Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment

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Abstract

The efficacy of cover crops and non-inversion tillage regimes at minimising farm-scale nutrient losses were assessed across a large, commercial arable farm in Norfolk, UK. The trial area, covering 143 ha, was split into three blocks: winter fallow with mouldboard ploughing (Block J); shallow non-inversion tillage with a winter oilseed radish (*Raphanus sativus*) cover crop (Block P); and direct drilling with a winter oilseed radish cover crop (Block L). Soil, water and vegetation chemistry across the trial area were monitored over the 2012/13 (pre-trial), 2013/14 (cover crops and non-inversion tillage) and 2014/15 (non-inversion tillage only) farm years. Results revealed oilseed radish reduced nitrate (NO_3-N) leaching losses in soil water by 75–97% relative to the fallow block, but had no impact upon phosphorus (P) losses. Corresponding reductions in riverine NO_3-N concentrations were not observed, despite the trial area covering 20% of the catchment. Mean soil NO_3-N concentrations were reduced by ~77% at 60–90 cm depth beneath the cover crop, highlighting the ability of deep rooting oilseed radish to scavenge nutrients from deep within the soil profile. Alone, direct drilling and shallow non-inversion tillage were ineffective at reducing soil water NO_3-N and P concentrations relative to conventional ploughing. Applying starter fertiliser to the cover crop increased radish biomass and nitrogen (N) uptake, but resulted in net N accumulation within the soil. There was negligible difference between the gross margins of direct drilling (£731 ha^{-1}) and shallow non-inversion tillage (£758 ha^{-1}) with a cover crop and conventional ploughing with fallow (£745 ha^{-1}), demonstrating farm productivity can be maintained whilst mitigating diffuse pollution. The results presented here support the wider adoption of winter oilseed radish cover crops to reduce NO_3-N leaching losses in arable systems, but caution that it may take several years before catchment-scale impacts downstream are detected.

Keywords: Mitigation; Agriculture; Nitrate; Phosphorus; Conservation tillage; River;

1. Introduction

Diffuse nutrient pollution from intensive arable agriculture is a major driver behind the eutrophication of freshwater environments and leads to an array of detrimental economic (Dodds et al., 2009; Smith and Schindler, 2009) and environmental (Skinner et al., 1997; Némery and Garnier, 2016) impacts. As naturally limiting nutrients of plant growth in aquatic systems, the enhanced land-to-river transfer of fertiliser derived nitrogen (N) and phosphorus (P) fuels blooms of phytoplankton, periphyton and neuro-toxin secreting cyanobacteria colonies which can dramatically lower species diversity and lead to a fundamental breakdown of ecosystem functioning (Smith et al., 1999; Hilton et al., 2006). Treating eutrophic water also incurs significant economic costs, with water companies having to remediate problems with taste, colour and odour whilst lowering concentrations of contaminants in order to make the water potable (Pretty et al., 2000). In the United Kingdom, the total costs of eutrophication have been estimated at £75–114 million per year (Pretty et al., 2003). Consequently, on-farm mitigation measures are required to help reduce land-to-river nutrient transfers, with such schemes being financially incentivised through agri-environmental stewardship programmes (Kay et al., 2009; Deasy et al., 2010).

The efficacy of two commonly applied mitigation measures at reducing nutrient losses from arable land, cover crops (Snapp et al., 2005; Tonitto et al., 2006; Valkama et al., 2015) and non-inversion tillage (Tebrügge and Düring, 1999; Stevens and Quinton, 2009; Soane et al., 2012), have been widely studied for several decades. Cover crops are typically non-cash crops sown in the autumn to provide winter groundcover when the field would otherwise be fallow, thereby reducing the risk of soil nutrient losses from leaching and erosion (Dabney et al., 2001; Hooker et al., 2008). A range of species can be grown, including N fixing leguminous (e.g. clover, vetch and pea) and non-leguminous (e.g. rye, sorghum and brassicas) varieties. Cover crops have primarily been used to minimise NO_3 leaching by scavenging highly soluble residual soil NO_3 and converting it into relatively immobile organic N (Aronsson and Torstensson, 1998; Beaudoin et al., 2005; Premrov et al., 2014). However, they have also been shown to protect surface soils from erosive flows, increase soil organic matter content, enhance soil structure, suppress weeds and improve soil moisture balance (Lu et al., 2000; Dabney et al., 2001; Stevens and Quinton, 2009). Unfortunately, an array of negative agronomic impacts of cover crops have also been reported and include the cost of establishment, difficulty in destroying the cover crop prior to sowing the subsequent cash crop, the harbouring of insect pests and the complexity of predicting the release of mineralised N as the cover crop residues degrade (Snapp et al., 2005; Deasy et al., 2010).

The main objective of non-inversion, or conservation, tillage systems is to improve soil structure and stability (Holland, 2004; Lal et al., 2007). 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 non-inversion tillage systems the soil is either disturbed to a lesser degree (i.e. 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 (i.e. direct drilling) (Morris et al., 2010). By improving soil structure, non-inversion tillage methods have been shown to reduce soil erosion, increase organic matter content, improve drainage and water holding capacity and increase microbial and earthworm activity (Deasy et al., 2009; Soane et al., 2012; Abdollahi and Munkholm, 2014). However, the lack of inversion can increase pest populations and lead to an accumulation of nutrients near the soil surface which can be readily mobilised by surface flows and thus pose a risk to freshwater environments (Holland, 2004; Bertol et al., 2007; Stevens and Quinton, 2009).

To date, much of the research into the effectiveness of cover crops and non-inversion tillage at reducing arable nutrient losses has come from small, controlled plot scale studies (e.g. Catt et al., 1998; Bakhsh et al., 2002). Whilst such studies are typically able to yield definitive conclusions as to the effectiveness of certain measures by controlling for the multiple sources of variability that exist within agroecosystems, they are unable to demonstrate how effective these measures would be when applied in real world situations on large, commercial, arable farms. Specifically, plot-scale studies typically fail to account for the impacts of mitigation measures upon crop yields, farm profit margins, catchment-scale nutrient losses, or the practicalities for the farmer of deploying such measures. Consequently, there is a need for more farm- and catchment-scale approaches to help better inform government decision making on agri-environmental policy, particularly in the UK (Kay et al., 2009). Addressing this deficiency, in 2010 the UK government launched the Demonstration Test Catchment (DTC) research platform to evaluate the extent to which on-farm mitigation measures could cost-effectively reduce the impacts of diffuse agricultural pollution on river ecology whilst maintaining food production capacity (McGonigle et al., 2014). Across the UK, three DTCs were established with each concentrating on a different farming system. This paper focuses upon the intensive arable River Wensum DTC in Norfolk, UK, where cover crops and non-inversion tillage methods were trialled as diffuse pollution mitigation measures on a large, commercial arable farm over a three-year period (Wensum Alliance, 2016).

The primary objectives of this paper are as follows:

(i) To assess the effectiveness of cover crops and non-inversion tillage regimes at reducing N and P losses at the farm-scale;

(ii) To examine the impact of cover crops and non-inversion tillage methods on soil fertility;

(iii) To assess the sub-catchment scale impacts of the mitigation measures by monitoring river water chemistry downstream of the trial area;

(iv) To compare the economic viability and farm practicalities of cover crops and non-inversion tillage operations with those of conventional farm practice.

2. Methods

2.1 Study location

This study focuses upon the large (20 km^2) commercial Salle Park Estate located within the Blackwater sub-catchment of the lowland calcareous River Wensum, Norfolk, UK (52°47'09"N, 01°07'00"E). The estate is situated 40–50 m above sea level with gentle slopes (< 1°) meaning that subsurface leaching rather than surface runoff is the dominant pollution pathway. Intensive arable cropping comprises 79% of the land use and is managed with a seven-year rotation of winter wheat, winter and spring barley, winter oilseed rape, spring beans and sugar beet. The estate also includes 15% improved grassland, 5% mixed woodland and 1% rural settlements. Surface soils are predominantly clay loam to sandy clay loam (<0.5 m depth) and these are underlain by Quaternary deposits of chalky, flint-rich boulder clays and glaciofluvial and glaciolacustrine sands and gravels (0.5–20 m). The bedrock is Cretaceous white chalk (>20 m) (Hiscock et al., 1993; Lewis, 2011). River channels draining the catchment have been extensively deepened and straightened to reduce water residence times resulting in the river no longer connecting to its floodplain. The site experiences a temperate maritime climate, with a mean annual temperature of 10.1°C and a mean annual rainfall total of 674 mm y^{-1} (1981-2010) (Meteorological Office, 2016). Farm year (September to August) precipitation totals were 624 mm (2012/13), 759 mm (2013/14) and 683 mm (2014/15) during this study.

2.2 Cultivation methods

In 2013, 143 ha of arable land was identified for the trialling of winter cover crops and non-inversion tillage practices aimed at reducing diffuse nutrient losses into the River Blackwater (Figure 1; Table 1). This consisted of nine fields split into three mitigation measures blocks, with each block sown with the same crop and the same fertiliser application rate during the 2013/14 (spring beans; 0 kg N ha^{-1}, 30 kg P ha^{-1}, 55 kg K ha^{-1}) and 2014/15 (winter wheat; 220 kg N ha^{-1}, 22 kg P ha^{-1}, 85 kg K ha^{-1}) farm years. **Block J** (two fields, 42 ha) was kept as a control and was cultivated by conventional mouldboard ploughing to 25 cm depth prior to sowing. **Block P** (three fields, 52 ha) underwent shallow non-inversion tillage to a depth of 10 cm using a Väderstad Carrier and Topdown cultivator prior to sowing with a Rapid drill. **Block L** (four fields, 53 ha) was direct drilled into the previous crop residue using a Väderstad Seed Hawk. To minimise the risk of background variability in soil conditions and historic cultivation practices masking the impacts of the mitigation measures trial, each block contained the same range of soil textures (i.e. clay loam and sandy clay loam in all three blocks; Figure S1) and historically had been subjected to the same seven-year crop rotation, meaning that all blocks would have had comparable fertiliser inputs.

In addition to the different tillage regimes, Blocks L and P were sown with an oilseed radish (*Raphanus sativus*) cover crop (seed density = 18 kg ha^{-1}) using a Lemken Karat cultivator in late-August 2013 (Figure 2). The radish was sprayed with herbicide (glyphosate) in mid-January 2014 to kill it prior to establishment of the spring beans. Oilseed radish was chosen because it provides good winter groundcover and has extensive, deep tap roots to help loosen compacted soil and scavenge nutrients at depth. Since there was some debate among local agronomists about the merits of applying a starter fertiliser to cover crops, this was evaluated by applying 30 kg N ha^{-1} to five of the fields whilst the other two received no fertiliser. In addition to the three mitigation measures blocks, **Block N** (two fields, 63 ha), being managed by normal farm practice but with different crop rotations, was also monitored to facilitate comparison with the trial area. The efficacy of the cover crops and non-inversion tillage regimes at reducing N and P losses was assessed by monitoring soil, water and vegetation chemistry across the study area during three September to August farm years:

2012/13 (pre-trial), 2013/14 (cover crops and non-inversion tillage), and 2014/15 (non-inversion tillage only).

2.2 Field installations and sample collection

2.2.1 Porous pots

Nine sets of porous pots were installed across the mitigation measure blocks in late 2013 to facilitate soil water sampling, with three sets installed in each of Blocks J, L and P (Figure 1). Locations within each block were selected to incorporate the full range of soil textures. Each set consisted of ten individual pots installed in a row 1 m apart and buried to 90 cm depth. Soil water was collected on five occasions during the study period (February, April and May 2014, March and May 2015). On each occasion, pots were placed under vacuum to evacuate and dispose of any residual water and were then left under vacuum for 4–5 h to draw in a fresh sample of soil water. Recovered volumes from each pot were typically 20–50 mL, although five of the nine sets yielded no sample in May 2014. Where volumes were <10 mL, individual samples were bulked together to provide sufficient water for analysis.

2.2.2 Field drains

Most of the arable land in the Salle Park Estate is extensively under-drained by a dense network of clay and plastic field drains installed at 100–150 cm depth and which discharge into the River Blackwater at a density of 43 outflows per km. Highest recorded discharges were >10 L s^{-1}, although discharge varied depending upon season, drain depth, catchment area and antecedent moisture conditions. Most drains dried up entirely between June and September. Of 125 drains identified, a subset of 11 was selected for routine monitoring at 1–2 week intervals between March 2013 and March 2015 (Figure 1). Two drains drained the control Block J (D08L, D10L), three Block L (D02L, D04L, D06L), three Block P (D01R, D03R, D16R) and three Block N (D07R, D09R, D13L). On each sampling occasion, a 1 L grab sample was collected from the drain outflow and the discharge (L s^{-1}) recorded.

2.2.3 Soils

Soils in Blocks J, P and L were sampled on five occasions during the study. Samples were collected from four locations within each individual field, with the locations selected to capture the full range of textural variability (Figure 1). On the first two sampling occasions (September 2013 and February 2014), a powered hydraulic Hydrocare auger collected 90 cm depth soil cores in two concentric circles at 12 points within 10 m of each sampling location. The cores were then divided into three depths (0–30 cm, 30–60 cm, 60–90 cm) and the soils combined to produce a single bulked sample (~250 g) for each depth at each location. In total, 108 bulked soil samples were collected on each sampling occasion (i.e. 9 fields x 4 locations x 3 depths). On the following three occasions (July 2014, February 2015 and July 2015) sampling was restricted to the topsoil layer (0–15 cm depth) with soil collected from 12 points within 2 m of the sampling location using a hand operated Dutch auger. Again, these 12 samples were combined to produce one bulked soil for each sampling location. In total, 36 samples were collected on each of these sampling occasions (i.e. 9 fields x 4 locations). All soil samples were placed into air-tight polyethylene bags and stored in cool boxes prior to analysis.

2.2.4 Vegetation

To assess cover crop nutrient uptake rates, in January 2014 oilseed radish samples were collected from the same locations within Blocks L and P as the soil samples. Within a 0.25 m^2 quadrat at each location, all oilseed radish plants were dug up and the leaf and root material separated for individual analysis. A combined root and leaf fresh weight of ~700 g was collected at each location. Cover crop samples were differentiated by fields with or without a starter fertiliser application (Table 1).

2.2.5 Riverine bankside monitoring

To assess the impact of the mitigation measures on nutrient concentrations in the River Blackwater, an automated bankside monitoring kiosk 650 m downstream of the trial area analysed a range of water quality parameters at 30-min resolution throughout the study period (September 2012 – August 2015). 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. Stream stage was determined by a pressure transducer housed in a stilling well and was converted to discharge using a manual stage-discharge rating curve. Further details are provided in Outram et al. (2014).

2.3 Laboratory analysis

2.3.1 Water samples

Field drain and porous pot NO_3-N concentrations were determined by ion chromatography using a Dionex ICS-2000. 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^- = 214 µmol L^{-1}) with each sample batch. Phosphate (PO_4-P) and 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.

2.3.2 Soil samples

All soil samples were chopped, mixed and sieved to 2 mm. Soil 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 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) concentrations were determined by flame photometry after shaking the soil with ammonium nitrate (NH_4NO_3) to extract available K. Soil organic matter (SOM) content was determined by loss-on-ignition (430°C).

2.3.3 Cover crop samples

Cover crop leaf and root material was separated, air-dried, ground and sieved to 0.5 mm. On representative portions of each, the total nitrogen (TN) content was determined by chromatography using the Dumas method (Bremner, 1965). TP contents were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) after first digesting material in nitric (HNO_3) and hydrochloric (HCl) acids using a temperature controlled digestion block.

3. Results

3.1 Impacts of mitigation measures on soil water

3.1.1 Nitrate

During the pre-trial period (2012/13) when all blocks were under either winter wheat or spring barley, there were no significant differences in mean field drain NO_3-N concentration between Blocks L (5.5 mg N L^{-1}), P (6.4 mg N L^{-1}) and J (9.6 mg N L^{-1}) (Figure 3; Table 2). Concentrations of 10.0 mg N L^{-1} were observed in the normal practice Block N, with the two fields in this block under winter barley and spring beans.

However, during the cover crop and non-inversion tillage period (2013/14), pronounced contrasts in soil water NO_3-N concentrations were recorded between blocks with or without a cover crop (Figure 3; Table 2). Mean field drain NO_3-N concentrations in cover crop Blocks P (3.5 mg N L^{-1}) and L (1.8 mg N L^{-1}) were significantly ($p < 0.05$) smaller than the ploughed fallow control Block J (14.0 mg N L^{-1}). This pronounced contrast was even more apparent in the porous pot samples (Figure 4), where mean soil water NO_3-N concentrations in Blocks P and L were 96–97% lower than Block J during

February 2014 and 79–80% lower during April 2014. A peak in Block J field drain NO_3-N concentrations (37.4 mg N L^{-1}) in late May 2014 coincided with a period of increased rainfall and thus increased NO_3-N leaching. However, an increase in mean porous pot NO_3-N concentration in Block L (15.5 mg N L^{-1}) during the same period may also reflect NO_3-N release during mineralisation of the cover crop residues (Figure 4). In Block N, NO_3-N concentrations were high in the two drains (D07R, D13L) discharging underneath a field of winter wheat in autumn 2013 (>10 mg N L^{-1}), but steadily declined throughout the winter to ~4 mg N L^{-1} by March 2014. The other drain in Block N (D09R) under winter oilseed rape performed similarly to the cover crop blocks, with low NO_3-N concentrations (mean 2.9 mg N L^{-1}) throughout winter 2013/14.

During the non-inversion tillage only period (2014/15), there were no significant ($p > 0.05$) differences in field drain NO_3-N concentrations between any of the blocks. Mean concentrations recorded under shallow non-inversion tillage (5.5 mg N L^{-1}) and direct drill (6.2 mg N L^{-1}) regimes were very similar to that recorded in the ploughed Block J (4.3 mg N L^{-1}). Similarly, there were no significant or consistent differences in the NO_3-N concentrations recorded in the porous pots of the three blocks during March or May 2015.

3.1.2 Phosphorus

In contrast to NO_3-N, there were no significant ($p > 0.05$) differences in soil water TP or PO_4-P concentrations between the different cover crop and cultivation blocks in either the field drains or the porous pots (Figures 3 and 4; Table 2). During the pre-trial period (2012/13), mean field drain TP concentrations ranged from 16 µg L^{-1} in Block N to 26 µg L^{-1} in Block J, although differences were not significant due to large variability within each block. Similarly, during the cover crop period (2013/14) mean field drain TP concentrations in Blocks P (14 µg L^{-1}) and L (16 µg L^{-1}) with a cover crop were very similar to the control Block J (15 µg L^{-1}) and normal practice Block N (17 µg L^{-1}). During the same period, mean PO_4-P concentrations in the porous pots ranged from 31–67 µg L^{-1} in the cover crop Blocks L and P to 42–54 µg L^{-1} in the control Block J, although large variability within each block again meant differences were not significant (Figure 4). During the non-inversion tillage only period (2014/15), mean field drain TP concentrations in the shallow non-inversion tillage Block P (14 µg L^{-1}) were very similar to that recorded in the direct drill Block L (15 µg L^{-1}), the control Block J (16 µg L^{-1}) and the normal practice Block N (11 µg L^{-1}). Mean porous pot PO_4-P concentrations in March 2015 were larger in Block P (55 µg L^{-1}) than Block J (24 µg L^{-1}), but differences were not significant.

3.2 Impacts of mitigation measures on soil nutrients

3.2.1 Nitrate-N

There were no significant differences ($p > 0.05$) in topsoil NO_3-N concentrations between the three mitigation blocks during any of the five sampling occasions (Figure 5a; Table 3). High mean soil NO_3-N concentrations (32.3–37.3 kg N ha^{-1}) were recorded in all blocks during the pre-trial period in September 2013 due to residual NO_3-N remaining from the previous crop. Similarly, mean concentrations in all blocks tended to be lower in February 2015 (1.6–3.4 kg N ha^{-1}) than in July 2015 (5.6–10.3 kg N ha^{-1}), likely indicating both the increased leaching of soil NO_3-N during the winter and the accumulation of applied NO_3-N in the topsoil over the course of the farm year. However, despite the lack of contrast in topsoil NO_3-N between blocks, there were significant reductions in concentration at depth beneath the cover crop and non-inversion tillage blocks in February 2014 (Figure 5b). In both Blocks L and P, mean soil NO_3-N concentrations were reduced by 35–37% at 30–60 cm depth and by 76–77% at 60–90 cm depth relative to control Block J.

3.2.2 Phosphorus

Topsoil P concentrations were significantly ($p < 0.05$) greater in Blocks L and P than in Block J during the cover crop and non-inversion tillage period (Table 3). However, mean concentrations in Blocks L (142.5 kg P ha^{-1}) and P (132.0 kg P ha^{-1}) were also significantly greater than Block J (96.4 kg P ha^{-1}) during the pre-trial period, thus indicating these contrasts more likely reflect pre-existing differences in soil type rather than the impacts of the mitigation measures. There were no significant differences between Block L and Block P during any of the five sampling rounds.

3.2.3 Potassium

Mean topsoil K concentrations were significantly ($p < 0.05$) greater in Blocks L (292 and 648 kg K ha^{-1}) and P (250 and 687 kg K ha^{-1}) than in Block J (193 and 427 kg K ha^{-1}) during both the cover crop and non-inversion tillage only periods, respectively (Table 3). With no significant difference between Block J and Blocks L and P in September 2013, these results indicate that covers crops and non-inversion tillage were likely responsible for the increased topsoil K concentrations observed during the trial period. Concentrations in the direct drill Block L were marginally higher than the shallow non-inversion tillage Block P during February and July 2015, although due to large variability these differences were not significant.

3.2.4 Organic matter

There were no significant ($p > 0.05$) differences in SOM content between the three blocks during any of the five sampling occasions, with mean SOM concentrations in Block J (2.0–2.1%) always greater than Blocks P (1.7–1.9%) and L (1.5–1.8%) (Table 3). The similarity of SOM content in Blocks L and P during February and July 2015 also indicated no measurable difference between direct drill and shallow non-inversion tillage options. However, there was evidence of a small increase in the mean SOM content of Blocks L and P over the 22-month study period, with relative concentrations increasing by 20% and 12%, respectively, between September 2013 and July 2015.

3.3 Impacts of mitigation measures on river water quality

In pronounced contrast to the field drain and porous pot data, Figure 6 reveals there was no corresponding reduction in riverine NO_3-N concentrations during the cover crop and non-inversion tillage period. Mean NO_3-N concentrations in the River Blackwater varied from 6.8 mg N L^{-1} (range =

3.0–12.8 mg N L^{-1}; st. dev. = 2.3 mg N L^{-1}) during the 2012/13 farm year, to 7.4 mg N L^{-1} (range = 2.1–17.5 mg N L^{-1}; st. dev. = 2.9 mg N L^{-1}) during 2013/14 and 6.0 mg N L^{-1} (range = 0.5–18.8 mg N L^{-1}; st. dev. = 2.2 mg N L^{-1}) during 2014/15. Periods of elevated NO_3-N concentration predominantly corresponded with periods of greater stream discharge, with higher concentrations observed during the winter months (November – March) and during heavy rainfall events (e.g. late May 2014). However, the highest concentrations (>15 mg N L^{-1}) recorded in May, June and October 2014 could also partly relate to the mineralisation of the cover crop residues releasing a flush of NO_3-N, especially as increases in Block L porous pot NO_3-N concentrations were also recorded at this time. Riverine NO_3-N concentrations exceeded the 11.3 mg N L^{-1} EU Drinking Water Directive (98/83/EC) standard 4.5% of the time between September 2012 and August 2015.

For TP, mean concentrations were observed to decline over the study period, from 93 µg P L^{-1} (range = 41–1000 µg P L^{-1}; st. dev. = 49 µg P L^{-1}) during 2012/13, to 78 µg P L^{-1} (range = 38–1000 µg P L^{-1}; st. dev. = 43 µg P L^{-1}) during 2013/14 and to 66 µg P L^{-1} (range = 34 – 1000 µg P L^{-1}; st. dev. = 39 µg P L^{-1}) in 2014/15. These declines in instream TP concentrations arose despite the absence of similar such declines in TP and PO_4-P concentrations of field drains and porous pots, respectively, indicating the mitigation measures are unlikely to have been the dominant casual factor. Large peaks in TP concentration (>200 µg P L^{-1}) were almost exclusively associated with heavy precipitation events.

3.4 Impacts of applying starter fertiliser

Nutrient analysis of the oilseed radish cover crop revealed there was a significant difference ($p < 0.05$) in the mean N uptake between cover crops grown with (79.4 kg N ha^{-1}) or without (69.6 kg N ha^{-1}) a starter fertiliser (Table 4). This was due to a combination of both greater dry matter production in fields with (2.8 t ha^{-1}) rather than without (2.6 t ha^{-1}) a starter fertiliser, and because the combined mean N content of root and leaf material was greater in the five fields where the fertiliser was applied (2.85%) than in the two fields where it was omitted (2.63%). Despite this, mean NO_3 concentrations recorded in the porous pots during February 2014 were significantly higher in the fertilised fields (0.8 mg NO_3-N L^{-1}) compared to the unfertilised fields (0.3 mg NO_3-N L^{-1}). The uptake of K was significantly ($p < 0.05$) greater in fields with (90.0 kg K ha^{-1}) rather than without (76.8 kg K ha^{-1}) a starter fertiliser application. However, P uptake was not influenced by fertiliser application, with both treatments yielding mean uptake rates of 11.5 kg P ha^{-1}.

4. Discussion

4.1 Effectiveness of the cover crop

The oilseed radish cover crop proved to be highly effective at reducing soil water NO_3-N levels, thereby minimising NO_3-N leaching losses and lowering diffuse pollution risk. Concentrations in the 90 cm depth porous pots were reduced by 96–97% in late winter (February 2014) and by 79–80% in mid-spring (April 2014) compared to the fallow control block, whilst concentrations were reduced by 75–87% in the 100–150 cm depth field drains across the 2013/14 farm year. This beneficial effect compares favourably with a range of previously reported NO_3-N reductions under cover crops of 40–50% (Aronsson and Torstensson, 1998), 38–70% (Hooker et al., 2008), 0–98% (Stevens and Quinton, 2009) and 25–60% (Valkama et al., 2015). Importantly, soil water NO_3-N concentrations under the cover crop blocks were consistently below the EU Drinking Water Directive (98/83/EC) standard of 11.3 mg N L^{-1}, whilst concentrations under the fallow block were above this standard for ~88% of the 2013/14 farm year.

The substantial reductions in soil NO_3-N at 60–90 cm depth highlight that deep rooting oilseed radish is capable of scavenging N from deeper within the soil profile than likely would be possible by shallower rooting cover crop varieties (e.g. rye grass). Interestingly, the significantly reduced NO_3-N concentrations recorded in field drain D09R during 2013/14 reveals that winter sown oilseed rape had a similar performance as the oilseed radish in absorbing residual soil NO_3-N and thus reducing leaching risk, an observation also reported in other studies (Catt et al. 1998; Macdonald et al., 2005).

This finding suggests that it is the establishment of actively growing groundcover early in the autumn which is central to minimising NO_3-N leaching losses.

The cover crop did not have any significant impact upon P concentrations in either soil or soil water, a finding consistent with previous studies (Abdollahi and Munkholm, 2014). This result is not surprising given that leaching, rather than surface runoff, is considered the dominant nutrient loss pathway in this catchment and P has substantially lower mobility in soil than N due to sorption onto metal oxyhydroxides. Soil K concentrations were, however, significantly impacted, with mean concentrations increasing by 12–26% in the cover crop blocks between September 2013 and February 2014, compared to a 14% decline observed in the control block. This increase in topsoil fertility can in part be explained by the cover crop providing both winter groundcover to reduce leaching losses and a source of organic matter for mineralisation at the soil surface.

4.2 Effectiveness of non-inversion tillage

Non-inversion tillage alone was ineffective at reducing soil water NO_3-N concentrations during the 2014/15 farm year, with neither direct drilling nor shallow non-inversion tillage significantly reducing concentrations compared to the control or normal practice blocks. In fact, between October 2014 and March 2015, field drain NO_3-N concentrations in the direct drill Block L exceeded the drinking water standard (11.3 mg N L^{-1}) on 14% of sampling occasions, compared to 3% under the control Block J and 2% under shallow non-inversion tillage (Block P). This is broadly consistent with the findings of previous studies which reported no clear differences in NO_3-N leaching losses between conventional and non-inversion tillage practices (Stevens and Quinton, 2009; Soane et al., 2012; Premrov et al., 2014). The effectiveness of non-inversion tillage at minimising NO_3-N leaching tends to vary depending upon soil type, infiltration pathways and mineralisation rates of crop residues (Soane et al., 2012). Leaching losses of P were also not decreased by either non-inversion cultivation regime relative to the control or normal practice blocks. Previous studies have reported reductions in surface runoff losses of TP under shallow non-inversion cultivation (e.g. Deasy et al., 2009), however low topographic gradients in the Blackwater catchment provide limited opportunity for the initiation of surface runoff. Overall, the results presented here indicate that when employed alone, neither direct drilling nor shallow non-inversion tillage are effective at reducing nutrient leaching losses from arable land.

Nevertheless, the increase in soil K levels does indicate a general improvement in soil nutrient status over the duration of the study, particularly in the direct drilled Block L where mean concentrations were 26–53% higher during 2013/14 and 2014/15 than those recorded during the 2012/13 pre-trial period. Such increases in topsoil K concentrations under non-inversion systems have been widely reported in the literature (Dabney et al., 2001; Bertol et al., 2007; Abdollahi and Munkholm, 2014) and been attributed to the accumulation of crop residues on the soil surface. Similarly, whilst not statistically significant, the mean SOM content showed a relative increase of 20% under direct drill and 12% under shallow non-inversion tillage over the study period, compared with a 5% increase in the control block. Considering that topsoil organic carbon contents across the River Blackwater catchment are widely <2% (Rawlins et al., 2013), any increase in organic matter arising from employing non-inversion tillage systems could ultimately yield considerable benefits in terms of both soil fertility and soil structural stability (Puget and Lal, 2005). Given this was a relatively short two-year study, the results presented here are encouraging considering that previous research has demonstrated it can take many years of employing non-inversion tillage and/or cover crop systems before substantial improvements in soil carbon content and nutrient availability are achieved (Thomsen and Christensen, 2004). Further study to determine longer-term changes in SOM content would be beneficial.

4.3 Nitrogen balance

The application of starter N fertiliser to five fields of oilseed radish cover crop in August 2013 increased the mean N uptake rate of the cover crop by 9.8 kg N ha^{-1} relative to the two unfertilised fields, primarily due to an increase in biomass. However, this enhanced uptake by the cover crop was smaller than the fertiliser application rate (30 kg N ha^{-1}), leading to a net accumulation of N of 20.2 kg N ha^{-1} within the fertilised fields. Evidence of this accumulation can be seen in the soil N contents at 0–30, 30–60 and 60–90 cm depths which were 3.6, 3.1 and 1.0 kg NO_3-N ha^{-1} greater in the fields where fertiliser was applied compared to those without (Table 5). Likewise, mean NO_3 leaching losses recorded in the porous pots in February 2014 were also significantly higher in the fields with fertiliser applied (0.8 mg NO_3-N L^{-1}) compared to those without (0.3 mg NO_3-N L^{-1}). These results confirm that, under these conditions, the application of starter fertiliser to the cover crop was detrimental to the objective of reducing nutrient leaching. However, the efficacy of a cover crop in reducing leaching depends upon its early establishment prior to the wetting up of the catchment in the autumn (Dabney et al., 2001). Therefore, if the cover crop is established later (e.g. in mid-September) or growing conditions are sub-optimal after sowing (e.g. due to poor soil quality or weather conditions), then an initial application of fertiliser may be merited to promote growth and enable the cover crop to take up sufficient quantities of residual soil N (see supplementary Figure S2 which presents more recent results by the authors that demonstrate application of a starter fertiliser can reduce nitrate leaching losses). However, caution should be exercised as such action could increase diffuse pollution risk if cover crop roots are underdeveloped and unable to absorb this added fertiliser. This was not the case during this study, with the mild autumn of 2013 promoting vigorous growth of the oilseed radish and thus negating the need to apply additional fertiliser.

4.4 Sub-catchment scale impacts

Despite recording substantial reductions in soil water NO_3-N during the cover crop period, it is clear from Figure 6 that there was no corresponding reduction in riverine NO_3-N concentrations during the 2013/14 farm year. This is despite the cover crop trial area covering 20% (143 ha) of the catchment upstream of the bankside monitoring location (714 ha). A potential explanation for this apparent anomaly arises from previous research in the same catchment (Outram et al., 2016) which established that there was no positive relationship between fertiliser application and riverine nutrient load in the River Blackwater over a three-year period. Outram et al. (2016) hypothesised that the catchment is in a state of biogeochemical stationarity, whereby 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 inter-annual changes in fertiliser application. By extension, we can apply the same principle here and hypothesise that nutrient reductions in soil water during the cover crop period do not immediately translate into reductions in riverine concentrations due to the mobilisation of nutrients from pre-existing legacy stores. It could potentially take 5–10 years or more for these nutrient stores to be depleted before major reductions instream are detected. Therefore, both repeated use of cover crops across a rotation and an extended monitoring period would be required to fully assess the effects of cover crops on river water quality at the sub-catchment scale.

4.5 Cover crop management

A number of practical management issues arose during the course of the trial. Prime among these were difficulties in destroying and incorporating the cover crop residues prior to the sowing of the subsequent spring bean crop in early 2014. The oilseed radish grew vigorously (up to 0.5 m in height) and was killed off with a glyphosphate herbicide in mid-January 2014 (Figure 2b). However, large quantities of fresh organic matter remained on the soil surface which proved difficult for the direct drill (Väderstad Seed Hawk) and shallow non-inversion tillage (Väderstad Rapid) machinery to handle. Slug populations were also considerably higher in the cover crop fields during both 2013/14 and 2014/15, as accumulations of fresh plant material provided optimal feeding and breeding conditions, an effect reported elsewhere (Soane et al., 2012). This outcome necessitated additional applications of a molluscicide (metaldehyde) to the cover crop blocks, increasing the variable production costs (section 4.6). This 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(i.e. pesticides) is inadvertently increased (Stevens and

Quinton, 2009). Other agronomic problems encountered included enhanced pea and bean weevil damage to the following spring bean crop and damper soil conditions under the decaying cover crop residues which delayed spring cultivation operations by a few days.

4.6 Farm economics

For cover crops and non-inversion cultivation measures to be economically viable, these approaches need to be financially competitive with traditional farm practice (Posthumus et al., 2015). Table 6 summarises the economic performance of the three mitigation blocks for the 2013/14 farm year. The application and variable costs of establishing and managing the cover crop under direct drill (£704 ha^{-1}) and shallow non-inversion tillage (£748 ha^{-1}) were higher than conventional ploughing with winter fallow (£589 ha^{-1}). Previous research indicated that lower operational costs (e.g. fuel and labour) of non-inversion tillage systems could increase farm margins by £10–85 ha^{-1} compared with conventional ploughing (Deasy et al., 2009; Morris et al., 2010). However, this study found that operational savings in the non-inversion tillage Blocks P and L were offset by increased costs associated with cover crop establishment, principally the purchasing of oilseed radish seed, application of starter N fertiliser and the application of additional molluscicide to control slugs. Nevertheless, higher yields for the 2013/14 spring bean crop in Blocks L (6.24 t ha^{-1}) and P (6.55 t ha^{-1}) compared with Block J (5.80 t ha^{-1}) resulted in only small differences in the overall gross margin between the cover crop/direct drill (£731 ha^{-1}), cover crop/shallow non-inversion tillage (£758 ha^{-1}) and fallow/mouldboard ploughing (£745 ha^{-1}) systems. Yield increases in cash crops in the years following a winter cover crop have also been reported elsewhere (e.g. Stobart and Morris, 2014) demonstrating that farm productivity can be maintained or even enhanced whilst mitigating diffuse agricultural pollution. It is also important to recognise that cover crops can provide a range of additional ecosystem services aside from mitigating nutrient losses, such as carbon sequestration, N_2O reduction and food production, which increase their environmental and socio-economic value (Schipanski et al., 2014). Overall, the positive economic performance of the trials presented here provides good evidence to support the wider adoption of oilseed radish for mitigating diffuse nitrate pollution on UK arable farms.

5. Conclusions

To date, the majority of research into the efficacy of on-farm measures for mitigating diffuse agricultural pollution has come from controlled plot scale studies which typically fail to account for the impacts of measures upon crop yields, farm profit margins, catchment-scale nutrient losses, or the practicalities for the farmer of deploying such measures. Here, we have addressed these issues by assessing the impacts of cover crops and non-inversion tillage regimes at the farm-scale. The key findings were as follows:

- **(i)** A winter oilseed radish cover crop reduced NO_3-N leaching losses by 75–97% relative to fallow, but had no impact upon P losses;
- **(ii)** Direct drilling and shallow non-inversion tillage were ineffective at reducing soil water NO_3-N and P concentrations relative to conventional ploughing;
- **(iii)** Soil NO_3-N concentrations were reduced by ~77% at 60–90 cm depth beneath the cover crop, highlighting the potential of long rooting oilseed radish to scavenge nutrients from deep within the soil profile;
- **(iv)** Despite covering 20% of the catchment, improvements in river water quality downstream of the trial area were not observed, indicating prolonged use of cover crops may be required before catchment-scale impacts are detected;
- **(v)** Higher operational costs associated with the establishment of cover crop and non-inversion tillage regimes were offset by increased yields in the subsequent cash crop, resulting in comparable gross margins (£731–758 ha^{-1}) to conventional ploughing with fallow (£745 ha^{-1}).

Given the paucity of existing farm- and catchment-scale studies, further research into the effectiveness of other cover crop varieties and crop mixtures at reducing arable nutrient losses, particularly in the UK, is highly recommended.

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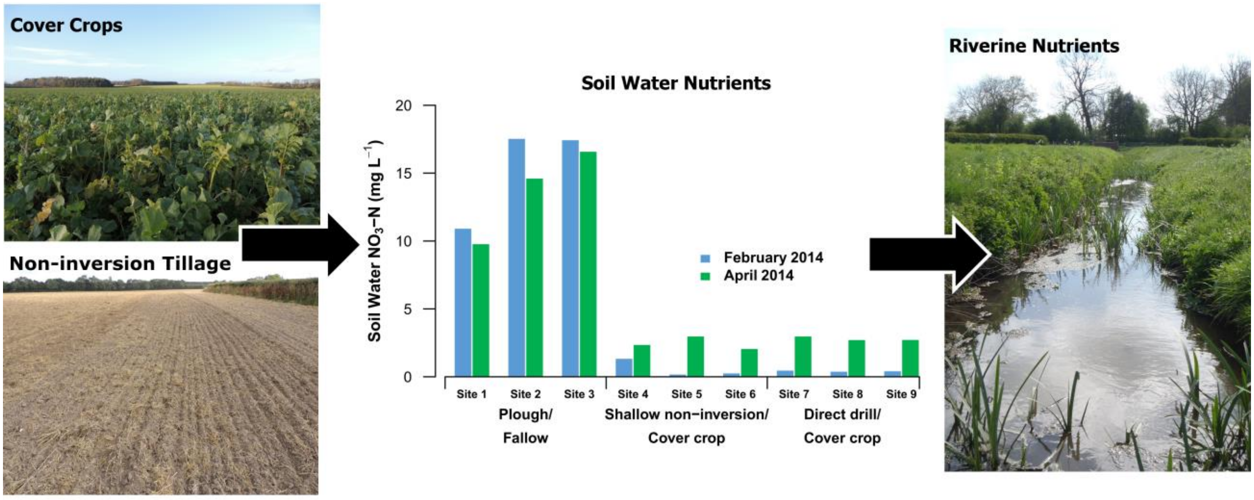
Figures



Graphical Abstract: The impact of cover crops and non-inversion tillage regimes on soil and riverine nutrient concentrations is assessed at the farm-scale.

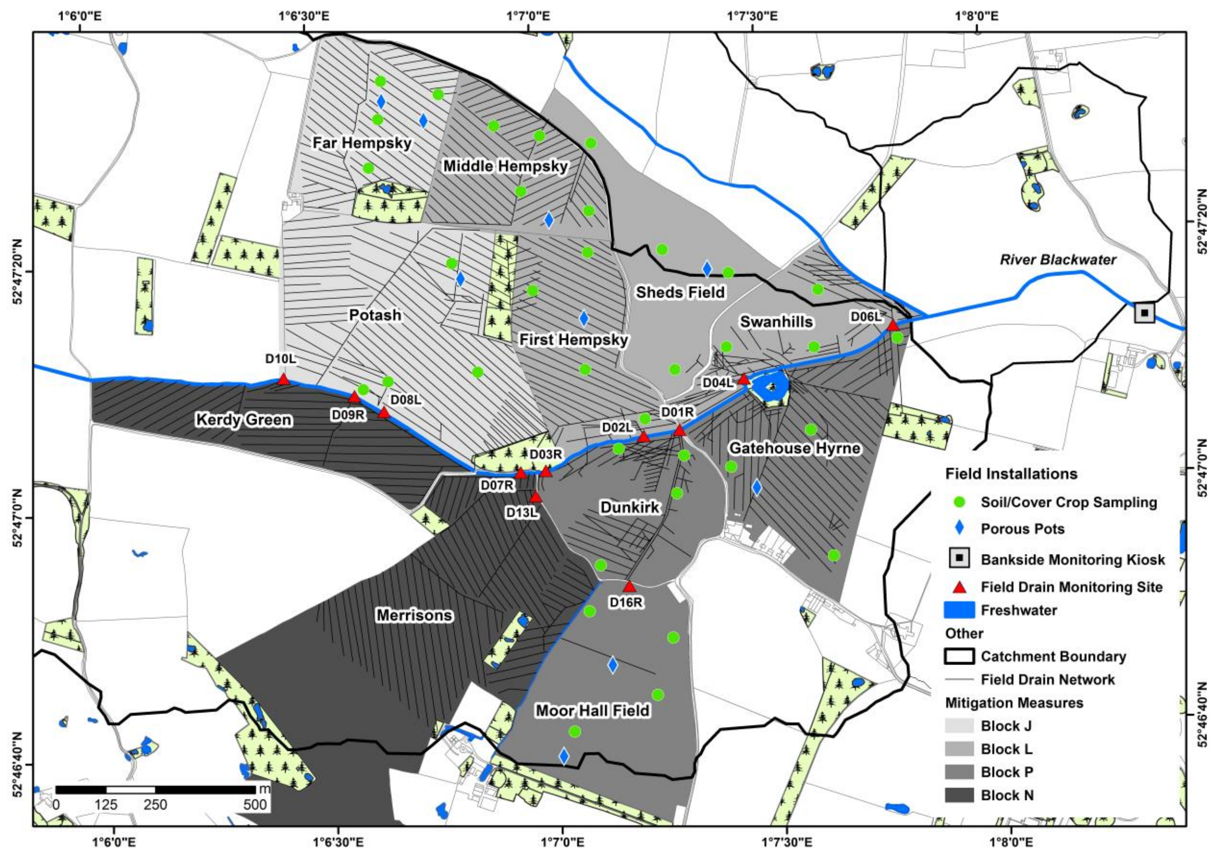


Figure 1: Map of the Salle Park Estate mitigation measures blocks in the River Blackwater sub-catchment, Norfolk, UK, showing the locations of field installations and sampling points.

Figure 2: Images of the Salle Park Estate. (A) Direct drilled oilseed radish on Sheds Field in September 2013. Crop residues from the previous spring barley crop can be seen on the surface; (B) Oilseed radish cover crop on Dunkirk field in February 2014; (C) Winter wheat on the shallow non-inversion tillage Dunkirk field in November 2014. Spring bean volunteers can be seen emerging through the wheat; (D) Bankside monitoring kiosk on the River Blackwater downstream of the mitigation measures trial area. River channel is 2.5 m wide.

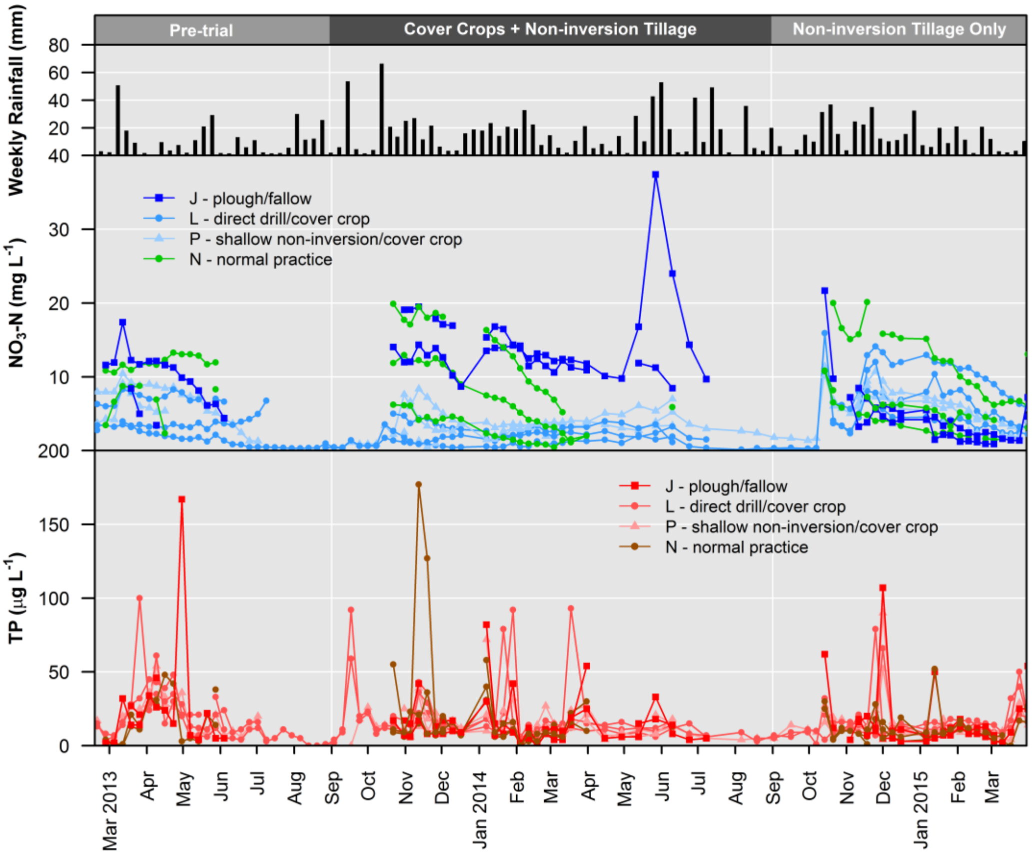


Figure 3: Field drain NO_3-N and TP concentrations measured in Blocks J, L, P and N between March 2013 and March 2015.

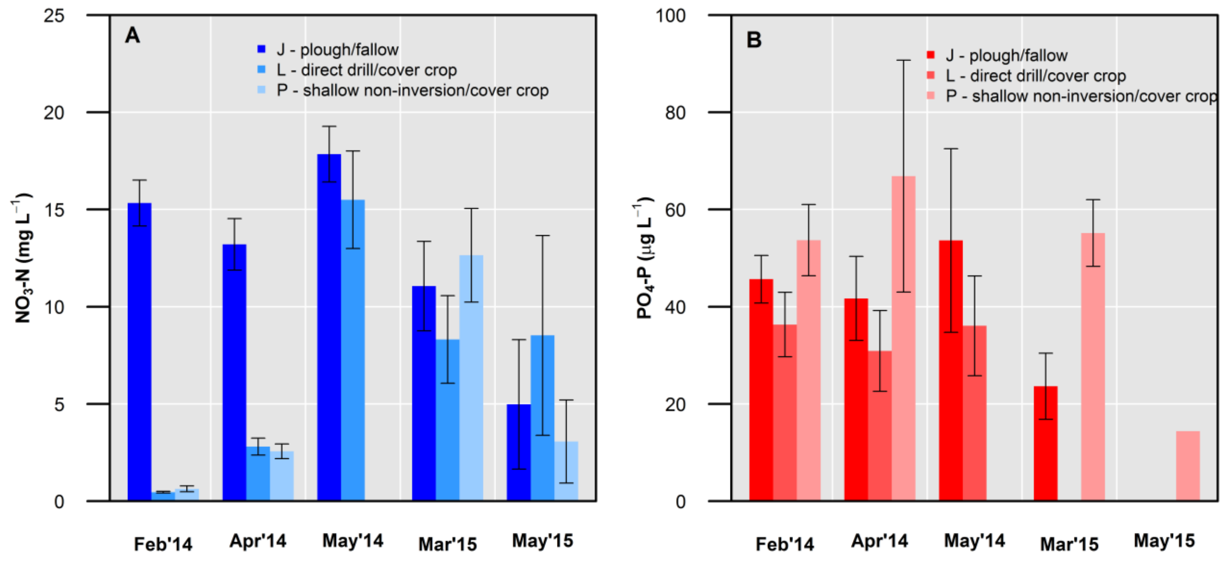


Figure 4: Porous pot (A) NO_3-N and (B) PO_4-P concentrations measured in Blocks J, L and P on five sampling occasions. Error bars represent one standard error.

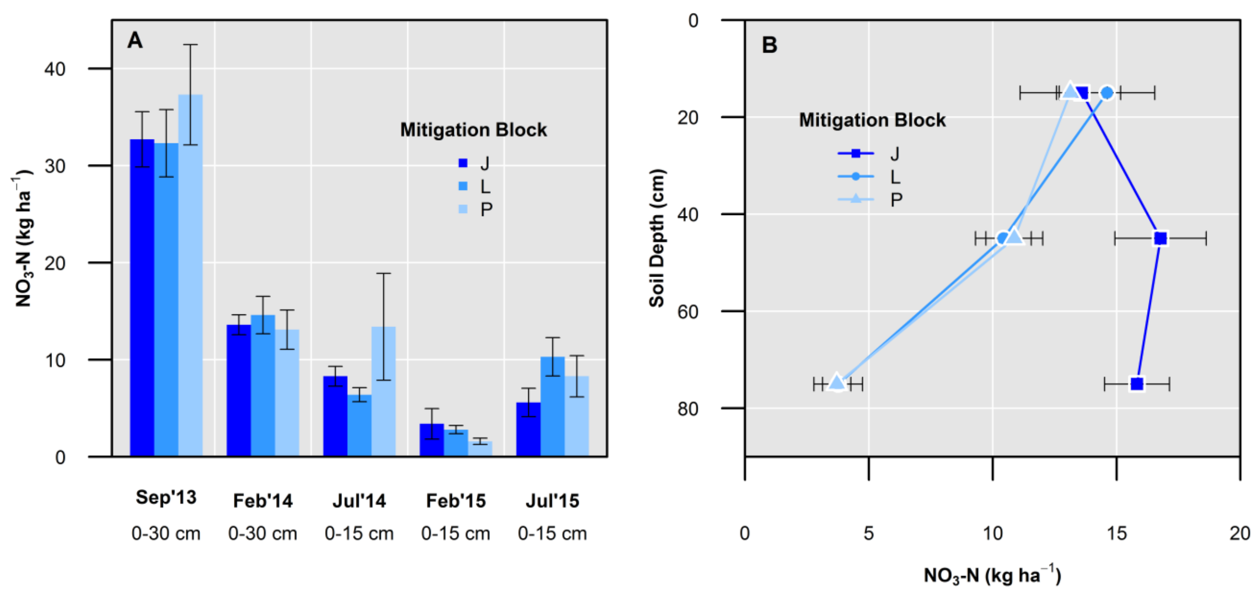


Figure 5: (A) Mean topsoil NO_3-N concentrations recorded in the three mitigation measures blocks on five sampling occasions; (B) Mean soil NO_3-N depth profiles recorded in February 2014. Error bars represent one standard error.

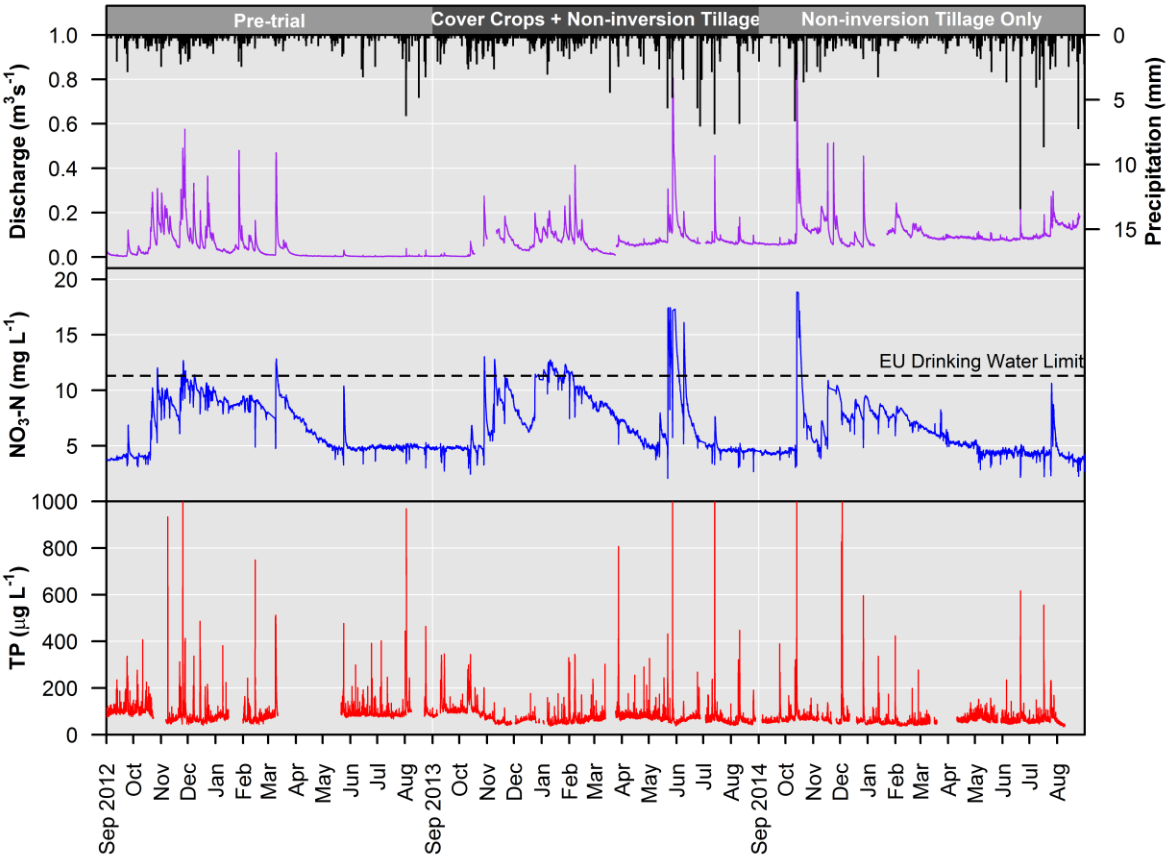


Figure 6: High-frequency (30 min) hydrochemical data for the River Blackwater recorded between September 2012 and August 2015 at the bankside monitoring kiosk downstream of the trial area.

Tables

Table 1: Summary of the crop types and cultivation methods employed in the mitigation measures blocks during three farm years. WW = winter wheat; WBAR = winter barley; SBAR = spring barley; SB = spring beans; OR CC = oilseed radish cover crop; OSR = winter oilseed rape. Monitored field drains also listed.

Field Name	Block	Soil Type	Size (ha)	2012/13 Crop	2013/14 Crop	Starter Fertiliser	2013/14 Cultivation	2014/15 Crop	2014/15 Cultivation	Field Drains
Potash	J	Clay loam	28.4	WW	SB	-	Plough	WW	Plough	D08L, D10L
Far Hempsky	J	Sand clay loam	13.3	SBAR	SB	-	Plough	WW	Plough	-
Gatehouse Hyrne	P	Clay loam	18.8	SBAR	OR CC/SB	Y	Shallow non-inversion	WW	Shallow non-inversion	-
Moor Hall Field	P	Sandy clay loam	20.2	SBAR	OR CC/SB	N	Shallow non-inversion	WW	Shallow non-inversion	D16R
Dunkirk	P	Sandy clay loam	12.9	WW	OR CC/SB	Y	Shallow non-inversion	WW	Shallow non-inversion	D01R, D03R
Middle Hempsky	L	Clay loam	12.6	SBAR	OR CC/SB	N	Direct drill	WW	Direct drill	-
First Hempsky	L	Sandy clay loam	14.6	SBAR	OR CC/SB	Y	Direct drill	WW	Direct drill	D02L
Sheds Field	L	Sandy loam	14.8	SBAR	OR CC/SB	Y	Direct drill	WW	Direct drill	-
Swanhills	L	Sandy loam	11.1	SBAR	OR CC/SB	Y	Direct drill	WW	Direct drill	D04L, D06L
Merrisons	N	Clay loam	48.7	SB	WW	-	Plough	WBAR	Plough	D07R, D13L
Kerdy Green	N	Clay loam	14.4	WBAR	OSR	-	Plough	WW	Plough	D09R

Table 2: Field drain flows, nutrient concentrations and loads recorded under each mitigation measure block between March 2013 and March 2015. Values presented as means ± one standard deviation. Asterisks indicate *t*-test significant differences (* = $p < 0.05$, ** = $p < 0.01$) from control Block J.

Parameter	Block	Pre-trial (2012/13)	Cover crops + non-inversion tillage (2013/14)	Non-inversion tillage only (2014/15)
Flow ($L\ s^{-1}$)	J	0.04 ± 0.04	0.19 ± 0.19	0.19 ± 0.17
	P	0.07 ± 0.11	0.17 ± 0.22	0.26 ± 0.41
	L	0.04 ± 0.03	0.07 ± 0.06**	0.08 ± 0.05**
	N	0.06 ± 0.07	0.23 ± 0.21	0.26 ± 0.24
NO_3-N concentration (mg N L^{-1})	J	9.6 ± 3.6	14.0 ± 4.6	4.3 ± 3.7
	P	6.4 ± 2.5	3.5 ± 1.6**	5.5 ± 2.5
	L	5.5 ± 2.2	1.8 ± 1.1**	6.2 ± 3.9
	N	10.0 ± 3.0	7.7 ± 5.7**	7.6 ± 5.0*
NO_3-N load (kg N $ha^{-1}\ a^{-1}$)	J	2.2 ± 5.8	71.9 ± 160.4	39.2 ± 137.6
	P	4.6 ± 14.7	13.8 ± 24.2**	102.1 ± 219.9*
	L	13.5 ± 26.7**	15.3 ± 26.6**	47.0 ± 53.4
	N	0.9 ± 3.2	9.0 ± 18.4**	15.7 ± 31.8
TP concentration (μg P L^{-1})	J	26 ± 37	15 ± 15	16 ± 20
	P	21 ± 14	14 ± 10	14 ± 12
	L	22 ± 18	16 ± 17	15 ± 12
	N	16 ± 15	17 ± 28	11 ± 9
TP load (kg P $ha^{-1}\ a^{-1}$)	J	0.02 ± 0.05	0.19 ± 0.73	0.20 ± 0.50
	P	0.02 ± 0.06	0.08 ± 0.24	0.26 ± 0.65
	L	0.13 ± 0.44*	0.13 ± 0.21	0.12 ± 0.17
	N	0.01 ± 0.01	0.03 ± 0.10	0.03 ± 0.08*

Table 3: Summary of the topsoil nutrient analyses for the mitigation measures blocks. Values presented as averages ± one standard deviation. Asterisks indicate *t*-test significant differences (* = $p < 0.05$, ** = $p < 0.01$) from control Block J.

Sampling Date	Mitigation Period	Mitigation Block	Nitrate-N (kg N ha^{-1})	Phosphorus (kg P ha^{-1})	Potassium (kg K ha^{-1})	Organic Matter (%)
September 2013 (0-30 cm)	Pre-trial	J	32.7 ± 8.1	96.4 ± 26.0	498.4 ± 105.5	2.0 ± 0.4
		P	37.3 ± 17.9	132.0 ± 47.9*	557.5 ± 157.5	1.7 ± 0.4
		L	32.3 ± 13.9	142.5 ± 51.7**	483.1 ± 101.1	1.5 ± 0.4
February 2014 (0-30 cm)	Cover crops + non-inversion tillage	J	13.6 ± 2.9	80.6 ± 23.7	426.6 ± 115.3	2.0 ± 0.6
		P	13.1 ± 7.0	130.8 ± 43.5**	687.4 ± 138.1**	1.9 ± 0.6
		L	14.6 ± 7.7	131.2 ± 41.6**	648.1 ± 153.2**	1.6 ± 0.5
July 2014 (0-15 cm)	Cover crops + non-inversion tillage	J	8.3 ± 2.9	-	-	-
		P	13.4 ± 19.0	-	-	-
		L	6.4 ± 2.9	-	-	-
February 2015 (0-15 cm)	Non-inversion tillage only	J	3.4 ± 4.4	46.0 ± 16.3	240.5 ± 71.1	2.1 ± 0.6
		P	1.6 ± 1.1	62.6 ± 25.6	306.0 ± 57.2*	1.8 ± 0.5
		L	2.8 ± 1.7	74.2 ± 29.7**	352.7 ± 107.1**	1.7 ± 0.5
July 2015 (0-15 cm)	Non-inverison tillage only	J	5.6 ± 4.2	54.0 ± 22.5	192.6 ± 72.7	2.1 ± 0.6
		P	8.3 ± 7.3	60.9 ± 24.9	249.7 ± 49.7	1.9 ± 0.5
		L	10.3 ± 7.9	77.4 ± 30.3*	292.0 ± 124.9*	1.8 ± 0.6

Table 4: Nutrient analysis of the oilseed radish cover crop undertaken in January 2014. Values presented as averages ± one standard deviation.

Parameter	Cover crop	With Starter Fertiliser	Without Starter Fertiliser
Nitrogen content (kg N ha^{-1})	Leaf	65.8 ± 12.6	57.3 ± 3.3
	Root	13.6 ± 5.5	12.3 ± 1.7
	Leaf + root	79.4 ± 13.7	69.6 ± 3.7
Phosphorus content (kg P ha^{-1})	Leaf	7.4 ± 1.7	6.6 ± 0.5
	Root	4.1 ± 1.2	4.9 ± 0.7
	Leaf + root	11.5 ± 2.0	11.5 ± 0.9
Potassium content (kg K ha^{-1})	Leaf	66.7 ± 13.8	53.6 ± 4.6
	Root	23.2 ± 4.5	23.2 ± 2.2
	Leaf + root	90.0 ± 14.5	76.8 ± 5.1
Dry matter (t ha^{-1})	Leaf	2.2 ± 0.3	1.9 ± 0.2
	Root	0.6 ± 0.1	0.7 ± 0.1
	Leaf + root	2.8 ± 0.3	2.6 ± 0.2

Table 5: February 2014 nitrogen balance for the cover crop fields applied with starter fertiliser compared to those without a starter fertiliser. Values reported as averages ± one standard deviation.

Parameter	Type	Units	With Fertiliser	Without Fertiliser	N Balance
Inputs	Applied fertiliser	kg N ha^{-1}	30.0	0.0	+30.0
Outputs	Oilseed radish	kg N ha^{-1}	79.4 ± 13.7	69.6 ± 3.7	-9.8
				Net	**+20.2**
Residuals	Soil 0-30 cm	kg NO_3-N ha^{-1}	15.0 ± 8.1	11.4 ± 4.3	+3.6
	Soil 30-60 cm	kg NO_3-N ha^{-1}	11.5 ± 4.7	8.4 ± 1.1	+3.1
	Soil 60-90 cm	kg NO_3-N ha^{-1}	4.0 ± 3.4	3.0 ± 2.6	+1.0
	Porous pots	mg NO_3-N L^{-1}	0.8 ± 0.8	0.3 ± 0.2	+0.5

Table 6: Summary of the economic performance of the three mitigation measures blocks during the 2013/14 farm year.

Profit/Cost	Mitigation Measure Block (£ ha^{-1})		
	J	**L**	**P**
Yield (t ha^{-1})	5.80	6.24	6.55
Income*	1334	1435	1506
Establishment costs	96	67	128
Application costs	90	120	120
Harvesting costs	85	85	85
Variable costs	318	432	415
Total Costs	589	704	748
Gross margin	**745**	**731**	**758**

*Assuming £230 t^{-1}