e. the speed at which water enters the soil) of each of the fields was measured using a double-ring infiltrometer. This was conducted at a single location in each field and in both the north-western and south-eastern end of NT-C, in Spring 2018, Autumn 2018 and Spring 2019.

Soil Organic Matter (SOM) and Soil Moisture

Soil samples for SOM and soil moisture were collected monthly from two depths (0 to 10 cm and 10 to 20 cm) at nine sampling locations in the NT fields from 2015 to 2017. During the more detailed sampling regime in 2018 and 2019 soil samples were collected from nine sites in all fields, except CT-C where they were collected from six sites, and from five depths (0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 30 to 40 cm and 40 to 50 cm).

SOM was calculated using the loss-on-ignition method where the dry sample was burned at 550°C (1022°F). To determine the soil moisture, the water content was determined by oven-drying 5 g of wet sediment sample at 105°C (221°F) and recording the difference in weight between the wet and dry sample.

Bulk Density

Bulk density (i.e. the weight of soil in a given volume) samples were collected in Spring 2018, Autumn 2018 and Spring 2019 from three locations on each field (only two from CT-C) and from two depths at each location (surface: 0 to 10 cm and sub-surface: 15 to 25 cm). The sampling was carried out by the excavation method which was more suited for soils with a high content of rocks or gravels (such as the Cotswold Brash) than the standard core method. This consisted of digging a hole in the soil and sieving out all material greater than 2 mm (0.08 in) in size, the volume of the pit was measured by lining it with plastic wrap, placing the sieved rocks and gravel back inside and adding water from a syringe. The water volume was then recorded and the soil samples were oven dried and weighed in the laboratory and the following equations applied:

Soil bulk density (g/cm^3) = weight of oven-dried soil / volume of soil

Soil water-filled pore space (%) = (volumetric water content x 100) / soil porosity

Volumetric water content (g/cm^3) = soil water content x bulk density

Soil porosity (%) = 1 – (soil bulk density / 2.65)

Soil Nutrients

*S*oil nutrient samples were collected using the same sampling strategy as outlined above. Ammonia (NH_3) and Nitrate (NO_3) samples were extracted by shaking the soil sample with a 2M KCl solution, filtering and analysing by the use of a continuous flow AA3 Seal AutoAnalyzer with a colorimetric determination of dissolved nutrients. The soil orthophosphate (PO_4^{3-}) was extracted by the Olsen P method, filtered and analysed by the colorimetric method (molybdate) with a spectrophotometer.

Stream Water Quality

Water samples were collected from ten sampling locations in March and May 2018. The streams were running through or downstream of the two farms (five sampling locations per farm) and sampling took place in March and May 2019 after longer rainfall events to make sure that there was enough water in the smaller streams during sampling. The samples were filtered by a 50 ml plastic syringe (sterile) with filter attachment containing a cellulose Nitrate filter (0.45 μm). The Phosphate (PO_4) and Phosphorous (P) analysis were carried out by the University of Exeter using a Seal Analytical AutoAnalyzer (4 Channel Serial) providing the Total Phosphorous (TP) and Dissolved Reactive Phosphorous (DRP).

Statistical Analysis

Rstudio (version 1.1.463) software was used for statistical analysis of the data. A nested ANOVA was carried out for variance analysis of the different variables nested within the different fields within the farming practices (e.g. for differences in concentrations of SOM and nutrients with sampling depth for each practice or soil type). A one-way ANOVA was used for the variance analysis of within-field values, and a Tukey multiple pairwise-comparison analysis was carried out to compare values between fields. Pearson's correlation tests were carried out for correlations between variables, while Principle Component Analysis (PCA) was used to determine the variance and find the quality of representation of different variables.

Results and Discussion

Farming Practice: Comparison of No-tillage (NT) and Conventional Tillage (CT) Farming

SOM levels are an important indicator for soil structure and aggregate stability (Schoumans et al. 2014; Mhazo et al. 2016; Teasdale 2007), and Kreiselmeier et al. (2019) found higher temporal stability of soil structure and comparably lower transmission (water movement) but more retention (storage pores) under NT than under reduced tillage and CT. This meant that the soil structure of NT was more resilient to erosion with regards to precipitation extremes than under CT, with comparably low bulk density and high porosity favouring rapid infiltration (Golabi et al., 1995). In this study, there were no significant differences between the bulk densities of the two practices (NT vs. CT) ($p > 0.05$), but there were significant differences between separate fields. The bulk density of CT-C (with the lowest mean bulk density) was significantly lower ($p < 0.05$) than of NT-C (table 1). This reflected the higher compaction of topsoils that often occur under NT as it is not loosened with a plough as under CT.

The Tukey multiple pairwise-comparisons showed that significant differences in SOM only occurred between NT-S and the three other fields (with significantly higher SOM levels ($p < 0.001$) in NT-S), while no significant difference was found between NT-C, CT-S and CT-C (figure 2). The mean SOM level of NT-S was 9.2 %, while the lowest mean SOM level of 7.1% occurred at CT-S.

Higher soil moisture levels are often expected under NT as the crop residue and soil structure reduce the evaporation from the field, thus the total ecological respiration tends to respond more intensely to rainfall events under CT than NT (Chi et al. 2016). The soil

Table 1 Structural properties of the four test fields measured in Spring 2018, Autumn 2018 and Spring 2019.

Date	**Field**	**Bulk Density (g/cm3)**	**Soil porosity (%)**	**Soil water content (g/g)**	**Volumetric water content (g/cm3)**	**Soil water-filled pore space (%)**	**Infiltration rate (mm/min)**
Spring 18	CT-C	1.03 (±0.127)	0.61	0.25	0.26	42.4	†
	NT-C	1.28 (±0.121)	0.52	0.24	0.31	60.1	0.35
	CT-S	1.51 (±0.294)	0.43	0.18	0.27	63.4	0.50
	NT-S	1.17 (±0.199)	0.56	0.21	0.24	43.4	1.4
Autumn 18	CT-C	1.03 (±0.128)	0.61	0.26	0.27	43.6	0.40
	NT-C	1.37 (±0.141)	0.48	0.27	0.37	76.7	0.35
	CT-S	1.31 (±0.246)	0.51	0.17	0.23	44.6	0.80
	NT-S	1.32 (±0.157)	0.50	0.24	0.32	63.1	1.5*
Spring 19	CT-C	1.14 (±0.087)	0.57	0.22	0.25	43.8	0.40
	NT-C	1.27 (±0.173)	0.52	0.22	0.28	54.3	0.50
	CT-S	1.22 (±0.131)	0.54	0.19	0.23	42.3	0.70
	NT-S	1.03 (±0.262)	0.61	0.22	0.23	37.1	1.0

*Unstable and rapid infiltration (flow did not properly stabilise).
†Not possible to record any accurate infiltration measurements as the field was extremely dry and contained large cracks which the water flushed through.

water-filled pore space from our study agreed with this (table 1), with NT fields (mean value: 55.8%) higher than CT fields (mean value: 46.7%). This ability to retain soil moisture is an advantage in soils exposed to drought. NT was originally developed to conserve moisture during a drought period in Central and South America (Kassam et al. 2012; Lahmar 2010); as shown with our study where soil retention was higher in NT fields following a water scarce

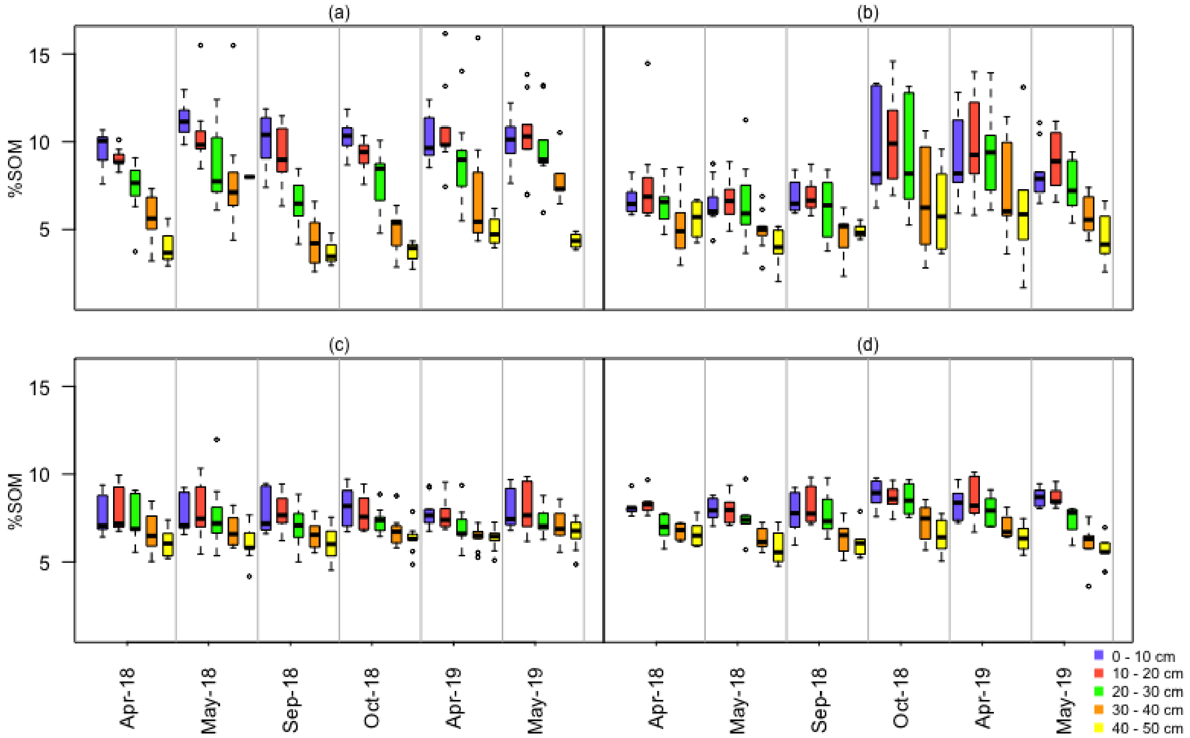

Figure 2 Soil organic matter (SOM) levels at (a) NT-S, (b) CT-S, (c) NT-C, and (d) CT-C at different depths sampled (represented by the different colours; key provided above) from Spring 2018 to Spring 2019 showing mean values and 75% confidence intervals.

period in summer 2019 (average values for soil water-filled pore space: NT = 69.9%, CT = 44.1%).

Nevertheless, high soil moisture content can be a challenge in areas with a wetter climate and can restrict the window of opportunity for field operations and increase the risk of soil compaction. This was supported by other studies that found poorer soil structure and higher compaction in NT fields compared to CT (Peigné et al. 2009; Peigné et al. 2013 Franzluebbers et al. 1995). There can be temporal variability in bulk density values (Wuest 2015) and Franzluebbers et al. (1995) found differences in bulk density values between CT and NT with large seasonal dependence. The largest variation was found under CT as the bulk density decreased due to tillage but increased with time after tillage to the level of NT resulting from densification processes, causing more changes in the physical condition of the CT soil.

In our study, elevated bulk density values were found in the two NT fields during Spring 2018 (table 1). In an American study where the relationship of bulk density and water table depth with soil properties were compared at 16 study sites, Logsdon (2012) found a negative correlation between volumetric water content and bulk density, but mainly on dry dates and not wet dates. This is one possible explanation for the elevated bulk density values found in the two NT fields in November 2018 (table 1) as these fields retained a higher level of the soil moisture over what was an extended period of dry conditions (Summer 2018).

There was an increase in the NO_3 concentrations in the two CT fields (figure 3). The Nitrogen (N) cycle is complex and a number of conditions determine the forms of N, such as the amount of fertiliser applied by the farmer. However, other likely explanations for the lower NO_3 concentrations in the NT fields was that denitrification processes often increase with higher SOM levels, meaning that NO_3 was reduced to gaseous forms of N (primarily N_2O and N_2) by microbes. Denitrification was also a likely outcome of anaerobic conditions as a result of high soil saturation or increased bulk density (due to less aeration). This has been confirmed by earlier studies (Constantin et al. 2010; Rochette 2008) that demonstrated increased N_2 emissions under NT management.

No significant trends were found for the NH_3 concentrations between practices (figure 3), while the highest concentrations of soil PO_4^{3-} were found in the NT fields (NT-C = 4.86 mg/L

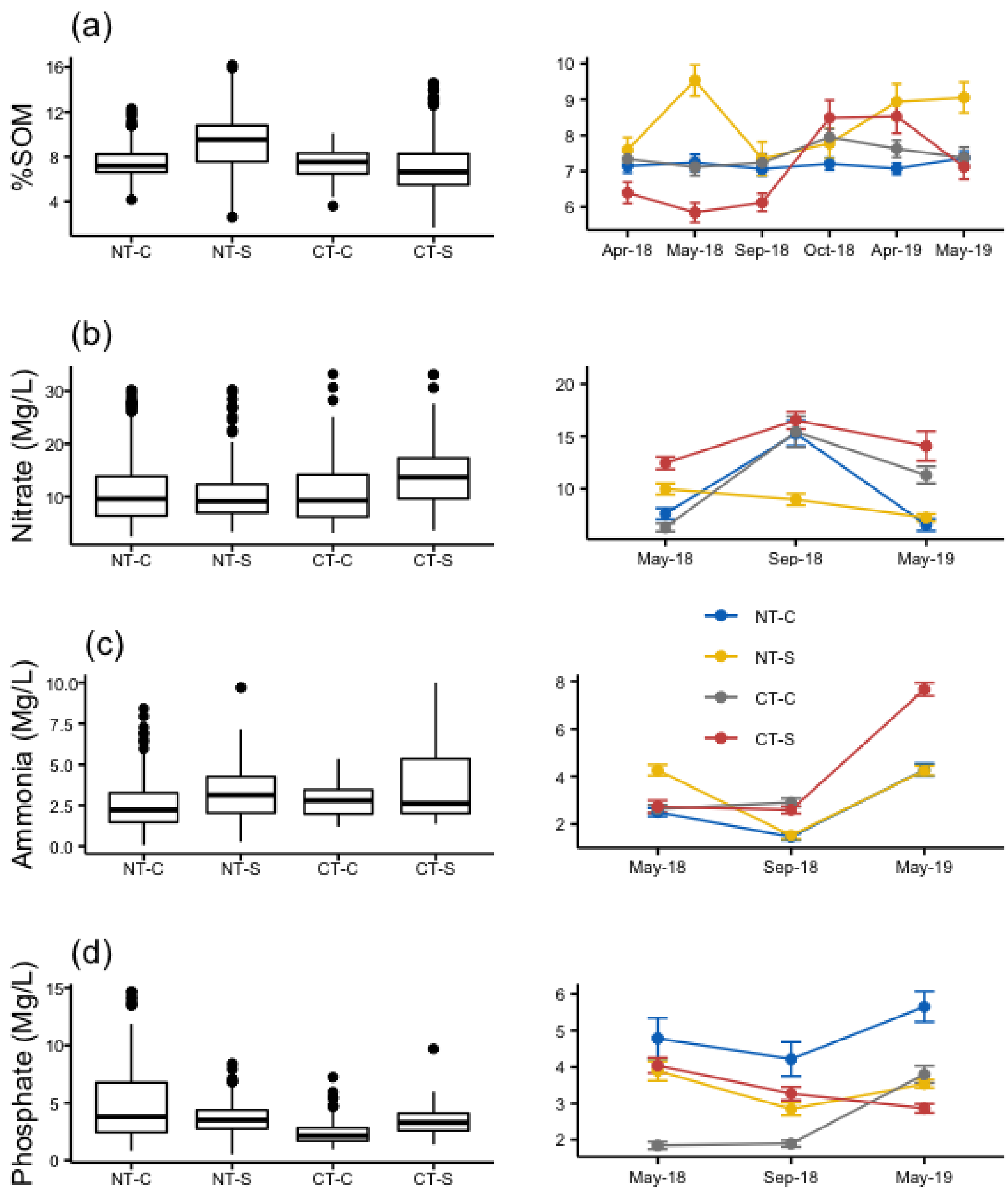

Figure 3 Mean values with 75% confidence intervals of (a) soil organic matter (SOM), (b) Nitrate (NO_3), (c) Ammonia (NH3) and (d) Phosphate (PO_4^{3-}) for the four fields (shown on the left) and plotted temporally between Spring 2018 and Spring 2019 (shown on the right).

and NT-S = 3.68 mg/L), with the lowest level at CT-C (2.50 mg/l). The concentrations measured at NT-C were significantly higher than for all three of the other fields ($P < 0.001$) and there were significant differences between soil PO_4^{3-} concentrations for all of the combinations of fields apart from between NT-S and CT-S. The increased soil PO_4^{3-} levels under NT was probably a result of the increased input of plant material and crop residues under this practice, this increased the TP and organic P concentrations which in turn can increase the activities of phosphatase, which is the mechanism that makes P available to plants (hydrolysed into PO_4^{3-}) (Wang et al. 2011). However, other scholars have found that the most important effect of different tillage practices on soil P is the stratification to the topsoil layer resulting from crop residues, fertilisation and the lack of mixing (Tracy et al. 1990), so the increased overall PO_4^{3-} levels in this study was also a likely result of differing fertilisation regimes between the farms.

With regards to the water samples, there were higher levels of total P downstream of the NT fields (mean: 0.547 mg/L) than those collected downstream of CT (mean: 0.166 mg/L) shown in figure 4a, however, this was partly caused by a highly elevated concentration at the O2 (NT) sampling location in March 2019 (3.699 mg/l). The difference between the streams downstream of NT and CT fields was greater for DRP concentrations (NT = 0.188 mg/L, CT = 0.0316 mg/L) shown in figure 4b. The concentrations of TP and DRP were generally higher in May (Summer-time) than in March (Spring-time), probably as a result of elevated water discharge during the sampling in May causing a dilution effect.

The P loss potential can vary both with soil type and practice (Li et al. 2019). Previous research has analysed the differences in P inputs from different farming practices and found that the decreased erosion rates expected under NT (with more soil protection) also reduced the TP inputs to downstream waters as a large fraction of the total P is bound to particles (Svanbäck et al. 2014; Ulén and Kalisky 2005; Ulén et al. 2010; Schoumans et al. 2014). However, studies have also found that the concentration of DRP can increase

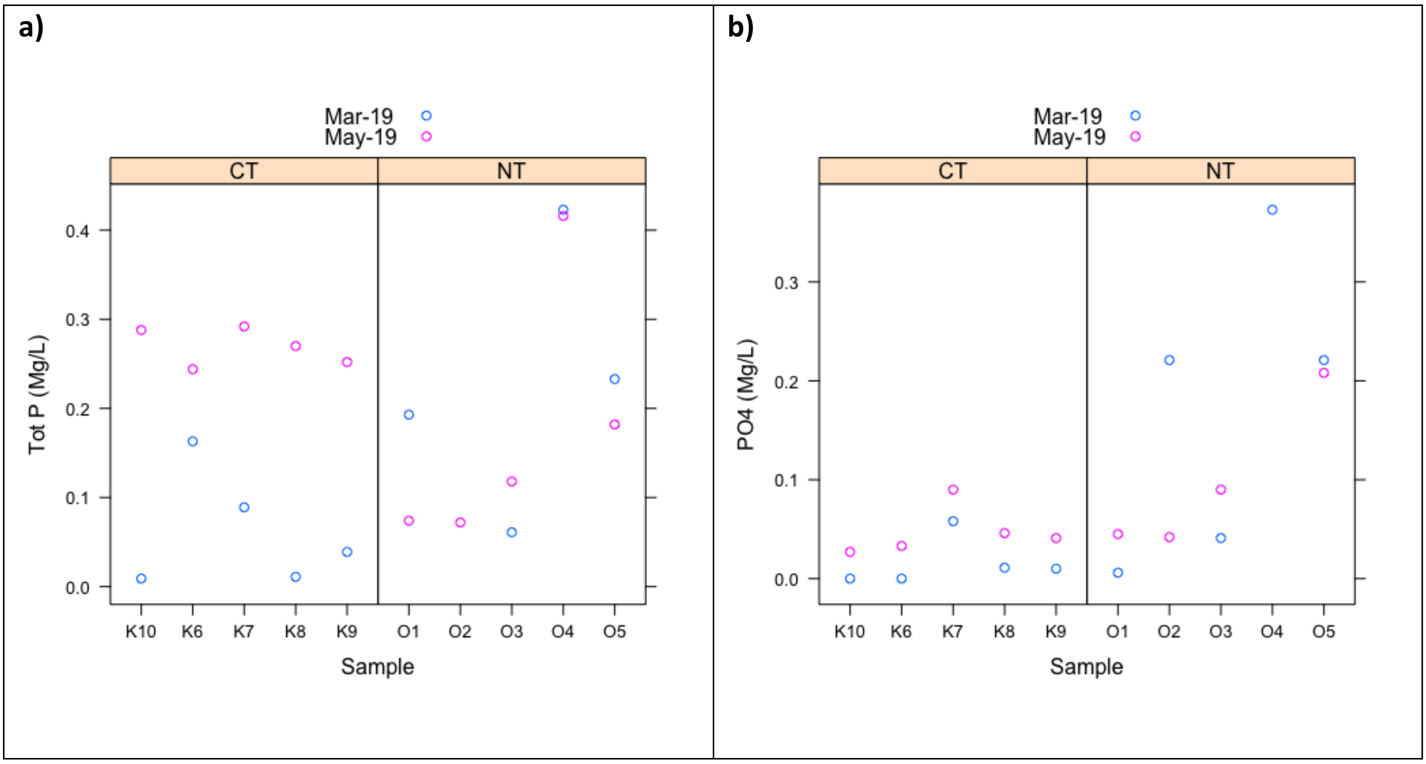

Figure 4 Concentrations of (a) Total Phosphorous (TP) and (b) Dissolved Reactive Phosphorous (DRP) in water samples collected from streams in close proximity to the no-tillage (NT) and conventional tillage (CT) farms in March (blue) and May (pink) 2019.

downstream of NT fields, in accordance with the findings in this study, which can therefore have implications on the water quality as this form of P is highly reactive (Ulén and Kalisky 2005; Ulén et al. 2010; Schoumans et al. 2014). Increased DRP concentrations by the NT fields can be a result of leaching through vertical water movement through the soil (Daniel et al. 1994) and then entering watercourses via tile drainage (Ulén et al. 2010). The increased risk of DRP losses from NT fields can be explained by the increased enrichment of nutrients in the topsoil under this practice (Taylor et al. 2016) and releases of DRP from the plant material that is accumulated on the soil surface (cover crop and crop residues) (Ulén et al. 2010). The elevated concentrations of soil PO_4^{3-} found in the NT fields compared to the CT fields was also a likely contributor to the higher values of P in the water samples downstream of these fields.

Similar patterns as found for P were also true for N, and in a long-term field experiment Autret et al. (2019) compared different farming practices and found that NT had the highest C and N storage potential, but the absence of tillage did not reduce NO_3 leaching. Cover crop destruction and decomposition during autumn and winter increased the soil mineral N in this system. This was in accordance with Himanshu et al. (2019) who used a hydrological model in an Indian watershed and found higher nutrient losses, but lower sediment concentrations under NT.

Soil Type

In this study, the only significant difference between soil moisture values was found between NT-S and NT-C ($P = 0.0224$), with the mean soil moisture values highest at NT-S (20.3%) followed by CT-C (20.0%), and the lowest mean soil moisture level was at CT-S (15.4%, significantly lower than the three other fields: $P < 0.001$). An important difference between the NT and the CT fields was that the soil moisture distribution in the soil profile was different (figure 5) as the NT-C field did not show the same declining trend with depth as in the rest of the fields, while NT-S showed the greatest soil moisture gradient resulting from much higher moisture content in the topsoil.

There was a significant difference in bulk density between fields ($P < 0.05$), but not for the different sampling depths (surface and subsurface) nested within the fields ($P > 0.05$). Although there was no significant difference between the practices ($P > 0.05$), there was a significant difference between the different soil types nested within the different practices ($P < 0.05$). The lowest mean bulk density was found in the topsoil of NT-S (mean: 1.04 g/cm^3), that might partly be explained by the elevated levels of topsoil SOM in this field

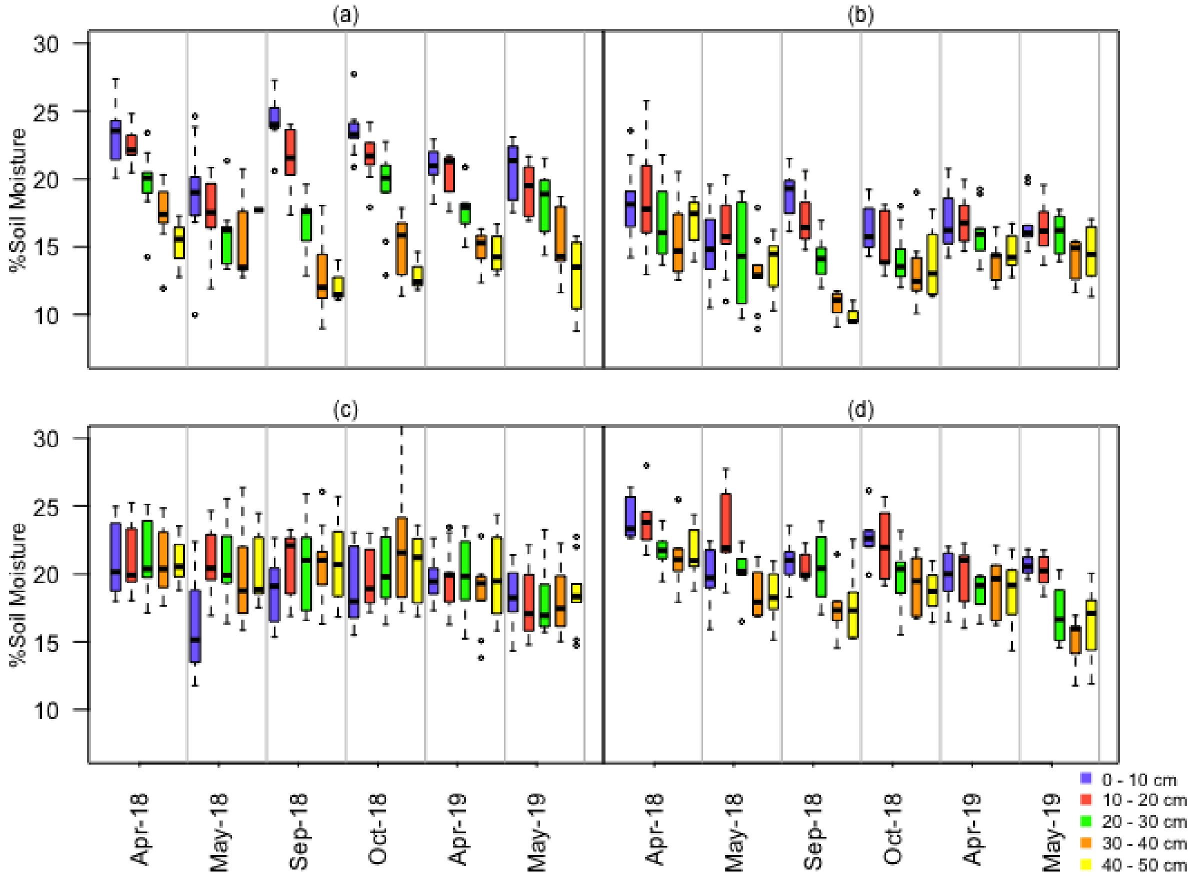

Figure 5 Soil moisture levels at (a) NT-S, (b) CT-S, (c) NT-C, and (d) CT-C at different depths (represented by the different colours; key provided above) sampled from Spring 2018 to Spring 2019 showing mean values and 75% confidence intervals.

(figure 2) compared to the three other fields (Behrends Kraemer et al., 2019). However, the variation was very high within this field and the subsoil bulk density was markedly higher (1.31 g/cm^3) meaning that the soil is more compacted at greater depths in this field. Both the highest and the lowest SOM levels were found in the Cotswold Brash fields (figures 2 and 3a). There was a large variation between the two lime-rich loamy fields with higher compaction in the NT field than the one of CT (table 1).

The suitability of NT is highly related to soil type and soil characteristics such as drainage and structural properties (Soane et al. 2012). Cannell et al. (1978) devised a three-tier classification system for UK soil types based on their suitability to NT; Calcareous selfmulching clays derived from limestone or chalk were considered to be one of the most suitable soil types, while undrained clay soils with poor structure were found to be unsuitable for this practice. Therefore, Alskaf et al. (2020) reported that in their study low disturbance farmers (reduced tillage) were forced to plough their heavy clay soils during wet years to help drainage. The potential challenges associated with water logging under low disturbance practices in a wet climate clearly showed the importance of climatic factors for the suitability of different farming practices, in addition to soil types. The higher bulk density found in NT-C (table 1) could be a result of a combination of the soil type, poor structure and low drainage. The lime-rich loamy fields in this study cracked during the dry summer months (especially during 2018 when the region underwent severe water deficit), which has been suggested as another factor that can degrade the soil structure by reducing the aggregate stability (Behrends Kraemer et al. 2019) and therefore increase the risk of compaction.

Chi et al. (2016) found higher correlation between soil moisture and C under NT than CT and suggested that soil disturbance could be a possible explanation, where disturbance under CT break the C water connections. The highest correlation between SOM content (directly related to the C content) and soil moisture in this study was found in NT-S, however, overall these findings contradict the findings of Chi et al. (2016) as the soil type had a more significant influence than farming practice, with similarly high correlations between SOM and soil moisture in the Cotswold Brash field under CT.

The highest mean NO_3 level was found at CT-S (14.3 mg/L) that was significantly higher than all the three other fields ($P < 0.01$), the lowest was NT-S (10.8 mg/L) and the two lime-rich loamy fields had very similar concentrations (NT-C = 11.1 mg/L, CT-C = 11.0 mg/L) (figure 3). There were no significant differences between the latter three. The NH_3 content was significantly higher ($P < 0.05$) at CT-S (mean concentration of 3.79 mg/L) than the three other fields. The lowest mean level was found at NT-C (2.51 mg/L).

For the SOM and NO_3, the lime-rich loamy fields under CT and NT had similar concentrations and patterns (figure 3). There was an overall positive correlation between SOM and soil NO_3, but this correlation was not evident when comparing between fields as there was an inverse relationship between the SOM and NO_3 levels, meaning that the fields with the highest SOM levels also had the lowest NO_3 levels. In contrast, the PO_4^{3-} concentrations were similar for the two Cotswold Brash fields and there was a greater variation between the two lime-rich loamy fields (figure 3). One possible explanation was the differences in pH between these fields, as the NT field had much lower pH (6.9) than the CT field (8.1), while the Cotswold Brash fields both had pH value of 8.1. Soil P cycles in various forms, both organic and inorganic, and PO_4 is the plant available form, and the soil pH is one of the determining factors for P availability. The lower pH of the NT lime-rich loamy field was more suited for P availability than the more alkaline pH found in the three other fields due to fixation by aluminium, calcium or iron, partly explaining the differences in PO_4^{3-} levels between the two lime-rich loamy fields.

The NO_3 form of N is crucial for plant growth but can cause pollution if leaching to ground- or surface-waters. The degree of NO_3 leaching varies with soil type, geomorphology and groundwater level (affecting oxygen concentrations and therefore denitrification losses), land use (affecting organic C contents and therefore denitrification), precipitation surplus (oxygen levels) and root depth (decreasing root depths increase the risk of leaching) (Velthof et al. 2007). Additionally, fertiliser applications (excess amounts are more likely to leach) and the retentive properties of the soil that are depending on soil texture, SOM and cation exchange capacity (Gaines and Gaines 1994) can influence NO_3 leaching.

The infiltration capacity of the soil depends on the porosity, which differs from one soil to another; loose sandy soils are associated with high infiltration rates, while heavy clay or loam soils often have smaller infiltration capacities. The lowest infiltration rates were found at NT-C (table 1), but readings were challenging during the spring because of crack formations in the soil (in both NT-C and CT-C). Low infiltration rates can contribute to increased NO_3 leaching as increased surface runoff is an important contributor to water pollution by NO_3. Erosion is however a lesser problem, in contrast to P losses, as N is more soluble than P and therefore more often transported with water than with particles.

Gaines and Gaines (1994) found that soils with higher levels of clay, silt and SOM retained more NO_3 than more sandy soils. Often the amount of N added by the farmers exceeds the amount that is taken up and removed by harvesting of crops and grazing by animals, leading to a N surplus that can be immobilized by the soil or lost to the environment through leaching or emissions (Galloway et al. 2003; Sutton et al. 2011). Velthof et al. (2007) found that parameters that increased the risk of N surface runoff were the weather conditions (heavy precipitation, snowmelt etc.), soil conditions (infiltration rates), fertilizer inputs, type of vegetation and length of growing season, type of tillage and slope steepness. The steepest fields in this study were the Cotswold Brash fields, but the rapid infiltration rates at these two fields were likely to prevent most of the NO_3 surface runoff. However, NO_3

leaching was more likely in these fields than on the poorly drained wet soils, but fields of high SOM content (NT-S) increases denitrification and can therefore decrease NO_3 leaching.

Significant NH_3 losses in the form of volatilization and gaseous emission is an important contributor to the overall N losses and occur especially after application of animal manure or mineral fertilizer applications to agricultural fields (Oenema et al. 2007). The elevated concentrations of NH_3 in NT-C and CT-S measured in May 2019 (figure 3c) was most likely the result of sheep grazing in these fields in the Spring of that year.

In-Field Variations

PCA analysis determined that the strongest quality representation related to sampling depth (figure 6), contributing more than 30% of the first dimension of explained variance. The correlogram showed a strong negative correlation with increasing sampling depth and SOM, soil moisture, NO_3 and PO_4^{3-}, although there is no correlation between NH_3 and soil depth. The differences with soil depth were significant in all four fields for SOM ($P = < 0.001$), NO_3 ($P < 0.001$) and PO_4^{3-} ($P < 0.01$), while significant for soil moisture in all fields apart from NT-C for ($P = < 0.001$) and only significant for NH_3 in NT-S and CT-C ($P < 0.01$). There were significant differences in SOM concentrations with time for all fields apart from CT-C, where there was an increasing trend in the Cotswold Brash fields (particularly for NT-S), while the values in NT-C experienced very little change over the sampling period. All fields apart from CT-S had significant changes in soil moisture with time ($P < 0.01$) with a declining trend particularly in the lime-rich loamy fields, probably as a result of the unusually dry weather in this part of the UK during the monitoring period that led to a serious water deficit. There were significant differences in NO_3 concentrations with time within all the fields ($P < 0.05$), with an increasing trend for the CT fields, while declining in NT-S. A similar increasing trend was found for NH_3 with significant differences in concentrations with time for all fields ($P < 0.001$), while the changes in PO_4^{3-} with time were significant ($P < 0.05$) for all fields apart from NT-S, increasing for the Cotswold Brash fields and slightly decreasing for CT-S.

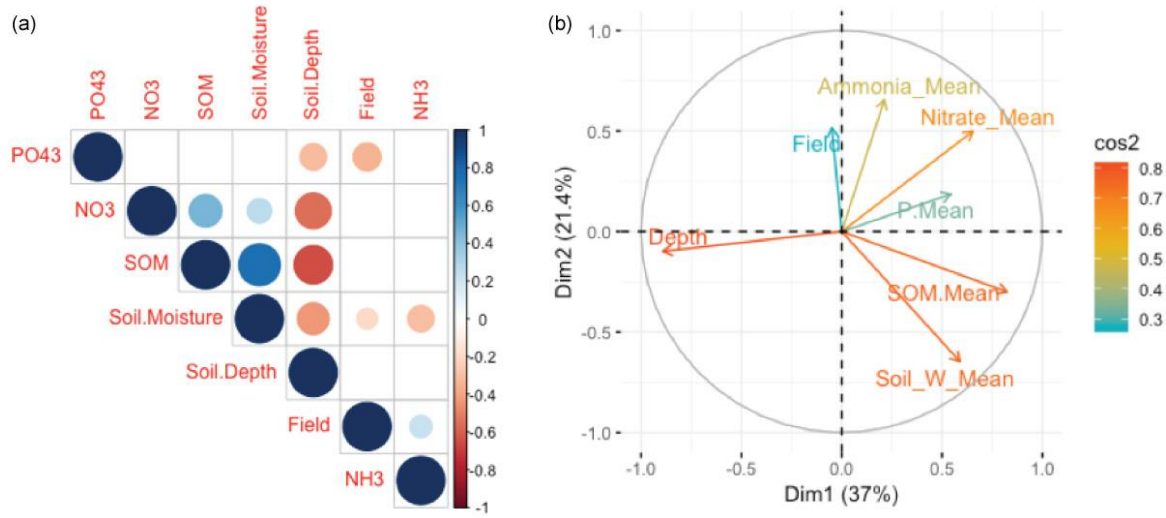

Figure 6 Results of the correlations between Phosphate (PO_4^{3-}), Nitrate (NO_3), Ammonia (NH_3), soil organic matter (SOM), soil moisture content, soil depth and the four different fields (field): (a) combined correlogram and significance test (insignificant values are left blank) and (b) the Principle Component Analysis (PCA) chart showing the direction and strength of correlations based on the two major principal components (Dim1 and Dim2).

Vertical Variability

The correlation between SOM, soil moisture, NO_3 and PO_4^{3-} with depth demonstrated by this study (figure 6) demonstrates the importance of considering sampling depth when collecting soil samples, and also when reporting the data. Figure 7 illustrates how NO_3 and PO_4^{3-} concentrations vary as you move deeper in the soil in the two Cotswold Brash fields (NT-S and CT-S), with a reduction in concentration as you move away from the soil surface. Our results demonstrate that samples should be collected from several depths, or as a mixed sample from the soil profile, as the distribution of nutrients varied with depth and this concentration varied between sites and temporally; for example in CT-S the highest concentrations of NO_3 were at 10 to 20 cm depth during the 2018 sampling but at 0 to 10 cm depth in Spring 2019 (figure 7b), whereas the highest concentrations in NT-S were consistently found at 0 to 10 cm depth (figure 7a).

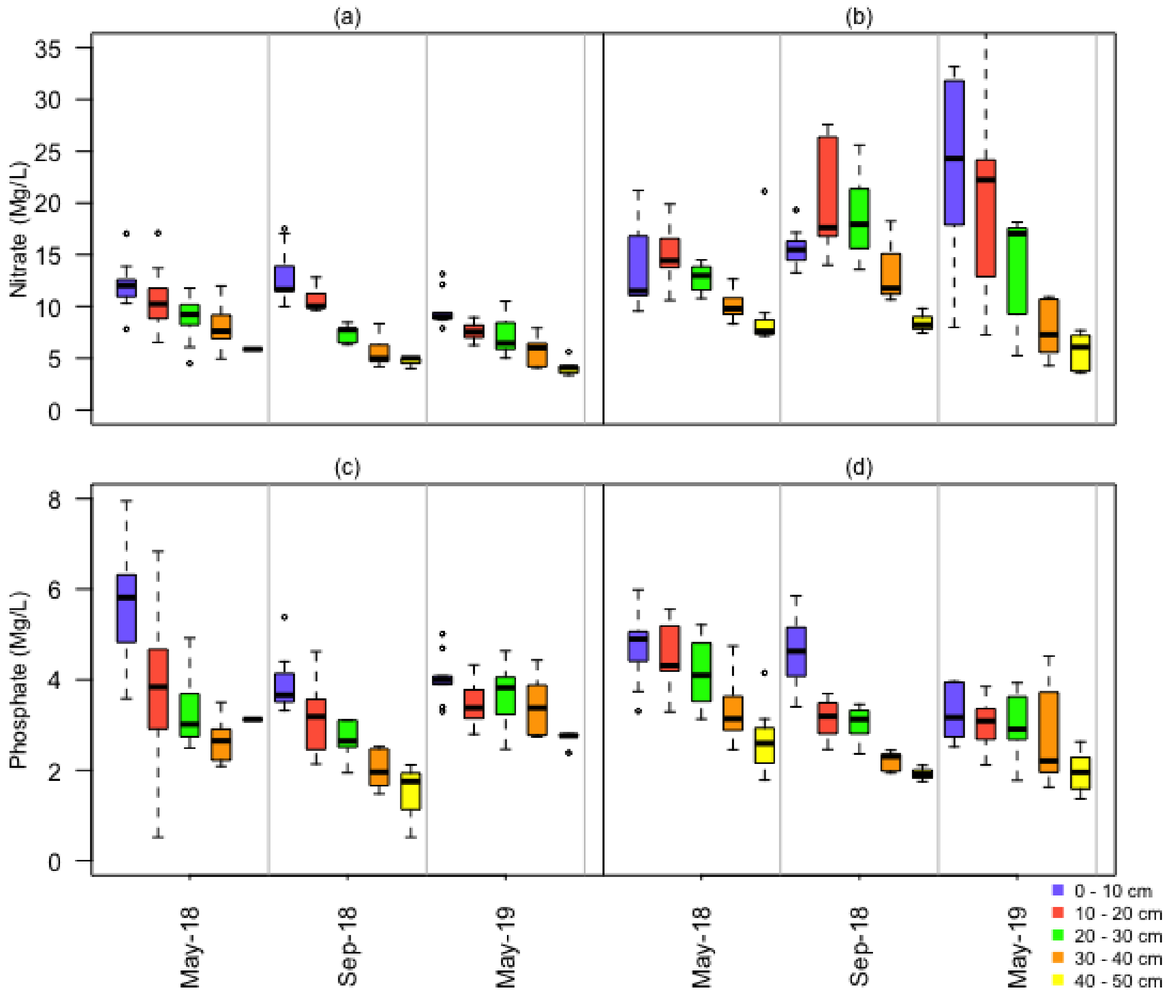

Figure 7 Soil Nitrate (NO_3) concentrations in (a) NT-S and (b) CT-S and soil Phosphate (PO_4^{3-}) concentrations at (c) NT-S and (d) CT-S showing mean values and 75% confidence intervals at different sampling depths (represented by the different colours; key provided above).

Spatial Variability

The second strongest quality representation in the PCA related to SOM levels, followed by NO_3, while NH_3 and soil moisture had the highest contributions to the second dimension (Dim2) (figure 6). The highest variance within fields of both SOM (NT-S = 3.71, CT-S = 2.68) and NH_3 (CT-S = 1.51 and NT-S = 1.28) were found in the two Cotswold Brash fields, while the highest NO_3 variance was found within the lime-rich loamy fields (NT-C = 4.88 and CT-C = 3.57). There were no such trends with soil type for the within field variation of soil moisture or PO_4^{3-}, but the largest heterogeneity was found within NT-C for both soil moisture (4.47) and PO_4^{3-} (12.86).

The findings of this study demonstrate the importance of considering spatial sampling intervals when collecting soil samples, and the significance of reporting on the sampling depth and also spatial variability across fields. Figure 8 demonstrates the variability in NO_3 concentrations across the four fields, there were a range of concentrations measured depending on the spatial position in each field, with those under CT having the greatest variance between sampling points (figures 8b and 8d). This highlights that one sampling point per field was not sufficient to determine the situation across a whole field, let alone over multiple fields that have different soil types, composition and management history. The number of samples required to accurately represent the area depends on the soil type, field size and the variable that is being measured. In accordance with other studies (Oorts et al. 2006; Hazarika et al. 2009; Ulrich et al. 2006) our results show that there was spatial variability across the fields for all of the variables that we monitored, but these were distributed differently dependent upon both soil type and farming practice, showing the absolute necessity of designing sampling regimes that were collecting soil from several depths and field locations. Soil analysis based on only one depth and one sampling location, as is often the case for the analysis carried out for farmers themselves (which they use to inform their management decisions), is problematic as it is revealing only a limited part of the in-field complexity and might give an incorrect picture of the field conditions. Knowledge about the soil heterogeneity of a field is crucial to determine the best location for sampling points, and at what spatial interval they should be collected.

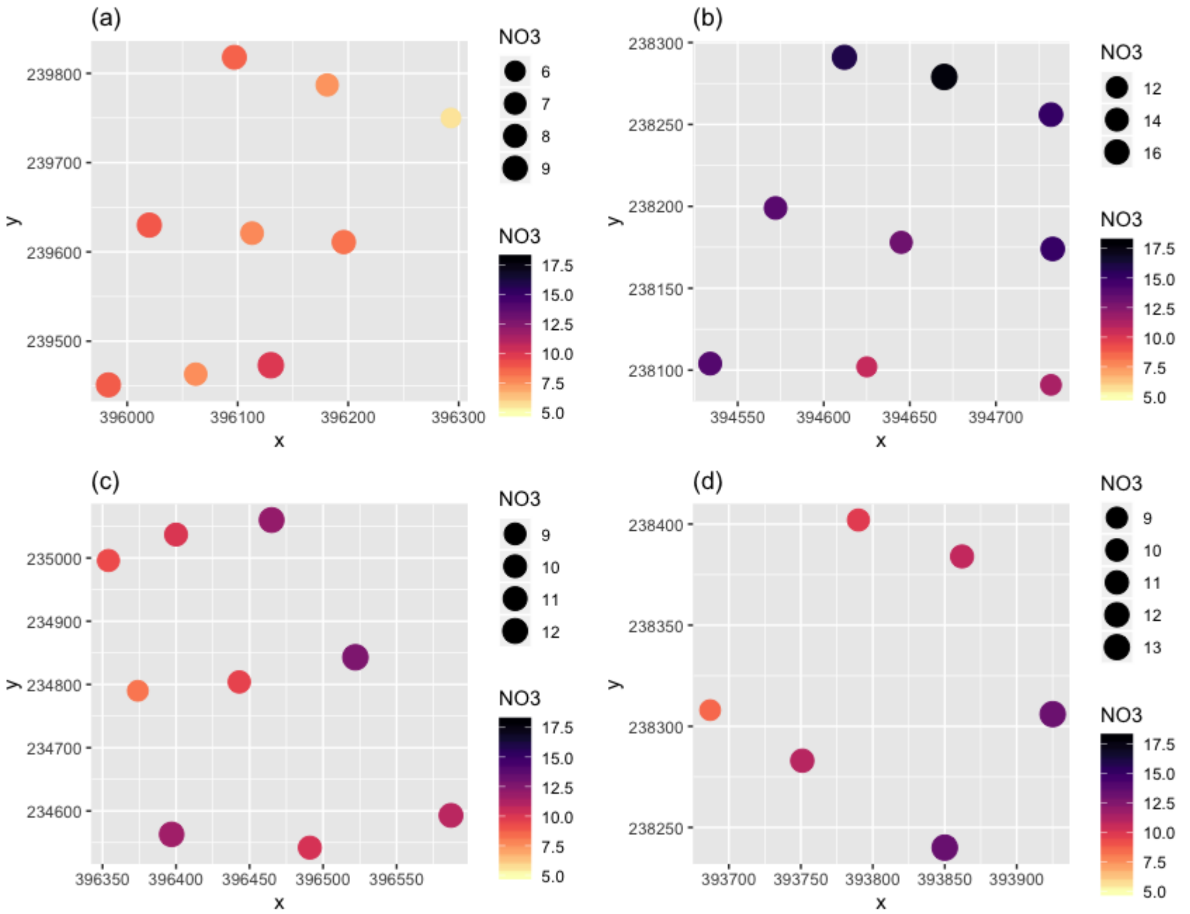

Figure 8 Spatial plot of field sampling locations illustrating variations in the mean values of Nitrate (NO_3 in Mg/L) concentrations across the four fields: (a) NT-S (variance of 1.47), (b) CT-S (variance of 4.88), (c) NT-C (variance of 2.06) and (d) CT-C (variance of 3.57). The colour scale shows the range of Nitrate values in general (to compare between fields), while the size scale specifies the actual range that the field is within.

Summary and Conclusions

This study aimed to assess the impact of NT and CT on soil chemical and physical processes and functions of two different soil types and determine their impact on water related soil functions at a field scale, and to investigate the in-field variability. The effects of NT and CT varied between the soil types and variance was often as high within the fields as between fields of different practice. Interestingly, the variables were often more similar between soil types although there were different farmers operating these fields that were using different farming systems.

Our study reveals the following:

1. The impact of NT on soil nutrients is complex. The increased plant material cover on the soil surface under NT increased the levels of soil PO_4^{3-} and led to the leakage of plant available PO_4^{3-} in surface runoff, thereby increasing the levels of P in watercourses in close proximity to NT fields. However, the higher SOM and soil moisture levels under NT can lead to higher denitrification rates and therefore reducing soil NO_3. There were no notable trends found in NH_3 concentrations between NT and CT.
2. The effect of NT on the SOM levels in this study are dependent on soil type, with higher concentrations in the Cotswold Brash field, indicating that there could be higher benefit in implementing NT on this type of coarse, free-draining, weaker-structured soil than the finer, low permeability soils with a stronger structure.
3. The importance of including soils of different characteristics, texture and mineralogy in the assessment of farming systems; highlighting the risk of applying 'catch-all' indicators and recommendations across soil types (Behrends Kraemer et al. 2019).
4. That consideration of spatial variability within fields, both horizontally and vertically, needs to be made when designing the sampling regime for monitoring. Farmer knowledge about the in-field soil conditions and heterogeneity could be particularly useful for this.

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