Conservation tillage and soil health: lessons from a 5-year UK farm trial (2013 – 2018)

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Abstract

In 2010, the UK government launched the Demonstration Test Catchments (DTC) platform to evaluate the extent to which on-farm mitigation measures can cost-effectively reduce the impacts of agricultural water pollution on river ecology whilst maintaining food production capacity. In this paper, we compare the impacts on soil health of two types of conservation tillage (direct drill and shallow non-inversion) against conventional mouldboard ploughing after five years (2013–2018) of adoption within the River Wensum DTC. Across the 143 ha conservation tillage trial area, temporal changes in the physical, chemical and biological condition of the soils were examined through the analysis of 324 soil samples, whilst the impacts on soil water chemistry were assessed through the analysis of 1176 samples of subsurface field drainage. Riverine water pollution was also explored through high-resolution (30 min) hydrochemistry measurements generated by an automated, *in-situ* bankside monitoring station located 650 m downstream of the trial area. Results revealed that conservation tillage did not significantly alter the soil physical, chemical or biological condition relative to conventional ploughing during the first five years. In addition, conservation tillage did not reduce nutrient leaching losses into field drainage and did not significantly impact upon river water quality, despite the trial area covering 20% of the catchment. Economically, however, conservation tillage yielded net profit margins 13% higher than conventional ploughing after five years of practice due to a combination of operational efficiency savings and improved yields. Overall, the results of this study demonstrate that conservation tillage alone is ineffective at improving the short-term environmental sustainability of farming practices in this lowland intensive arable setting and indicates that a broader, integrated approach to conservation agriculture is required incorporating aspects of cover cropping, crop rotations and precision farming techniques. The improvements in farm business performance do, however, demonstrate land managers can make important financial gains by converting to a conservation tillage system.

Keywords: reduced tillage; ploughing; water quality

1. Introduction

The Demonstration Test Catchment (DTC) platform was a UK government initiative funded by the Department for Environment, Food and Rural Affairs (DEFRA) working in four English catchments to evaluate the extent to which on-farm mitigation measures can cost-effectively reduce the impacts of agricultural water pollution on river ecology whilst maintaining food production capacity (McGonigle et al., 2014). Each DTC focused on a different type of farming system, namely, intensive arable (River Wensum DTC, Norfolk), upland livestock (River Eden DTC, Cumbria) and mixed farming (River Avon DTC, Hampshire; River Tamar DTC, Devon/Cornwall). This paper focuses on the intensive arable system of the River Wensum DTC, where monitoring of water quality and soil parameters commenced in April 2011 and now provides an invaluable record of baseline conditions before and after the implementation of mitigation measures since autumn 2013 (Cooper et al., 2018; Cooper et al., 2020). The measures implemented within the River Wensum DTC include a biobed to degrade waste pesticides (Cooper et al., 2016), constructed wetlands to capture sediment-rich road runoff (Cooper et al., 2019) and the extensive use of cover crops and conservation tillage practices to reduce nutrient leaching and improve soil health within a seven-year crop rotation (Cooper et al., 2017).

Conservation tillage, also known as non-inversion tillage or reduced tillage, is primarily employed to improve soil structure and stability (Holland, 2004; Lal et al., 2007; Skaalsveen et al., 2019). In conventional tillage systems, the soil is typically inverted to a depth of >20 cm using a mouldboard plough prior to secondary cultivation to create a seedbed into which the subsequent cash crop is sown (Morris et al., 2010). However, under conservation tillage systems the soil is either disturbed to a lesser degree (e.g. shallow non-inversion tillage to a depth of <10 cm using discs or tines) or not disturbed at all, with sowing occurring directly into the residue of the previous crop (e.g. direct drill) (Morris et al., 2010). By improving soil structure, these conservation tillage methods have previously been shown to reduce soil erosion, increase soil organic matter content, improve drainage and water holding capacity and increase microbial and earthworm activity (Abdollahi and Munkholm, 2014; Deasy et al., 2009; Soane et al., 2012). Non-inversion tillage methods also have the potential to improve farm economic performance by reducing fuel and labour costs associated with energy intensive deeper soil inversion approaches (Kassam et al., 2014; Townsend et al., 2016).

However, reducing the intensity of tillage is not universally beneficial. The lack of soil inversion can lead to compaction of the soil surface, increased insect and weed pest populations and an accumulation of nutrients near the soil surface which can be readily mobilised by surface flows and thus pose a risk to freshwater environments (Bertol et al., 2007; Holland, 2004; Skaalsveen et al., 2019; Stevens and Quinton, 2009). There is also evidence that conservation tillage may deleteriously impact upon crop yields due to sub-optimal seedbed preparation (Van den Putte et al., 2010).

Despite there being considerable uncertainty concerning the comparative advantages and disadvantages of conservation tillage practices relative to conventional ploughing, Farm Business Survey data from 2010 indicate that conservation tillage was already a fairly common practice across the UK a decade ago, with 32% of arable land established under non-inversion tillage practices and 46% of farms adopting some form of reduced tillage (Townsend et al., 2016). Adoption of conservation tillage practices more widely across Europe is, however, substantially lower than occurs across the United States, Brazil and Australia, where it has historically been adopted to tackle severe soil erosion (Lahmar, 2010). Hence, improving our understanding of the impacts on long-term soil health and the environment is of the upmost importance if conservation tillage is to be incentivised under future agri-environment schemes in the UK.

In this paper, we review the impacts of conservation tillage on soil health after five years (2013–2018) of adoption within the River Wensum DTC, examining temporal changes in the physical, chemical and biological condition of the soils as well as exploring the impacts on soil water chemistry and riverine water pollution. Additionally, we discuss the agronomic lessons learnt through transitioning from a plough-based to reduced cultivation-based farming system across a large (2500 ha) commercial arable estate, considering both the economic and land management implications for the farmer. The outputs of this research are relevant to future government agri-environmental policy in the UK for arable landscapes.

2. Methods

2.1 Study Location

The River Wensum DTC was based upon the large (25 km^2) commercial Salle Park Estate located within the Blackwater Drain sub-catchment of the lowland calcareous River Wensum, UK (52^{o}47’14”N, 01^{o}08’14”E; **Figure 1**). Topographically, the Blackwater Drain is ideally suited to arable farming, being 30-50 m above sea level and having gentle slopes that rarely exceed 0.5^O of inclination, meaning that subsurface leaching rather than surface runoff is the dominant pollution pathway. Intensive arable cropping comprises 79% of the land use on the Salle Park Estate and is managed with a seven-year rotation (**Table 1**) of winter wheat (*Triticum aestivum*), winter and spring barley (*Hordeum vulgare*), winter oilseed rape (*Brassica napus*), spring beans (*Vicia faba*) and sugar beet (*Beta vulgaris*). The estate also includes 15% improved grassland, 5% mixed woodland and 1% rural settlements.

The western side of the study area (incorporating the fields Far Hempsky, Middle Hempsky, First Hempsky, Potash, Dunkirk and Moor Hall Field) is underlain by a complex sequence of Mid-Pleistocene chalky, flint-rich, argillaceous glacial tills of the Sheringham Cliffs (0.2 – 7 m depth) and Lowestoft (8 – 16 m depth) Formations, with interdigitated bands of glaciofluvial and glaciolacustrine sands and gravels. In turn, these are superimposed onto the quartzite-rich marine sands and gravels of the Lower Pleistocene Wroxham Crag Formation (16 – 22 m depth), which overlies the Cretaceous Chalk (>22 m depth). The soils in this western section are predominantly clay loams of the argillic brown earths (Freckenham series) and stagnogley (Beccles series) groups which, together with the argillaceous tills, result in moderately impeded drainage conditions (Cooper et al., 2018; Hiscock et al., 1996). Most of the arable land in this western section is therefore extensively under-drained by a dense network (43 outflows per km of river) of plastic and concrete agricultural field drains installed in a herringbone layout at depths of 1.0–1.5 m during numerous phases of land drainage over past decades. Drain flow rates vary depending on antecedent conditions, but most drains flow between October and March at discharges of up to 10 L s^{-1}, with limited flow during April to September.

In contrast, the eastern section (incorporating the fields Swanhills, Gatehouse Hyrne and Sheds Field) is more freely draining with sheets of glacial outwash sands and gravels of the Mid-Pleistocene Briton's Lane Formation (0.2–7 m depth) overlying the clay-rich Bacton Green Till Member (6–10 m depth). As with the western section, Sheringham Cliffs Formation tills are present containing interdigitated higher permeability glaciolacustrine sands (8–10 m). Underlying this is a comparatively thin layer of chalky, argillaceous till of the Lowestoft Formation (10–12 m depth), which in turn overlies glaciofluvial, glaciolacustrine and glaciogenic sands, gravels and tills of the Happisburgh Formation (12–17 m depth). Lastly, as in the western section, the Wroxham Crag Formation (17–22 m depth) overlies Cretaceous Chalk (>22 m depth). The soils in the eastern section are predominately freely draining, sandy loams of the brown sands (Hall series) and brown earth (Sheringham series) groups and consequently artificial land drainage is less extensive (Cooper et al., 2018).

The site experiences a temperate maritime climate, with a mean annual temperature of 10.1^{o}C and a mean annual precipitation total of 680 mm observed during the study period (2011-2018). Precipitation, air temperature and net solar radiation for the study period were recorded at 30-min resolution by a weather station located in the Swanhills field (**Figure 2**).

2.2 Experimental Design

Working across nine fields covering 143 ha of arable land, three contrasting tillage regimes were established in September 2013 (**Figures 1 & 3**):

- **Block J**: conventional mouldboard ploughing to 25 cm depth (42 ha);
- **Block P**: shallow non-inversion to 10 cm depth using discs and tines (52 ha);
- **Block L**: direct drill with zero inversion using a direct drill (53 ha).

All three of the blocks were in a rotation of spring beans (2013/14), winter wheat (2014/15), winter barley (2015/16), oilseed rape (2016/17) and winter wheat (2017/18). To minimise the risk of background variability in soil conditions and historic cultivation practices masking the impacts of the trial, each block contained a similar range of soil textures and historically had been managed with the same seven-year crop rotation since 1993, meaning that all blocks were subjected to comparable agrochemical inputs and organic amendments **(Table 1)**. The impact of the tillage regimes was assessed by regular monitoring of soil properties at four locations within each field (4 locations x 9 fields = 36 sites in total), whilst the assessment of nutrient losses from each block was determined through monitoring of field drain outflows. Note, that for farm operational reasons, Block J underwent shallow non-inversion tillage in 2017/18 instead of mouldboard ploughing.

In addition to the conservation tillage trial, a cover crop trial was also conducted in 2013/14 on the same nine fields. Block J was managed by usual farm practice and left in cereal stubble (i.e. fallow) over winter until the sowing of the spring bean crop in March 2014. Conversely, Blocks P and L were sown with an oilseed radish (*Raphanus sativus*) cover crop in late August 2013 which was grown through to mid-January 2014 when it was destroyed with glyphosate herbicide in preparation for spring bean sowing.

2.3 Soil Sampling and Analysis

Soils in Blocks J, P and L were sampled for nutrients and physical properties on nine occasions between September 2013 and August 2018, with sampling carried out in spring (February/March) and post-harvest (July - November) each year. Samples were taken from four locations within each field, with the locations selected to capture the full range of textural variability (**Figure 1 & Figure S1**). Samples were collected from the topsoil layer (0–30 cm depth) at 12 points around each sampling location using a Dutch auger, with these 12 samples combined to produce one bulked soil sample for each sampling location. In total, 36 bulked samples were collected on each occasion (i.e. 9 fields x 4 locations). All soil samples were placed into air-tight polyethylene bags and kept in cold storage (4^{o}C) until analysis by NRM Laboratories.

For the analysis, all soil samples were air-dried, chopped, mixed and sieved to 2 mm. Soil nitrate (NO_3-N) concentrations were determined colorimetrically after shaking a fresh portion of each sample with 2 mol potassium chloride (KCl) to extract the mineral N fractions and reacting with sulphanilamide ($C_6H_8N_2O_2S$) and *n*-(1-Naphthyl)ethylenediamine ($C_{12}H_{14}N_2$). Olsen's available phosphorus (P) was also determined colorimetrically after shaking a portion of air-dried soil with 0.5 mol sodium bicarbonate ($NaHCO_3$) solution and adding ammonium heptamolybdate ($(NH_4)_6Mo_7O_{24}$) and ascorbic acid ($C_6H_8O_6$). Soil potassium (K) and magnesium (Mg) concentrations were determined by flame photometry and atomic absorption spectroscopy, respectively, after shaking the soil with ammonium nitrate (NH_4NO_3) for 30 minutes to extract available K and Mg. Soil sulphate (SO_4) concentrations were determined by ICP-ES after extracting SO_4 using a phosphate buffer solution at a ratio of 1:2. Soil respiration rates were determined by CO_2 burst test, whereby the air-dried soil was moistened with deionised water to achieve 50% water-filled pore space to trigger microbial respiration and a burst of CO_2 production which was measured on a Solvita Digital Color Reader (DCR). Soil organic matter (SOM) content was determined by loss-on-ignition (430^{o}C).

Soil bulk density at 0-12 cm depth was determined gravimetrically by weighing a known volume (942 cm^3) of soil after oven drying at 105^{o}C for 48 hours.

2.4 Earthworm Population Survey

As a measure of soil biological health, earthworm populations were assessed across the three cultivation blocks on five occasions between 2016 and 2018, with all counts being conducted in either spring (March – May) or autumn (September – October) when soils were warm and moist and earthworm activity was expected to be higher. At each of the four soil sampling locations within each field, one spade depth and width of soil (0.02 m^3) was dug up and dissected to locate the earthworms. All worms found were counted and weighed before being returned to the soil. For consistency across blocks, all fields were sampled on the same day within a four hour window to minimise weather related bias. No species level identification was carried out and thus some deeper burrowing Anecic species may not have been captured by this method.

2.5 Field Drain Sampling and Analysis

Grab samples (1 L) of soil water were collected from the outflows of 10 subsurface field drains at 100-150 cm depth across the trial area at approximately weekly intervals between October and March each year (**Figure 1**). Drain flow rates (L s^{-1}) were also recorded at the time of sampling. Of these 10 drains, eight under-drained clay and clay loam soils, while just two under-drained sandy loam soils, reflecting the reduced requirement for artificial drainage under higher permeability soils.

Field drain nitrate (NO_3-N) concentrations were determined by ion chromatography using a Dionex ICS-2000 in the UEA analytical facilities laboratory. A sodium nitrate ($NaNO_3$) standard (0.50–7.50 mg L^{-1}) was used for calibration. Instrument accuracy (< 0.2 mg L^{-1}) was determined by analysing a certified reference material (NO_3^- = 13.3 mg L^{-1}) with each sample batch. Phosphate (PO_4-P) and total phosphorus (TP) concentrations were determined colorimetrically (molybdate) using a Skalar SAN++ continuous flow analyser. A potassium dihydrogen orthophosphate standard (KH_2PO_4; 10–500 µg L^{-1}) was used for calibration. Instrument accuracy for PO_4-P (< 7.8 µg L^{-1}) and TP (< 9.8 µg L^{-1}) were determined by analysis of certified reference materials (P = 78.0–97.4 µg L^{-1}) with each batch.

2.6 Riverine monitoring

To assess the impact of conservation tillage on nutrient concentrations in the Blackwater Drain, an automated bankside monitoring station located 650 m downstream of the trial area analysed a range of water quality parameters at 30-min resolution throughout the study period (**Figure 4**). NO_3-N concentrations were measured by a Hach Lange Nitratax SC optical probe, whilst total reactive phosphorus (TRP) and total phosphorus (TP) concentrations were measured by a Hach Lange Sigmatax SC coupled with a Phosphax Sigma. These analyses were supplemented for quality control by weekly grab sampling of the river at the same location prior to analysis in the laboratory following the same procedure described for the field drain samples (**Section 2.6**). River stage was determined by a pressure transducer housed in a stilling well and was converted to discharge using a manual stage-discharge rating curve. The tillage trial area (143 ha) occupied 20% of the catchment area (714 ha) upstream of the monitoring station. Further details of the riverine monitoring are provided in Outram et al. (2016) and Cooper et al. (2018).

3. Results & Discussion

3.1 Soil Physical Properties

Soil bulk density can be used as a measure of soil compaction and it therefore provides a useful indicator of soil physical condition. Previous studies of conservation tillage systems have found that soil compaction can become an issue if the soil surface is not regularly inverted through mouldboard ploughing (Abdollahi et al., 2014; Munkholm et al., 2003; Peigné et al., 2013). Soil bulk density on the Salle Park Estate was therefore monitored over the duration of the five-year cultivation trial to determine if there was any evidence of soil compaction on the conservation tillage Blocks L and P (**Figure 5**).

Bulk density time series reveal that all three blocks exhibited similar temporal variability in density, with no single block showing divergence in values based on cultivation type. In particular, bulk density values under direct drill did not increase over the five years of the trial, with average bulk densities actually lower in 2018 (1.44 g cm^3) than in 2013 (1.57 g cm^3). Average bulk densities over the whole period were significantly ($p < 0.05$) lower under plough (1.41 g cm^3) compared to shallow non-inversion (1.48 g cm^3) and direct drill (1.53 g cm^3), although this difference can largely be explained by Block J soils being slightly richer in low-density clay soils than the other two blocks (**Figure S1**), rather than this difference being due to cultivation technique (note that bulk density was lower on Block J at the start of the trial).The biggest temporal change in bulk density can be seen in summer 2017 after the oilseed rape harvest, with the reduced compaction here providing evidence of the dense oilseed rape root network loosening up the top 30 cm of soil, thus reducing its density.

Overall, it can be concluded that reduced cultivation systems have not deleteriously impacted upon the soil physical properties during the first five years of the trial, whilst acknowledging that other physical properties (e.g. aggregate stability, penetration resistance, particle size distribution) were not assessed during this study. It can also be concluded (**Figure 5**), that soil bulk density was not significantly reduced during the cover crop trial, despite previous research indicating that cover crops can help alleviate issues of soil compaction caused by reduced tillage practices (Skaalsveen et al., 2019). Note, however, that these results are for the 0-12 cm depth of topsoil and do not consider potential compaction deeper within the soil profile.

3.2 Soil Chemistry

3.2.1 Nitrogen

Previous studies have shown that conservation tillage can lead to an accumulation of nutrients at the soil surface as they are not incorporated deeper within the soil profile by inversion during mouldboard ploughing (Abdollahi and Munkholm, 2014; Shao et al., 2016). Evidence of higher topsoil nutrient concentrations on the conservation tillage blocks was therefore expected compared to plough. However, **Figure 5** shows that soil nitrate concentrations exhibit very similar temporal variability across all blocks during the five year trial, with no evidence that nutrients were accumulating at the soil surface under either direct drill or shallow non-inversion tillage methods. The high nitrate concentrations recorded in March 2017 reflect the high N fertiliser input to oilseed rape. Average soil nitrate concentrations across the whole period were 20.9 kg N ha^{-1} under plough, 17.9 kg N ha^{-1} under direct drill and 17.7 kg N ha^{-1} under shallow non-inversion, with no statistically significant difference ($p > 0.05$) between the blocks.

3.2.2 Phosphorus

Available phosphorus concentrations (**Figure 5**) in the upper 30 cm of soil were elevated under both direct drill and shallow non-inversion relative to plough. Average soil available P concentrations across the whole period were 83 kg P ha^{-1} under direct drill, 75 kg P ha^{-1} under shallow non-inversion and 54 kg P ha^{-1} under plough, although these differences were not significant ($p > 0.05$). However, it appears this pattern reflects the influence of increased nutrients available under the cover crop fields rather than the tillage regimes themselves, with the greatest difference between blocks occurring during the cover crop trial in 2013/14. In subsequent years, the temporal variability in available phosphorus was similar and differences in mean concentration were reduced to the point that by August 2018 there was negligible difference between blocks.

3.2.3 Magnesium and Potassium

Concentrations of available soil magnesium and potassium display almost identical temporal variability to that measured for phosphorus (**Figure 5**), with concentrations in all blocks peaking during the 2013/14 cover crop year and subsequently declining by ~60% by 2017/18.

Average soil available potassium concentrations across the whole period were 340 kg K ha^{-1} under direct drill, 331 kg K ha^{-1} under shallow non-inversion and 274 kg K ha^{-1} under plough ($p > 0.05$). For soil available magnesium, average concentrations across the whole period were 163 kg Mg ha^{-1} under plough, 141 kg Mg ha^{-1} under direct drill and 139 kg Mg ha^{-1} under shallow non-inversion, with these difference again being insignificant ($p > 0.05$).

3.2.4 Sulphate

Soil sulphate, in contrast, displayed more comparable temporal trends to soil nitrate, with the highest concentrations recorded during 2017/18 (**Figure 5**). Again, however, all three blocks displayed very similar temporal variability with no significant difference between the contrasting cultivation regimes. Average sulphate concentrations were 46 kg S ha^{-1} under plough, 40 kg S ha^{-1} under direct drill and 39 kg S ha^{-1} under shallow non-inversion ($p > 0.05$).

Overall, it can therefore be concluded that conservation tillage did not significantly alter soil nutrient concentrations relative to conventional ploughing during the five year trial. It can also be concluded that the presence of a cover crop had more influence on soil nutrient status than tillage regime.

3.3 Soil Biology

3.3.1 Soil Organic Carbon (SOC)

Soil organic carbon is important for providing both structural stability and fertility to soils and is therefore essential in supporting crop yields (Lal, 2006; Lehmann and Kleber, 2015). Increasing organic matter content within the soil can also help to sequester CO_2 from the atmosphere and mitigate climate change impacts (Lal, 2004, 2008). However, soil organic carbon contents are historically low across the Salle Park Estate and more widely across southeast England, with concentrations routinely falling below 2%. Thus, sustainable long-term functioning of soils cannot be maintained without significant organic and inorganic amendments. Previous research of conservation tillage has indicated that SOC contents increase under no-till systems due to both the retention of crop residues on the soil surface and due to the reduced exposure of soil organic matter to oxygen, which thereby restricts respiration and conversion of soil carbon to CO_2 (Baker et al., 2007; Balesdent et al., 2000; Ulrich et al., 2006).

In contrast to these previous studies, however, the plough block (2.2%) had significantly ($p < 0.01$) higher mean SOC content than either shallow non-inversion (1.9%) or direct drill (1.7%), whilst the plough block also experienced the largest relative increase in SOC content over the duration of the study at 25%, compared to 11% under shallow non-inversion and 21% under direct drill (**Figure 6**). Whilst these results appear counter-intuitive, it should be noted that Block J had the highest SOC content prior to commencement of the trial in 2013 which likely reflects the higher clay content of this block compared to Blocks P and L. With all blocks following a consistent upward temporal trend due to a consistent annual increase in organic fertiliser amendments (turkey manure) across all fields, it can be concluded overall that conservation tillage did not significantly improve SOC contents during the first five years of adoption.

3.3.2 Soil Microbial Respiration

As an indicator of soil microbial activity, a CO_2 burst test was also conducted to measure soil respiration rates across the blocks (**Figure 6**). Similar to SOC content, all three blocks experienced an increasing trend from 2015, with CO_2 production increasing by 503% under plough, 502% under shallow non-inversion and 640% under direct drill. Whilst these results indicate that rates have improved the most under direct drill, mean CO_2 production rates over the whole period were not significantly different between blocks (p >0.05), with 88 mg kg^{-1} under direct drill, 89 mg kg^{-1} under shallow non-inversion and 97 mg kg^{-1} under plough.

3.3.3 Earthworm Populations

Earthworm populations can provide a useful indicator of overall soil biological health. Previous studies have found that deep mouldboard ploughing of the soil can detrimentally impact upon earthworm populations because the plough both destroys the worms' habitat and directly kills them as the soil is cut and inverted (Crotty et al., 2016; Peigné et al., 2009; Piron et al., 2017; Ulrich et al., 2006). In theory, therefore, earthworm populations should increase over time under conservation tillage systems.

However, across the cultivation blocks there was considerable spatial and temporal variability in earthworm populations, with average earthworm counts ranging from a low of 5.8 worms per 0.02 m^{-3} of soil in September 2016 under shallow non-inversion, to a high of 27.4 worms per 0.02 m^{-3} of soil in March 2017 under plough (**Figure 6**). Across the whole period, average populations were higher under plough (20.1 worms per 0.02 m^{-3}) than under direct drill (16.2 worms per 0.02 m^{-3}) or shallow non-inversion (13.3 worms per 0.02 m^{-3}), although these differences were not statistically significant ($p > 0.05$).

When worm counts were analysed by soil textural class (**Figure 6**), the results revealed earthworm populations to be higher under plough in clay loam, sandy loam and sandy silt loams soils. Only in sandy clay loam soils were populations higher under the conservation tillage systems. This finding is in contrast to the expected outcome and further research is needed to understand exactly why earthworms do not appear to be benefiting from reducing tillage intensity after five years. Overall, the soil biological analyses reveal that conservation tillage has not significantly improved soil biology compared to conventional ploughing.

3.4 Water Quality

3.4.1 Field Drainage

A key aspect of the cultivation trial was to assess whether conservation tillage could reduce nutrient leaching losses from arable land into the neighbouring Blackwater Drain and thus help mitigate eutrophication in the main River Wensum. Previous studies have generally reported a negligible to small increase in nutrient leaching under conservation tillage due to the improved soil structure enhancing infiltration (Hansen et al., 2015; Oorts et al., 2007; Skaalsveen et al., 2019). Nutrient accumulation at the soil surface due to decomposing crop residues can also lead to enhanced leaching through the soil profile as well as elevating surface runoff risk under conservation systems (Schoumans et al., 2014; Ulén et al., 2010). This contrasts strongly with cover crops which have been widely shown to significantly reduce nutrient leaching losses (Cooper et al., 2017; Stevens and Quinton, 2009).

On the Salle Park Estate, the concentrations of dissolved nitrate recorded in field drain outflows at depths of 100-150 cm beneath the three trial blocks between February 2013 and February 2019 are shown in **Figure 7**. The greatest distinction between blocks occurred during the first cover crop trial (2013/14) when nitrate leaching losses were 75% lower under shallow non-inversion with a cover crop (Block P) and 88% lower under direct drill with a cover crop (Block L), than under plough and left fallow (Block J) (Cooper et al., 2017). Ignoring this cover crop year, during the subsequent four years when only conservation tillage was trialled, mean nitrate concentrations in the field drainage were significantly lower under plough (3.3 mg N L^{-1}), than under direct drill (5.4 mg N L^{-1}) and shallow non-inversion (5.8 mg N L^{-1}), confirming the results of previous studies. During this same period, the EU Drinking Water Directive (98/83/EC) standard of 11.3 mg N L^{-1} was exceeded just 1.1% of the time under plough, 7.2% of the time under shallow non-inversion and 11.6% of the time under direct drill.

The greatest contrast between blocks occurred during winter 2017/18 when nitrate concentrations were 6–9 times higher under conservation tillage than plough. In part, this difference can likely be explained by soils in Block J having a higher clay content (**Figure S1**) which increases the likelihood of water-logged soils developing, reducing oxygenation and thus promoting nitrate reduction conditions (i.e. denitrification) within the soil profile.

With respect to phosphorus, leaching into field drainage was consistently low across the entire monitoring period with concentrations in all three blocks rarely exceeding the UKTAG Water Framework Directive standard of 70 μg P L^{-1} for 'good' status (UKTAG, 2013). Excluding the cover crop year, mean total phosphorus concentrations were 15 μg L^{-1} under plough (2.4% exceedance), 14 μg P L^{-1} under shallow non-inversion (0.9% exceedance) and 17 μg P L^{-1} under direct drill (1.2% exceedance), with no significant difference between blocks.

3.4.2 Blackwater Drain

Ultimately, the primary purpose of the River Wensum DTC project was to evaluate the extent to which on-farm mitigation measures could cost-effectively reduce the impacts of agricultural water pollution on river ecology. River water quality 650 m downstream of the trial area was therefore monitored continuously at 30-minute resolution throughout the duration of the tillage trial to assess the impact of conservation tillage on nutrient concentrations in the Blackwater Drain (**Figure 8**).

Riverine nitrate concentrations were found to display a strongly seasonal pattern, with high concentrations observed during the winter (October to March) and low concentrations during the summer (April to September). This principally occurs because arable fields have limited vegetation to protect the soil surface during the winter and few opportunities for plants to take up excess soil nitrogen. Winter rainfall can therefore readily leach nitrate into the shallow groundwater from where it discharges into the river, either through the subsurface agricultural field drains or via upwelling through the riverbed (Di and Cameron, 2002; Outram et al., 2014). During the spring and summer, the reverse situation occurs. Rapidly growing crops within the fields take up excess nitrate and assimilated it in the form of organic nitrogen, thus leaving little residual nitrate within the soil to be leached into groundwater. However, this is not always the case as large summer storm events can flush nitrate through the river system, displacing nitrate stored within the catchment during the preceding months of lower flow conditions and resulting in large spikes in riverine nitrate concentration (**Figure 8**).

Despite this considerable temporal variability, there is no evidence to indicate a reduction in nitrate concentrations within the Blackwater Drain over the duration of the study. Mean farm year (September – August) nitrate concentrations recorded since one year prior to the tillage trial commenced were 6.8 mg N L^{-1} (2012/13), 7.3 mg N L^{-1} (2013/14), 5.9 mg N L^{-1} (2014/15), 5.8 mg N L^{-1} (2015/16), 5.9 mg N L^{-1} (2016/17) and 8.4 mg N L^{-1} (2017/18). Similarly, exceedance frequencies of the EU Drinking Water standard (11.3 mg N L^{-1}) for the same period were 1.5% (2012/13), 10.0% (2013/14), 1.5% (2014/15), 1.0% (2015/16), 1.3%

(2016/17) and 26.7% (2017/18), again highlighting that nitrogen enrichment has not been reduced by conservation tillage.

In contrast to temporal trends in nitrate concentration, total phosphorus concentrations (**Figure 8**) in the Blackwater Drain display no obvious seasonality. Instead, phosphorus displays a highly flashy response with concentrations strongly linked to individual rainfall events. This difference in behaviour can be explained by the majority of phosphorus existing in particulate form through sorption with clay minerals in soils and sediments (Cooper et al., 2015), meaning that phosphorus is predominantly mobilised via surface runoff pathways rather than leaching through the soil profile. Consequently, riverine phosphorus concentrations peak when there has been sufficient rainfall to trigger soil erosion and/or the movement of sediments stored upon the riverbed (Dupas et al., 2015a; Dupas et al., 2015b).

Whilst some studies have reported increased riverine phosphorus concentrations under conservation tillage due to an accumulation of readily mobilised phosphorus at the soil surface (Kelly et al., 2019), no robust evidence for this was found in the Blackwater Drain. Mean farm year total phosphorus concentrations recorded since one year prior to the tillage trial commenced were 93 μg L^{-1} (2012/13), 78 μg L^{-1} (2013/14), 66 μg L^{-1} (2014/15), 97 μg L^{-1} (2015/16), 72 μg L^{-1} (2016/17) and 59 μg L^{-1} (2017/18). Similarly, exceedance frequencies of the UKTAG WFD '*good'* status of 70 μg L^{-1} (UKTAG, 2013) for the same period were 76.9% (2012/13), 50.0% (2013/14), 21.0% (2014/15), 38.3% (2015/16), 37.4% (2016/17) and 14.0% (2017/18).

Overall, the results of the riverine monitoring reveal that conservation tillage has not significantly impacted upon water quality within the Blackwater Drain, this despite the tillage trial area covering 20% (143 ha) of the catchment upstream of the bankside monitoring station (714 ha). The lack of sensitivity of riverine nitrate and phosphorus concentrations to changing land management practices is consistent with the results of other studies which have linked this to 'noise' caused by inter-annual hydroclimatic variability (Dupas et al., 2016) as well as to biogeochemical stationarity (Outram et al., 2016). This is a concept where, as a consequence of decades of intensive fertiliser application, there exist legacy stores of nutrients within the catchment soils and sediments which act to buffer riverine nutrient concentrations from changes in land management. This suggests that a sustained effort is required to reduce nutrient loading into the Blackwater Drain and the River Wensum in order to meet good water quality standards, especially for phosphorus.

3.5 Farm Economics

A central component of the DTC platform was that all on-farm mitigation measures should be "cost-effective" and "maintain food production capacity" in order to ensure that they are economically viable and financially competitive with traditional farm practice. Failing to meet these criteria would make these measures unattractive to land managers and thus limit widespread adoption. Previous research has indicated that lower operational costs of conservation tillage systems associated with reduced fuel and labour requirements could increase farm profit margins by £10–85 ha^{-1} compared with more labour- and energy-intensive conventional mouldboard ploughing (Deasy et al., 2009; Morris et al., 2010; Townsend et al., 2016).

Here, during the first three years of the trial (2013/14 to 2015/16), operational savings in the conservation tillage blocks were offset by increased costs associated with additional fertiliser and pesticide applications (**Table 2**). This was particularly true under direct drill, where surface crop residues harboured larger slug populations which necessitated increased molluscicide applications. Excluding the 2013/14 farm year during the cover crop trial, the mean establishment, application and harvesting costs in 2014/15 and 2015/16 were £673 ha^{-1} under plough, £682 ha^{-1} under shallow non-inversion and £693 ha^{-1} under direct drill. However, these costs became more favourable for the conservation tillage systems in 2016/17 and 2017/18, when improved management of crop residues through additional mulching reduced slug populations and thus reduced the requirement for additional pesticide applications. During 2016/17 and 2017/18, the mean total costs were £683 ha^{-1} under plough, £659 ha^{-1} under shallow non-inversion and £650 ha^{-1} under direct drill, thus representing a ~£30 ha^{-1} efficiency saving for conservation tillage. The largest differences in total cost occurred during the cover crop year (2013/14) when establishment and destruction costs for the winter cover crop increased total costs on Blocks P and L (**Table 2**).

With respect to crop yields, shallow non-inversion tillage generated the highest mean output over the five year trial at £1529 ha^{-1}, with mean outputs 4% higher than observed under either direct drill (£1471 ha^{-1}) or plough (£1473 ha^{-1}) (**Table 2**). Conservation tillage generated the greatest yield benefits during 2013/14 when combined with cover crops to produce an 8-13% yield increase relative to conventional ploughing, whilst a 6-7% yield increase over plough was also achieved in the 2017/18 winter wheat crop. The lower yields under direct drill in some years can partly be explained by the sandier soil type on Block L being favourable for winter barley (2015/16), but not winter wheat (2014/15) or oilseed rape (2016/17).

Overall, mean net profit margins over five years were highest under shallow non-inversion tillage (£843 ha^{-1}), followed by conventional ploughing (£813 ha^{-1}) and direct drill (£793 ha^{-1}) (**Table 2**). Shallow non-inversion tillage therefore yielded a minor (+4%) improvement in economic performance relative to the plough-based system. Importantly, a larger 13% increase in net profits was recorded under both conservation tillage methods in 2017/18, reflecting the improved performance of crop and soil management during the later years of the trial as the farmers gained more experience with the conservation tillage methods.

3.6 Agronomic Issues

A number of agronomic issues arose during the trial on the Salle Park Estate. Chief among these was the elevated slug populations under direct drill, where accumulations of crop residues on the soil surface provided optimal feeding and breeding conditions. This problem was particularly prevalent during the 2013/14 cover crop trial that left large quantities of fresh organic matter on the soil surface which proved difficult for both the direct drill (Väderstad Seed Hawk) and shallow non-inversion tillage (Väderstad Rapid) machinery to handle. This necessitated additional molluscicide applications (metaldehyde) to the conservation tillage blocks, increasing the variable production costs (**Table 2**). It also raised important concerns regarding pollution swapping, whereby adopting mitigation measures to reduce one type of pollution (i.e. NO_3 leaching) inadvertently increases another source of pollution (i.e. pesticides) (Stevens and Quinton, 2009). Other agronomic problems encountered included enhanced pea and bean weevil damage to the spring beans where a cover crop had been used in combination with conservation tillage, and damper soil conditions under the decaying cover crop residues which were sprayed with glyphosate eight weeks prior to spring cultivation and which delayed sowing operations by a few days on the conservation tillage fields, a negative effect also reported elsewhere (Soane et al., 2012). Such agronomic concerns can have a major bearing on whether pollution mitigation measures, such as conservation tillage, are adopted by farmers at the catchment-scale.

3.7 Farmer perspectives

An interview was conducted with the two farm managers involved in the River Wensum DTC trials to document their perspectives on the various mitigation measures and what the associated drivers, barriers and opportunities had been. Reflecting on their involvement with the DTC, the farm managers reported one of the greatest lessons learnt from their participation had been the value of real-time, high-resolution data and local evidence. They showed great appreciation for such data, explaining it had helped raise awareness of the impacts field operation timings can have on soil and water quality, crop yields and farm economics. Incorporating such knowledge into their decision making, they believed reducing tillage intensity had the potential to bring opportunities and benefits, stating "*we are using less metal so it's cheaper to run… we are more flexible and versatile, given resources such as labour, time and money are not taken up by ploughing*". Considering the aforementioned agronomic issues experienced with conservation tillage, the interview highlighted the farm managers' overall desire to move away from methods which required the use of chemical substances due to the risks of future regulatory restrictions. They stated *"we cherry pick methods based* *on what seems to work"*, but have the aspiration to reduce ploughing and do light cultivation were possible, considering weather conditions and spraying needs. This, coupled with the improved economic performance of conservation tillage blocks, has led to a notable system change across the entire Salle Park Estate with a move away from intensive plough-based cultivation in favour of a reduced shallow non-inversion approach (**Table 3**).

Given the delicate balancing act of farmer's decision making, policymakers must therefore not only consider which mitigation measures should be adopted based on their environmental performance, but also how to encourage the adoption of measures through an appropriate combination of regulation, financial incentives and practical on-farm advice in order to achieve the greatest possible engagement of landowners (Inman et al., 2018; Vrain and Lovett, 2016).

4. Conclusions

The primary purpose of the River Wensum DTC platform was to support future government agri-environmental policy in the UK for intensive arable landscapes. On the basis of the results presented here, this study does not suggest that a policy of encouraging wider adoption of conservation tillage would, by itself, significantly improve soil conditions or reduce water pollution in the short-term. However, this conclusion only applies to comparable lowland, intensive arable systems in the UK, where shallow land gradients mean subsurface leaching, rather than surface runoff, is the dominant pollution pathway. Previous studies have demonstrated the benefits of conservation tillage at reducing soil erosion in catchments with steeper land gradients (Stevens and Quinton, 2009) and at reducing greenhouse gas emissions by minimising fuel consumption and limiting the oxidation of soil organic carbon (Chatskikh and Olesen, 2007). Reducing tillage intensity should also be viewed as just one part of a broader, integrated approach to conservation agriculture involving other aspects such as cover cropping, crop rotations and precision farming techniques. In addition, the current study suggests that conservation tillage can play a beneficial role within a wider system change, particularly through improvements in farm efficiency and financial returns. Shifting to a lower intensity tillage system could consequently boost agronomic performance and crop output and thus help address the challenges posed by an increasing demand for food from a growing human population.

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Tables

Table 1: Generalised details of the seven-year crop rotation practices employed on the Salle Park Estate in 2012 prior to the start of the conservation tillage trial. Further details on the Väderstad machinery used are available on the manufacturer website (Väderstad, 2019). Note that the cultivation trial area was managed according to the descriptions in **section 2.2**.

Stage	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Crop 7
Organic manure				Turkey manure		Turkey manure	
Liming	LimeX 70			LimeX 70			
First cultivation	Plough	Plough	Plough	Plough	Stubble Cutter	Plough	
Weed control					Glyphosate		
Second cultivation	Väderstad NZA tine harrow	Besson Discordon	Väderstad Press/NZA tine harrow	Väderstad Press/NZA tine harrow	Besson Discordon /Väderstad NZA tine harrow	Väderstad NZA tine harrow	Väderstad Press/NZA tine harrow
Drilling	Väderstad Rapid	Väderstad Rapid	Väderstad Rapid	Väderstad Rapid	Väderstad Rapid	Compactor / precision drill	Väderstad Rapid
Sown crop	Spring beans	Winter wheat	Winter barley	Winter oilseed rape	Winter wheat	Sugar beet	Winter wheat / spring barley

Table 2: Farm economic performance from 2013/14 to 2017/18. All values presented as £ ha^{-1}. CC refers to a winter cover crop preceding the cash crop.

Farm Year		**2013/14**	**2014/15**	**2015/16**	**2016/17**	**2017/18**
Crop type		**Spring beans + CC**	**Winter wheat**	**Winter barley**	**Oilseed rape**	**Winter wheat**
Block J	Total cost	589	784	561	600	766
(Plough)	Output	1334	1694	1086	1734	1515
	Gross margin	**745**	**910**	**525**	**1134**	**749**
Block P	Total cost	748	782	581	553	765
(Shallow non-inv.)	Output	1506	1695	1099	1729	1614
	Gross margin	**758**	**913**	**518**	**1176**	**849**
Block L (Direct drill)	Total cost	704	788	598	550	750
	Output	1435	1620	1086	1613	1600
	Gross margin	**731**	**832**	**488**	**1063**	**850**

Table 3: Generalised details of the seven-year crop rotation practices employed on the Salle Park Estate in 2018 after cultivation system change. Further details on the Väderstad machinery used are available on the manufacturer website (Väderstad, 2019).

Stage	Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Crop 7
Organic manure				Turkey manure		Turkey manure	
Liming	LimeX 70			LimeX 70			
Cover crop cultivation	Väderstad Opus					Väderstad Opus	
Cover crop drilling	Väderstad Bio-drill					Väderstad Bio-drill	
Cover crop control	Glyphosate (Nov/Dec)					Glyphosate (Nov/Dec)	
First cultivation			Väderstad Carrier + Straw harrow	Väderstad Opus	Väderstad Carrier + Cross Cutter		Väderstad Opus / Plough
Weed control			Glyphosate				
Second cultivation	Väderstad NZA tine harrow	Väderstad Opus	Väderstad Opus		Väderstad Opus	Väderstad NZA tine harrow	
Drilling	Väderstad Rapid	Väderstad Rapid	Väderstad Rapid	Väderstad Bio-drill	Väderstad Rapid	Compactor / precision drill	Väderstad Rapid
Sown crop	Spring beans	Winter wheat	Winter barley	Winter oilseed rape	Winter wheat	Sugar beet	Winter wheat / spring barley

Figure Captions

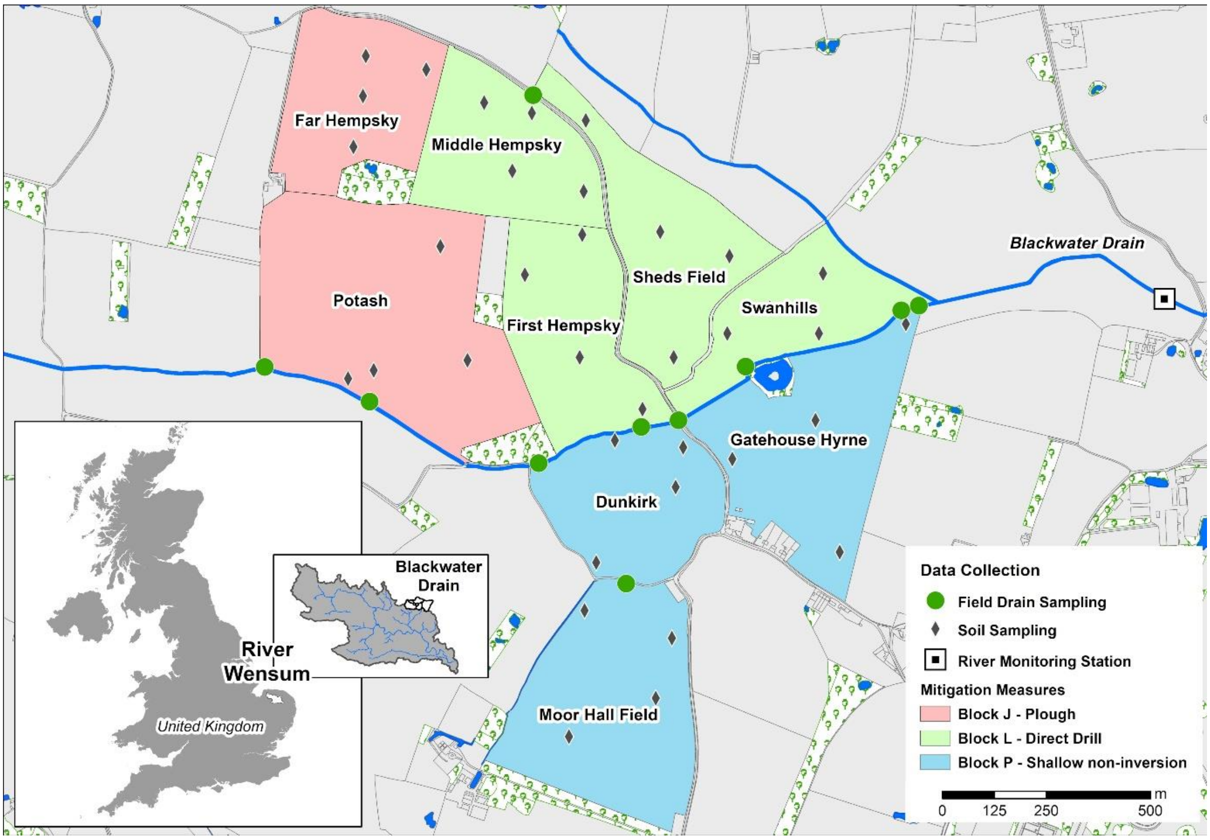

Figure 1: Location of the Salle Park Estate study area in the Blackwater Drain sub-catchment of the River Wensum, UK.

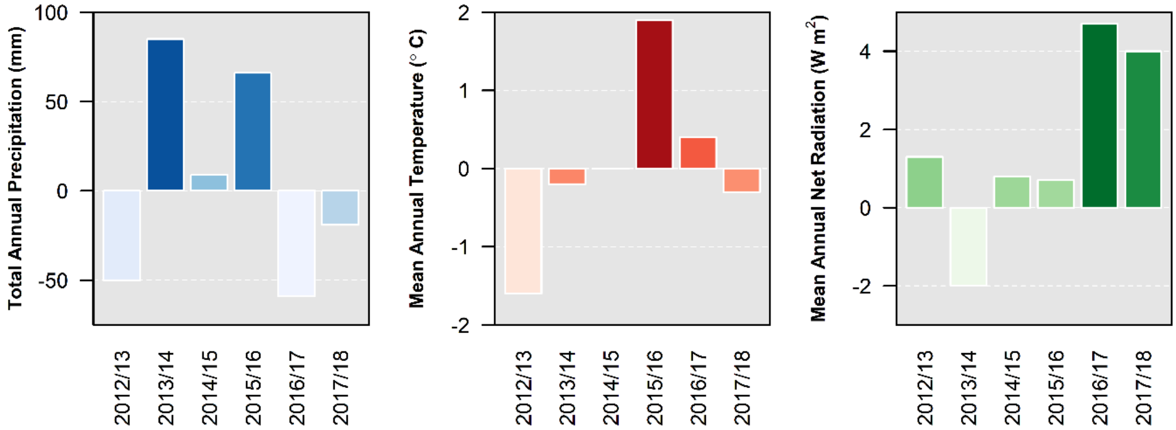

Figure 2: Precipitation, temperature and net radiation recorded on the Salle Park Estate over six farm years (September – August). Values presented relative to the 1981-2010 regional averages (Met Office, 2017).

Figure 3: Cultivation on (top left) Block J with a mouldboard plough and (top right) Block P with a Väderstad Carrier. Sowing of spring beans (*Vicia faba*) on (bottom left) Blocks J and P with a Väderstad Rapid drill and (bottom right) Block L with a Väderstad Seed Hawk direct drill.

Figure 4: The impact of conservation tillage practices was assessed through monitoring of (*top left*) soil properties, (*top right*) subsurface field drainage outflows and (*bottom*) river water quality in the Blackwater Drain using an automated high-resolution monitoring station.

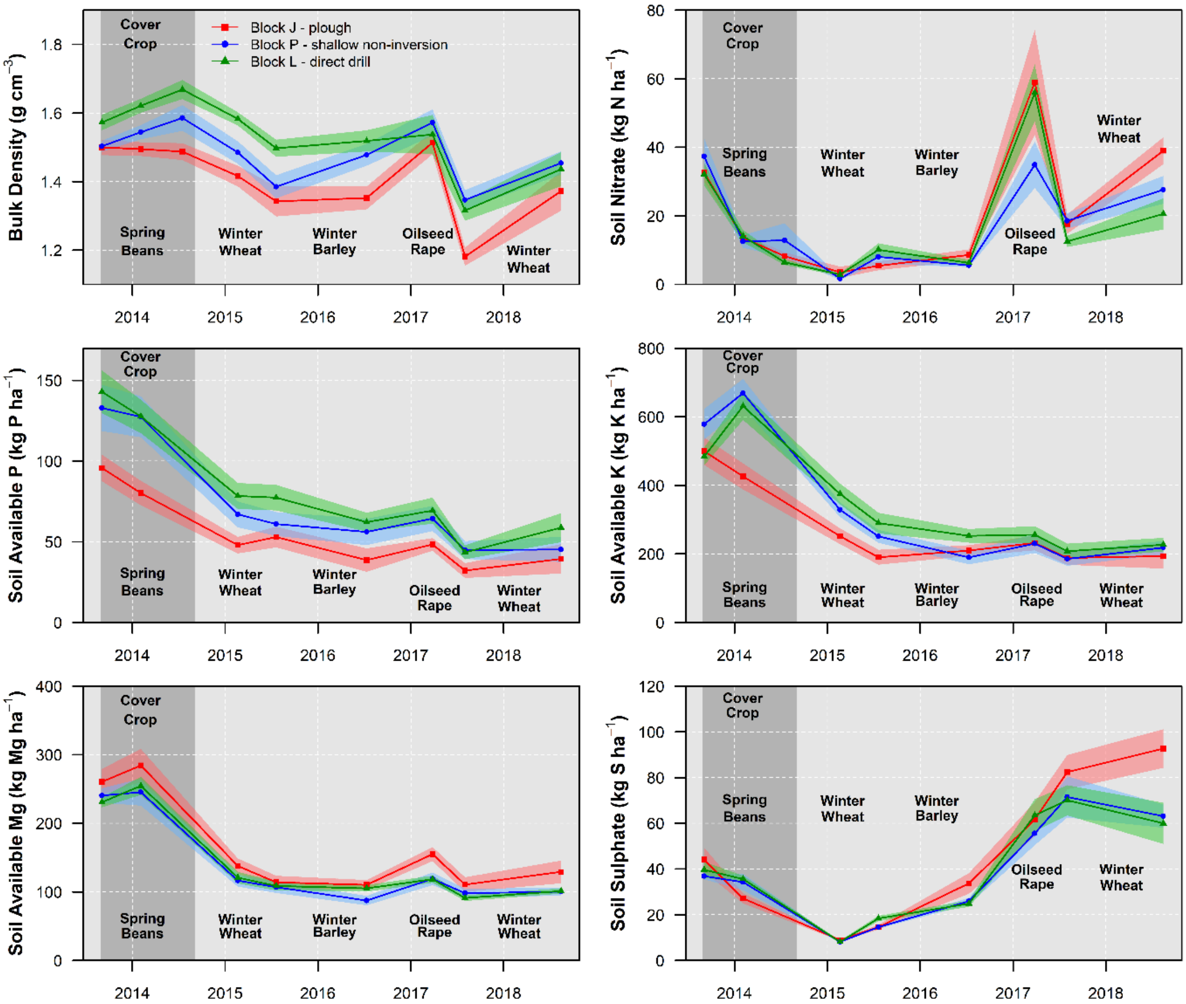

Figure 5: Temporal variation in soil physical (0-12 cm depth) and chemical properties (0-30 cm depth) for the three cultivation blocks. All values are presented as means with one standard error shading. The area shaded in dark grey is the period of the 2013/14 cover crop trial.

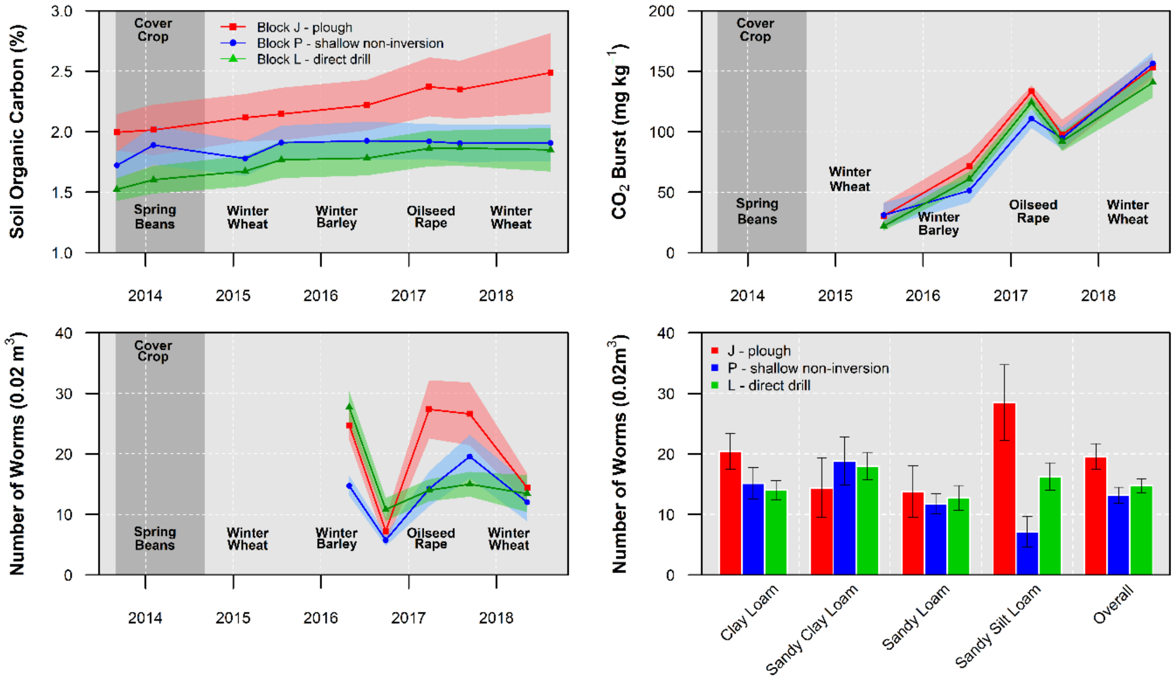

Figure 6: Temporal variation in soil biological properties for the three cultivation blocks. All values are presented as means with one standard error shading. The area shaded in dark grey is the period of the 2013/14 cover crop trial.

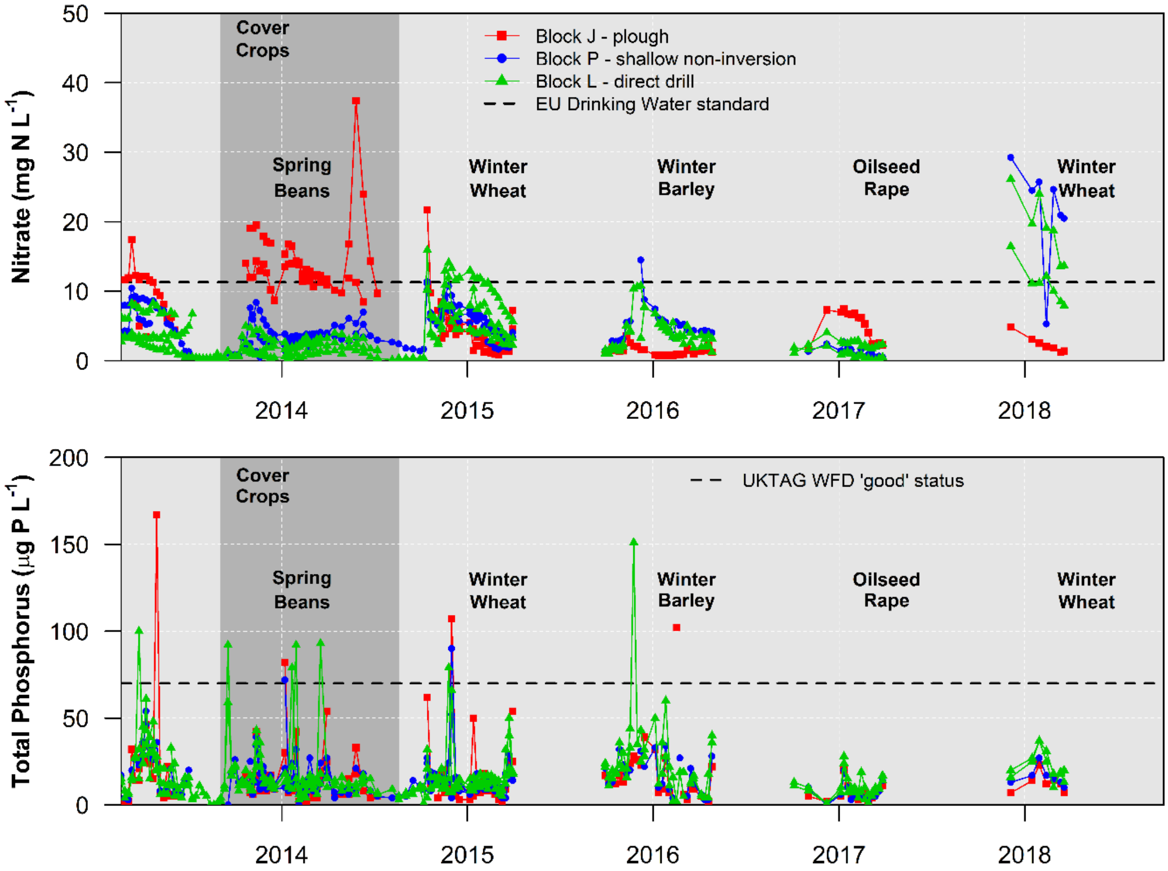

Figure 7: Field drain nitrate and total phosphorus concentrations discharging underneath the three cultivation blocks at depths of 100-150 cm for the period March 2013 – August 2018.

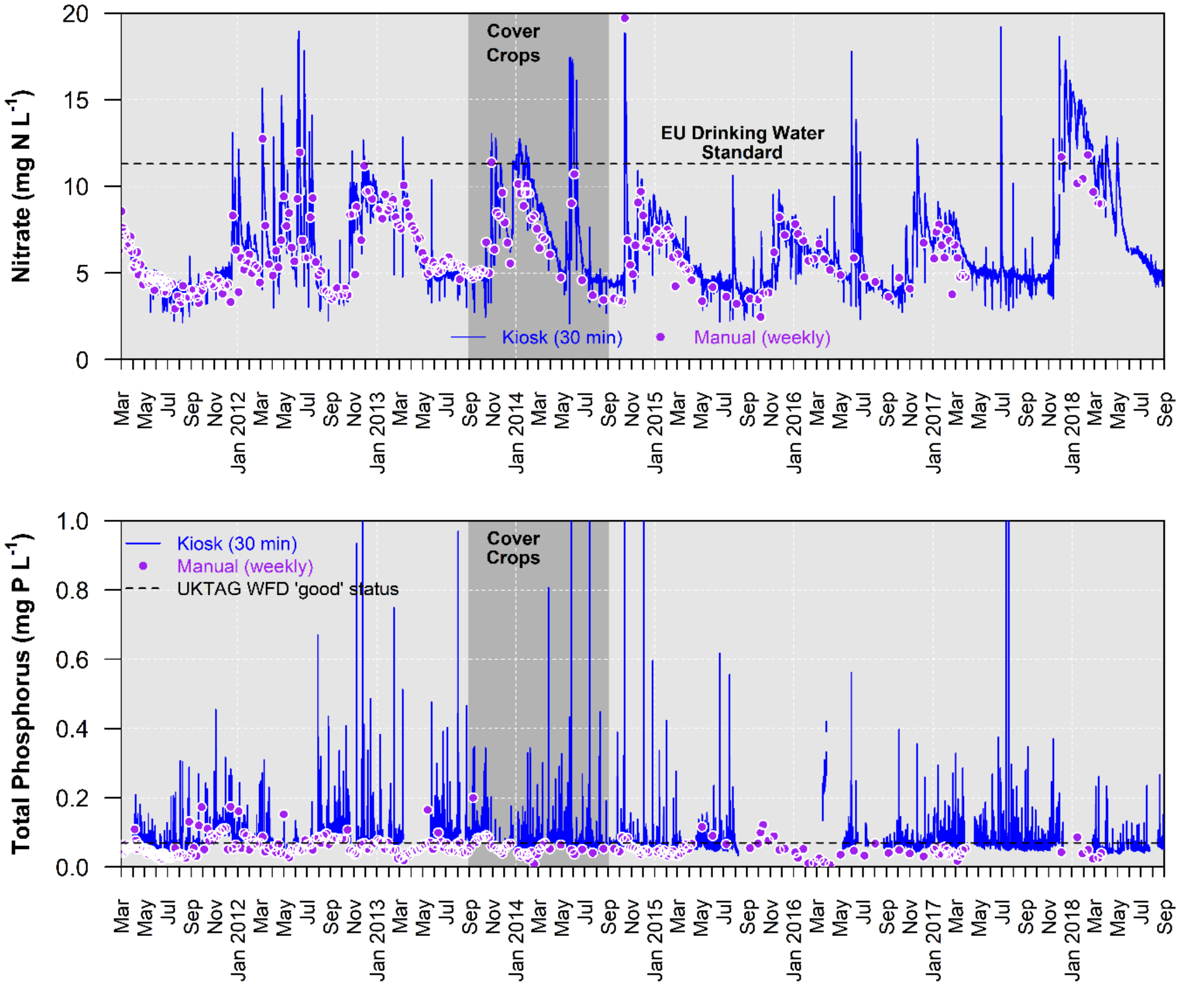

Figure 8: Concentrations of nitrate and total phosphorus recorded in the Blackwater Drain from March 2011 to August 2018. Data shown include both high-frequency (30 min), automatic, bankside monitoring kiosk data and lower frequency (weekly) manual grab sampling data.