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Surface and Subsurface Phosphorus Discharge from a Clay Soil in a Nine-Year Study Comparing No-Till and Plowing

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Abstract

No-till as a water protection measure is highly efficient in controlling erosion and particulate P (PP) loss but tends to increase dissolved reactive P (DRP) concentrations in runoff water. In a 9-yr field study on a clay soil in Southwest Finland, the effects of no-till and autumn plowing on surface runoff and subsurface drainage water quality were compared. The site had a 2% slope and was under spring cereal cropping, with approximately replacement fertilizer P rates. Vertical stratification of soil-test P that had developed during a preceding 6-yr grass ley was undone by plowing but continued to develop under no-till. During the 9-yr study period, no-till soil had 27% lower cumulative total P losses than plowed soil (10.0 vs. 13.7 kg total P ha^{-1}). Concentrations and losses of PP were clearly lower under no-till than under plowing (5.6 vs. 12.3 kg PP ha^{-1}), but DRP loss showed the opposite trend (4.3 vs. 1.4 kg DRP ha^{-1}). There was an increasing trend in subsurface drainflow DRP concentration under no-till, possibly because of development of a conductive pore structure from soil surface to drain depth. The potential benefit of no-till in water protection depends on how much of the PP transported to water is transformed into a bioavailable form and used by aquatic organisms. The beneficial effect of no-till in controlling P-induced eutrophication at the study site would only be realized if the bioavailable share of PP exceeds 43%. Otherwise, no-till would not be an efficient eutrophication control measure at this site.

Core Ideas

- No-till decreased total P losses by 27% compared with autumn plowing.
- No-till produced 4.5-fold higher DRP loss and 54% lower PP loss than plowing.
- When changes in DRP and PP are opposite, TP changes should be interpreted with caution.
- In this case, the effect on eutrophication largely depends on PP bioavailability.
- At the study site, increased DRP load is compensated if PP bioavailability is >43%.

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No-till is considered beneficial for important soil quality parameters, such as aggregate stability and soil water storage (Carter, 1992; Grandy et al., 2006). It promotes earthworm activity, which increases the number and continuity of biopores, thus facilitating water infiltration after storm events (Edwards et al., 1990). In low-rainfall environments, increased crop yields as a result of soil moisture preservation have been demonstrated, whereas in high-rainfall environments, no-till has been promoted as a water protection measure (Soane et al., 2012).

In continuous cereal cropping, no-till is undeniably the most effective means to control water and wind erosion (Edwards et al., 1990; Triplett and Dick, 2008). However, omission of soil inversion leads to gradual P stratification (i.e., accumulation of labile P in the uppermost soil layer) (Thompson and Whitney, 2000; Cook and Trlica, 2016; Baker et al., 2017). This layer is highly influential in determining dissolved reactive P (DRP) concentration in overland flow (Sharpley et al., 1978; Ahuja et al., 1982; Yang et al., 2015). Consequently, the P stratification in no-till soils results in elevated DRP concentrations in surface runoff and often higher DRP losses in overland flow than from plowed soil (Sharpley and Smith, 1994; Puustinen et al., 2005; Smith et al., 2015a).

Increased DRP concentration in surface runoff after transition from plowing to no-till has been consistently documented in field studies, but previous findings on subsurface drainflow P concentrations are inconsistent. In on-farm monitoring studies conducted in Indiana and Ontario by Smith et al. (2015a) and Zhang et al. (2017), respectively, no-till did not elevate DRP losses via tile drainage water. In Sweden, in a 3-yr study of 1.2-m-deep undisturbed soil monoliths retrieved from a clay soil in which macropore flow was the dominant solute transport pathway, Djodjic et al. (2002) found no statistically significant difference in DRP transport by percolation between tilled and no-till treatments. In storm event monitoring of tile drainage waters, Williams et al. (2016) reported a sharper increase in DRP losses after surface application of P fertilizer in a no-till field than in an adjacent plowed field. In their 3-yr study in Ontario, Gaynor and Findlay (1995) found that no-till produced higher DRP concentrations to tile drainage water than plowed soil (0.69 vs. 0.25 mg L^{-1}, respectively), although P fertilizer was subsurface banded. After a review of studies on drainage P losses, Christianson et al. (2016) concluded that subsurface DRP losses from no-till soils

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Abbreviations: DRP, dissolved reactive phosphorus; PP, particulate phosphorus; TP, total P.

tend to be higher than those from conventionally tilled soils, but that more field studies are needed to confirm this. In general, no-till is considered to increase the risk for P losses via subsurface drainage pipes, especially on fine-textured, structured soils (King et al., 2015). On these types of soils, subsurface tile drains are significant water discharge pathways and thus conduits of P loss (Turtola and Paajanen, 1995; Simard et al., 2000; Smith et al., 2015b; Van Esbroeck et al., 2016).

To clarify the effects of no-till on surface and subsurface transport of DRP and particulate P (PP), we performed a 9-yr study on a clay soil in Southwest Finland in which no-till and conventional autumn plowing to 20-cm depth were applied side by side in a 2-ha field under cereal cultivation. Fertilizer P was used at an approximately replacement rate, placed at or below seed depth in both tillage treatments. The tillage study was started after 6-yr monitoring of water and P discharges under uniform management to establish baseline P losses from the field plots.

Materials and Methods

Study Site and Soil Properties

The field site is in Kotkanoja, Jokioinen, Southwest Finland (60°49′ N, 23°30′ E), ~100 m above the current sea level. The field is 2 ha in size, divided in four 0.5-ha plots (Fig. 1), and it has a mean slope of 2% (range = 1–4%), with the steepest area around the middle part of the field (Supplemental Fig. S1). The soil at the site derives from an ancient Baltic Sea sediment that was exposed by land uplift ~10,000 yr ago. It was previously classified as a Vertic Cambisol (Yli-Halla and Mokma, 2001) but recently revised to a Protovertic Luvisol (Clayic, Cutanic) as a result of evident clay translocation and lack of stagnic color patterns (M. Yli-Halla, personal communication, 2018).

A detailed soil profile description with P fractionation can be found in Peltovuori et al. (2002). The clay content (<0.002 mm particle separate) ranges from ~50 to 60% in the surface layer to 75 to 90% at 0.5- to 1.2-m depth. In the 20- to 24-cm-thick Ap horizon, the organic carbon content is 2 to 3% and the soil pH_{H2O} is kept at around 6.5 by occasional liming. Oxalate-extractable Al concentration is 103 mmol kg^{-1}, and oxalate-extractable Fe concentration is 235 mmol kg^{-1} in the Ap horizon, decreasing to ~70 to 80 mmol kg^{-1} (for both elements) in the C horizon (tile drainage depth). Clay mineralogy consists of illitic mica, quartz, and K-feldspars, with chlorite being detected below 30 cm (Peltovuori et al., 2002).

Total P (TP) content in the Ap horizon, determined by the aqua regia-HF extraction method (Bowman, 1988), is ~1300 to 1400 mg kg^{-1}. According to the Chang-Jackson P fractionation technique, soil TP comprises 30 to 35% metal oxide-associated P (sum of NH_4F-P and NaOH-P fractions), 15% apatite-P (H_2SO_4–extractable), and 55 to 60% nonrecovered residual P (Peltovuori et al., 2002). According to data on the B horizon, which is devoid of organic C, the residual P is probably present as stable mineral-embedded P and organic P in equal proportions. The soil-test P concentration of the 0- to 20-cm layer, determined before the start of the present study, was 5 to 7 mg L^{-1} when determined by the acidic (pH 4.65) ammonium acetate test (Vuorinen and Mäkitie, 1955), 30 to 57 mg L^{-1} according to the Mehlich-3 test (Mehlich, 1984), and 31 to 45 mg kg^{-1} according to the Olsen test (Olsen and Sommers, 1982).

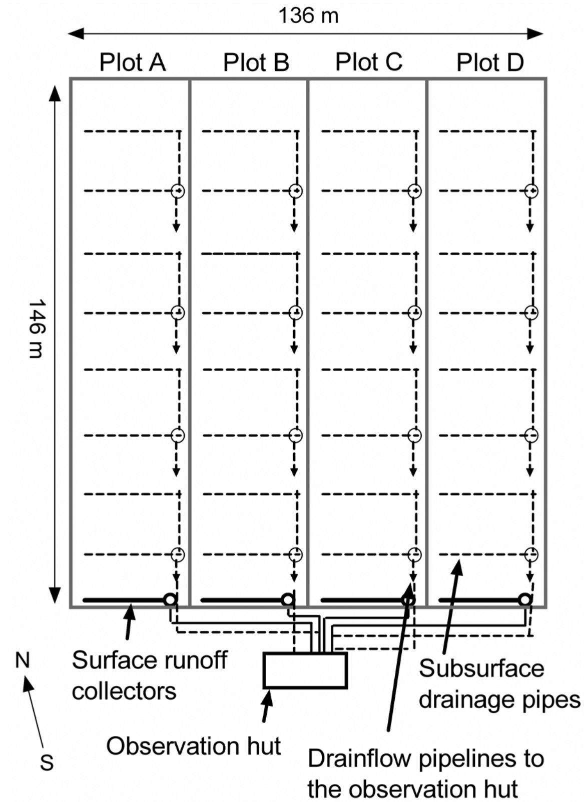

Fig. 1. Layout of the Kotkanoja field in Jokioinen, Southwest Finland.

Management

A summary of management practices before the present study is given in the supplemental material. Shortly, plowed plots were annually plowed until 2001, whereas plots under no-till were chisel-tilled to 5- to 8-cm depth in 1996 to 2001. In this paper, we first report P discharge for six annual cycles (September 2002–August 2008) when all plots were treated uniformly—hereafter referred to as the "grass period"—to provide baseline behavior of the plots before the tillage treatments were applied. Autumn moldboard plowing and no-till were then applied the following 9 yr (September 2008–August 2017) as tillage treatments in duplicate plots—hereafter referred to as the "treatment period."

Grass Period

In May 2002, cow manure (with peat bedding) was spread on all plots at a rate of 31 Mg ha^{-1}, supplying 170 kg total N and 32.6 kg P ha^{-1}, and mixed into the soil to 10-cm depth using a Lely power harrow. The whole field was cropped with oats (*Avena sativa* L.) in 2002, with undersown yellow lucerne [*Medicago sativa* ssp. *falcata* (L.) Arcang.] and tall fescue (*Festuca arundinacea* L.). The oat crop was harvested in autumn 2002, and in the following 5 yr (until autumn 2007), one cut of lucerne–fescue ley was taken per year, without any fertilizer application during the period. The ley was harvested in summer (except the wet summer of 2005, when it was cut later in October 2005, shredded, and left to decompose on the soil surface). In autumn 2007, the ley was terminated with glyphosate. In May 2008, all plots were sown with oats using a VM 300 DS no-till combidrill (Vieskan Metalli) that placed seeds and fertilizer at 3- to 4-cm depth within the same rows.

Treatment Period

Spring-sown cereals were grown during the following years, with two different tillage treatments applied in field plots from September 2008. In one treatment, Plots A and C were plowed to 20 cm, whereas the Plots B and D were left untilled and continued under no-till management during the rest of the study. The seedbed in the autumn-plowed plots was prepared in May using a tine harrow and drilled with a combidrill that placed seeds at 5-cm depth and side-banded fertilizer at 8-cm depth. The different fertilizer placement depths for the treatments follow from the different combidrill machines used for no-till and plowed treatments.

The oat crop grown from 2008 to 2010 was fertilized annually with 80 to 90 kg N, 7 to 13 kg P, and 10 to 40 kg K ha^{-1}. The barley (*Hordeum vulgare* L.) grown from 2011 to 2013 was fertilized with 90 kg N, 21 to 24 kg P, and 21 to 31 kg K ha^{-1}, whereas the spring wheat (*Triticum aestivum* L.) grown from 2014 to 2015 was fertilized with 100 kg N, 13 to 15 kg P, and 35 to 40 kg K ha^{-1}. Oats were grown again in 2016 to 2017 and were fertilized with 90 kg N, 12 kg P, and 31 kg K ha^{-1}. The P doses applied, P offtake with the harvested crop, resulting P balances, and harvested yields for plot pairs A + C and B + D are given in Table 1.

Water Sampling and Analyses

Surface runoff was collected at the lower end of the plots, in pits filled with a layer of 30 to 50 mm pebbles, under which a drainage pipe was laid to conduct water to collection wells. Movement of surface runoff between the plots is prevented by 20- to 30-cm-high barriers of mounded soil around the plot margins; belowground, the plots are separated from each other to 1-m depth with plastic curtains. Subsurface drainage water from each field plot was collected with four plastic drainage pipes and conducted separately to an observation hut. Water volume was recorded with tipping buckets equipped with magnetic counters. About 0.1% of the flow was diverted to plastic containers using small funnels placed under the tipping buckets. Water samples for laboratory analyses were retrieved from the field on a daily to biweekly basis, depending on flow. Changes in P speciation due to longer sampling intervals are likely, but delayed sampling was restricted to periods with negligible flow in summer and winter. Sampling vessels were also then checked and sampled as needed after major storm events.

The laboratory analyses reported in this paper include dissolved molybdate-reactive P (DRP) and TP. Samples used for DRP determination were pretreated by vacuum filtering through a 0.2-μm Nuclepore membrane (Whatman) within 24 h of sampling. The samples were then stored in a refrigerator, and DRP analyses were conducted within a few days. Total P was analyzed on unfiltered subsamples after hydrogen peroxide-peroxodisulfate digestion (at 120°C, 120 kPa for 30 min). Particulate P was calculated as the difference between TP and DRP. All P analyses were performed using a LaChat 8000 Quickchem flow-injection analyzer (LaChat Instruments).

Statistical Analysis

Statistical analysis was performed separately for the grass and treatment periods. Analyses for the grass period showed the baseline P discharges from all plots before the tillage experiment, which was necessary because earlier management studies (plowing to 20 cm vs. shallow tillage to 5–8 cm) had created differences in P stratification and P loss response in the field (Uusitalo et al., 2007).

To examine differences in responses between the pairs of plots, repeated measurement two-way ANOVA was performed. When a significant time × treatment interaction was found, the

Table 1. Averaged over the duplicate plots, doses of P applied, offtake of P, P balance, and harvested yields during the study. The oat crops sown in May 2002 (with undersown yellow lucerne and tall fescue) and 2008 are included in the grass period, because the whole field was treated uniformly.

Crop year	Crop	Plots A and C				Plots B and D			
		P applied	P offtake	P balance	Yield	P applied	P offtake	P balance	Yield
		kg ha^{-1}							
2002	Oats–grass	32.6†	9.2	23.4	2060	32.6†	8.8	23.8	1920
2003	Grass	0.0	8.3	−8.3	3640	0.0	6.7	−6.7	3190
2004	Grass	0.0	14.1	−14.1	4340	0.0	14.3	−14.3	4320
2005	Grass	0.0	0.0	0.0	0‡	0.0	0.0	0.0	0‡
2006	Grass	0.0	4.1	−4.1	2460	0.0	4.2	−4.2	2210
2007	Grass	0.0	10.7	−10.7	4990	0.0	7.8	−7.8	3890
2008	Oats (no-till)	6.9	7.7	−0.8	3590	6.9	7.0	−0.1	3330
2002–2008 avg.		5.6	7.7	−2.1	3510	5.4	7.0	−1.3	3140
		Plowed (from September 2008)				No-till (from May 2008)			
2009	Oats	12.9	19.8	−6.9	4640	12.9	15.8	−2.9	3910
2010	Oats	11.7	12.8	−1.1	2800	11.7	8.3	3.4	1860
2011	Barley	20.5	15.4	5.1	3650	20.5	10.9	9.6	2530
2012	Barley	20.5	14.3	6.2	3610	20.5	14.2	6.3	3430
2013	Barley	24.4	14.5	9.9	3760	24.4	17.9	6.5	4100
2014	Wheat	15.0	19.9	−4.9	4420	15.0	20.9	−5.9	4290
2015	Wheat	13.1	12.9	0.2	3010	13.1	9.4	3.7	2240
2016	Oats	11.7	15.8	−4.1	4160	11.7	12.3	−0.6	3290
2017	Oats	11.7	17.4	−5.7	4110	11.7	9.1	2.6	2310
2009–2017 avg.		15.7	15.9	−0.1	3800	15.7	13.2	2.5	3210

† P applied with cow manure and mixed in the 0- to 10-cm soil layer.

‡ Grass was not harvested due to risk of soil compaction in wet conditions.

Bonferroni post-test was applied, with GraphPad Prism 4.03 software (GraphPad Software, 2005). Annual, quarterly (every 3 mo), and monthly flow-weighted concentrations and discharges were calculated and tested by treating Plots A + C and Plots B + D as replicates, according to the layout in the treatment period and the earlier tillage experiments in the field. When examining water discharge and P losses, tests were run for surface runoff, subsurface drainflow, and their combined discharge. Annual and quarterly test results are summarized in this paper and in the supplemental material (Uusitalo et al., 2018). The results of monthly testing are not shown but are referred to in the text when considered relevant. Probability values of $p < 0.05$ were taken to indicate statistically significant differences.

Results

Hydrology

Total water discharge during the combined grass and treatment periods (September 2002–August 2017) averaged 230 mm yr^{-1}, which represented about one-third of mean annual precipitation (620 mm). Flow peaked during snowmelt, typically from mid-March to early April, when 55 to 60% of the annual surface runoff volume was discharged. Subsurface drainflow started at the end of the main snowmelt. There was another long, more diffuse period of higher discharge starting after harvest and continuing until the frost set in between November and January. For the autumn (September–November) discharge, 80% or more was often subsurface flow. Annual and quarterly data on rainfall, mean temperature, and plot-wise water discharge are given in Supplemental Tables S1 (grass period) and S5 (treatment period).

Of the annual mean flow in the grass period (218 mm), 40% was surface runoff and 60% was drainflow. For surface runoff, there were no significant differences between the pairs of plots (A + C, B + D) in mean annual (Fig. 2) or quarterly volume (Supplemental Table S1), although the 6-yr sum of surface runoff was 12% higher for Plots B + D than for Plots A + C. For subsurface drainflow, discharge from Plots A + C was significantly greater than discharge from Plots B + D during 1 yr included in the grass period (Fig. 2). However, calculated as cumulative total flow (sum of surface and subsurface), water discharge during the grass period only differed by 3% between the pairs of plots (Supplemental Table S1).

During the treatment period (September 2009–August 2017), with mean annual flow sum of 238 mm, no-till plots (B + D) had similar proportions of surface (37%) and subsurface (63%) flow as in the grass period, whereas discharge from autumn-plowed plots (A + C) occurred less as surface runoff (25%) and more as subsurface flow in drainage pipes (75%). Surface flow discharge from no-till plots occurred mostly during spring (March–May), the flow period associated with snowmelt, and in total was 60% higher (826 mm) during the 9-yr period than runoff from plowed plots (516 mm). Conversely, plowed plots discharged 10% more total drainflow (1535 mm) than no-till plots (1409 mm). This was partly a result of subsurface drainflow from plowed plots typically starting earlier than drainflow from no-till plots. Calculated as the sum of surface and subsurface water discharge, no-till plots discharged ~10% more water than plowed plots during the treatment period.

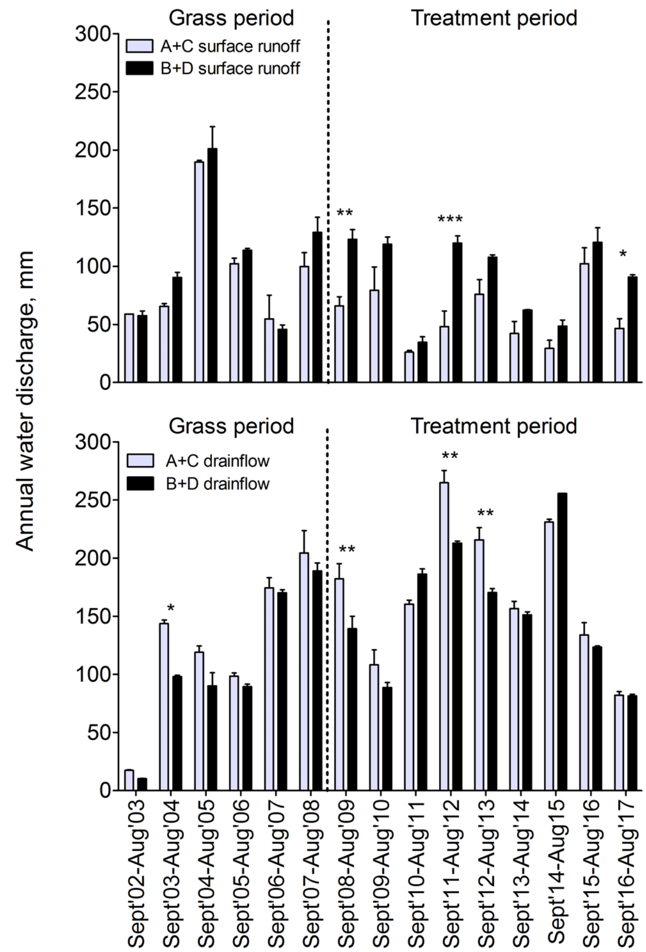

Fig. 2. Annual (September–August) water discharge in surface runoff (upper panel) and subsurface drainflow (lower panel) at the study site. Field Plots A + C and B + D were managed similarly during the grass period (September 2002–August 2008). During the treatment period, Plots A + C were plowed each autumn, whereas Plots B + D were under no-till. The grass and treatment periods are indicated by vertical dotted lines. Error bars indicate the range for duplicate field plots. Significance of differences in means between treatments: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Numerical values of annual and quarterly losses are given in Supplemental Tables S1 (grass period) and S5 (treatment period).

Grass Period: Baseline Phosphorus Concentrations and Losses

The concentrations of DRP in both surface and subsurface flow were, at the start of the grass period, somewhat higher for Plots B + D, but the concentrations for all plots became similar toward the end of the period (Supplemental Fig. S2). The effect on DRP concentrations of cow manure application (supplying 32.6 kg P ha^{-1}, mixed into the 0- to 10-cm soil layer) during grass establishment in May 2002 was not readily distinguishable from other variations during the grass period.

Mean annual DRP losses in the grass period did not differ significantly between Plots A + C and Plots B + D (Fig. 3). The more detailed quarterly analyses of DRP losses (Supplemental Table S2) showed that, of the 24 quarter-years studied, only one was associated with significantly different mean DRP losses (March–May 2004). Nevertheless, in total over the entire 6-yr grass period, Plots B + D had 26% higher cumulative surface runoff DRP losses than Plots A + C (1.58 vs. 1.25 kg ha^{-1}),

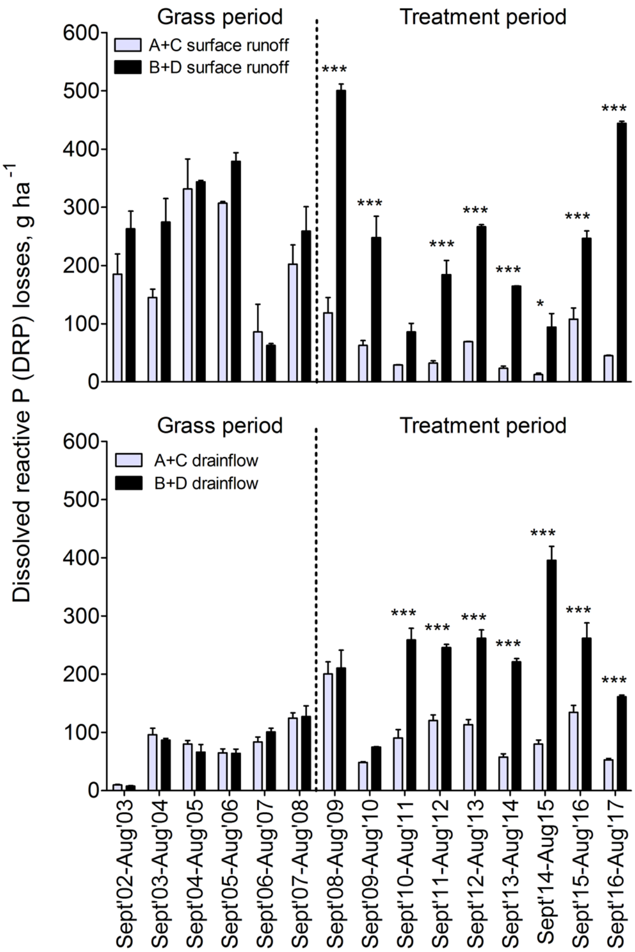

Fig. 3. Annual (September–August) losses of dissolved reactive P (DRP) in surface runoff (upper panel) and subsurface drainflow (lower panel) at the study site. Significance of differences in means between treatments: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Numerical values of annual and quarterly losses are given in Supplemental Tables S2 (grass period) and S6 (treatment period).

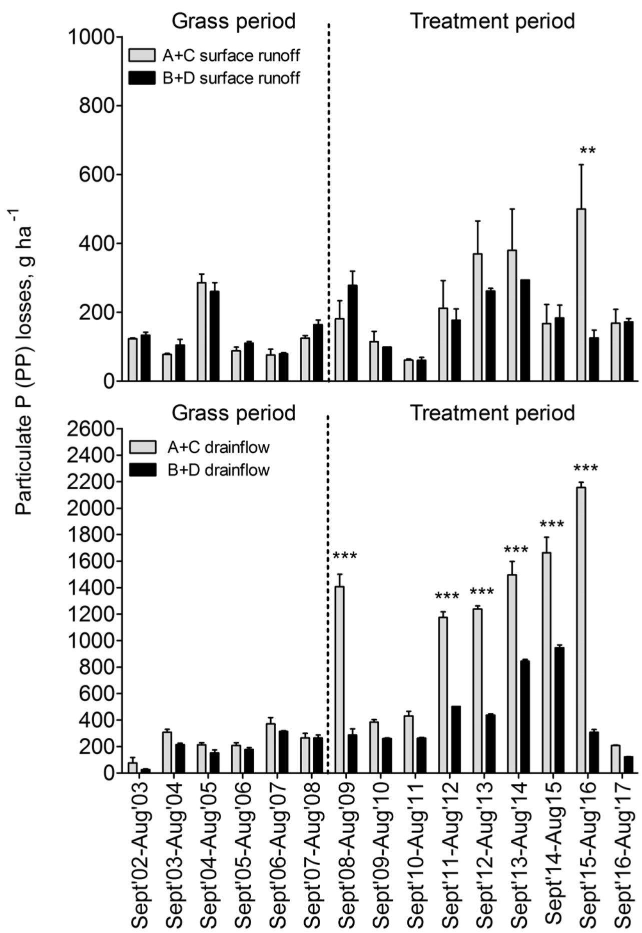

Fig. 4. Annual (September–August) losses of particulate P (PP) in surface runoff (upper panel) and subsurface drainflow (lower panel) at the study site; note the different *y* axis scales. Significance of differences in means between treatments: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Numerical values of annual and quarterly losses are given in Supplemental Tables S3 (grass period) and S7 (treatment period).

whereas mean subsurface drainflow DRP losses were similar for both pairs of plots (0.45–0.46 kg ha^{-1}).

The share of PP in TP losses during the grass period was, on average, 35 to 40% in surface runoff and 70 to 80% in drainflow. No significant differences between the pairs of plots in PP or TP concentrations were detected during the grass period (Supplemental Fig. S2). Moreover, there were no statistically significant differences in annual PP and TP losses between the pairs of plots during the grass period (Fig. 4 and 5). During the whole 6-yr grass period, cumulative surface runoff PP losses from Plots B + D were 10% higher and TP losses were 20% higher, on average, than those from Plots A + C, whereas subsurface drainage losses of PP and TP from Plots B + D were 20 and 16% lower, respectively. In total (sum of surface and subsurface losses), cumulative TP losses during the grass period were 3.93 and 4.04 kg ha^{-1} for the pairs A + C and B + D, respectively.

Treatment Period: Dissolved Reactive Phosphorus Concentrations and Losses

Flow-weighted mean DRP concentrations clearly differed with tillage method during the treatment period, with significantly higher DRP from no-till plots (Fig. 6). In surface runoff, there was a relatively constant difference in DRP between the treatments throughout the study. However, in subsurface drainflow from no-till plots, there was an increase in mean DRP concentration over time, from ~0.10 mg L^{-1} in 2014 to >0.20 mg L^{-1} in 2016. Such a trend was not obvious in drainflow from plowed plots, for which flow-weighted DRP concentrations seemed to vary rather irregularly.

Annual DRP losses from no-till plots were always higher than those from plowed plots (Fig. 3). Statistical analysis indicated significant differences in eight of the nine study years for surface runoff and in seven of the nine study years for subsurface drainflow. Snowmelt in particular appeared to be critical for DRP losses from no-till plots, as snowmelt water was almost entirely routed as overland flow. There was a total of five individual months in which monthly surface runoff DRP losses exceeded 100 g ha^{-1}, and all of these cases were associated with no-till management during snowmelt, with surface runoff comprising 92 to 100% of total discharge. Cumulative DRP losses were higher from no-till than plowed soil, with ~4.5-fold difference for surface runoff (2.2 vs. 0.5 kg DRP ha^{-1}), over twofold difference for subsurface drainflow (2.1 vs. 0.9 kg DRP ha^{-1}), and threefold difference in summed surface and subsurface DRP losses, 4.3 vs. 1.4 kg ha^{-1} (Supplemental Table S6).

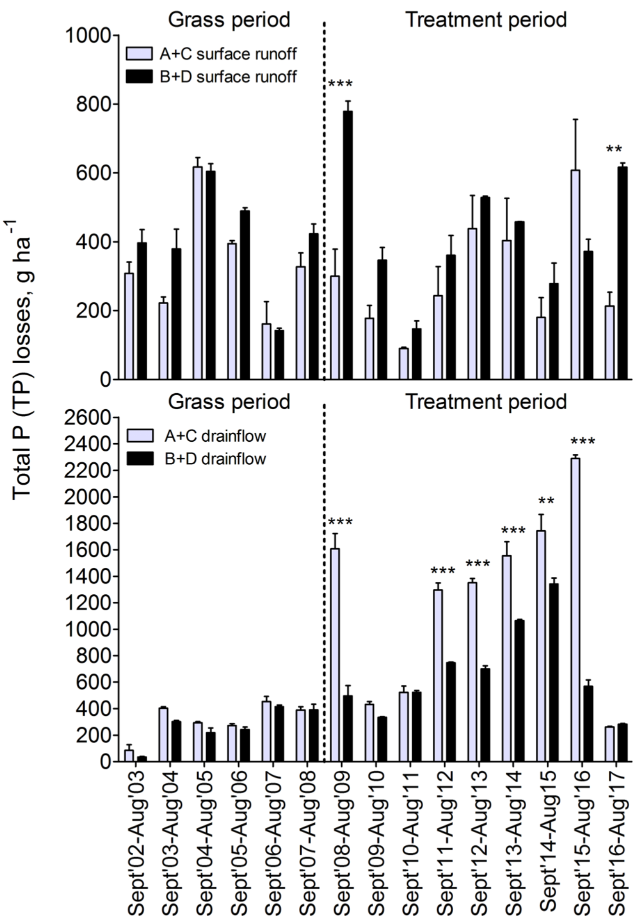

Fig. 5. Annual (September–August) losses of total P (TP) in surface runoff (upper panel) and subsurface drainflow (lower panel) at the study site; note the different *y* axis scales. Significance of differences in means between treatments: **p* < 0.05, ***p* < 0.01, ****p* < 0.001. Numerical values of annual and quarterly losses are given in Supplemental Tables S4 (grass period) and S8 (treatment period).

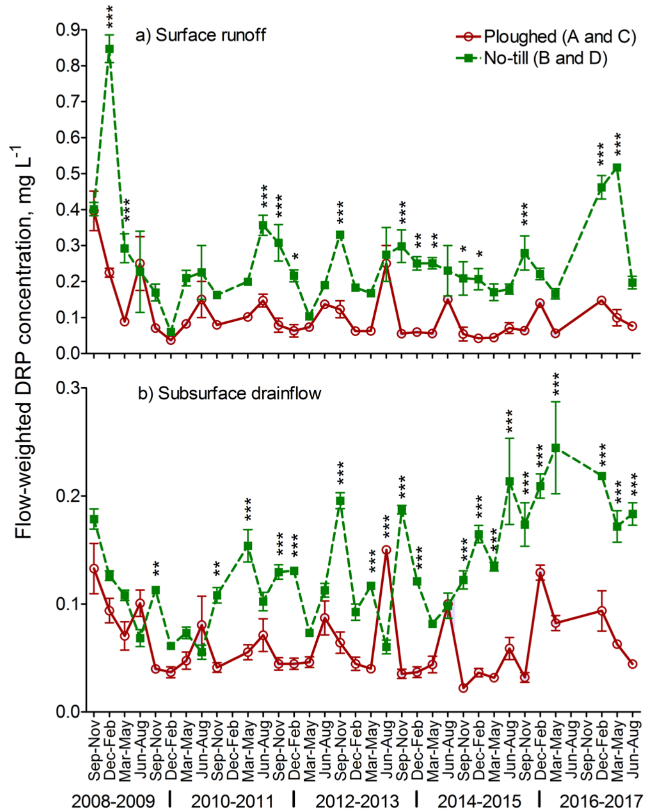

Fig. 6. Quarterly flow-weighted concentrations of dissolved reactive P (DRP) in (a) surface runoff and (b) subsurface drainflow from the annually plowed (open circles, solid line) and no-till plots (closed squares, dotted line); note the different *y* axis scales. Gray and white background colors are used to separate the hydrological years (September–August, starting from autumn tillage of Plots A and C). Error bars indicate the range for duplicate 0.5-ha field plots. Significance of differences in means between treatments: **p* < 0.05, ***p* < 0.01, ****p* < 0.001.

Treatment Period: Particulate and Total Phosphorus Concentrations and Losses

For both flow pathways, losses of PP were, in general, consistently higher from plowed soil than from no-till soil (Fig. 4), with the greatest differences between the management options in autumn and winter quarters (Supplemental Table S7). Cumulative 9-yr surface runoff PP losses from no-till plots (1.7 kg ha^{-1}) were 23% lower than those from plowed plots (2.2 kg ha^{-1}), and in subsurface drainflow, no-till discharged 61% less PP than plowed soil (4.0 vs. 10.2 kg ha^{-1}). The summed surface and subsurface PP losses from no-till plots were 54% lower than from plowed plots (5.6 vs. 12.3 kg PP ha^{-1}).

Total P concentrations in surface runoff showed much smaller differences as a result of tillage, due to the contrasting effects on DRP and PP, with plowed and no-till alternately showing higher mean TP concentration (Supplemental Fig. S4). However, plowed soil generally produced higher TP concentrations in subsurface drainflow, an effect driven by PP.

Annual surface runoff PP and TP losses only occasionally showed significantly different treatment means (Fig. 4 and 5). For subsurface drainflow, plowed plots discharged significantly more PP and TP than no-till plots in six of the nine hydrological years studied. Cumulative surface and subsurface TP discharges from no-till were, during the 9-yr treatment period, 27% lower than TP losses from plowed soil (10.0 vs. 13.7 kg ha^{-1}). In surface runoff, cumulative TP losses from no-till were 46% higher than from plowed soil (3.9 vs. 2.7 kg ha^{-1}), but subsurface drainlow from no-till discharged 45% less TP (6.1 vs. 11.1 kg ha^{-1}).

Crop Yield

During the 9-yr treatment period, no-till plots produced, on average, 16% lower mean cereal yield than plowed plots (Table 1). In 6 out of 9 yr, yields of no-till were 15 to 34% lower, and in one crop year 9% larger, than the yields of the plowed plots. However, already during the grass period, Plots B + D produced 10% lower average yield than Plots A + C, and some of the yield difference was assumed to be due to other reasons than no-till.

We expected that no-till plots would dry more slowly in spring, which would postpone their sowing, but in most years, sowing of no-till and plowed plots could be done within 2 d. The exceptions were in spring of 2012 and 2015, when no-till plots could be sown first 5 to 6 d later than the plowed ones. There were no clear patterns in yields, or treatment-wise yield differences, according to sowing dates (calendar date or days between sowing the two treatments). Also, differences in yield were not associated with some single cereal species, but years with >20% lower yields for no-till were obtained for oat, barley, and wheat crops.

Discussion

Several reports from northern Europe (Känkänen et al., 2011; Soane et al., 2012; Arvidsson et al., 2014) have noted comparable 5 to 10% yield gaps for no-till when compared with annual plowing. Our findings are also in line with those in many previous studies on P losses in that no-till effectively curbs erosion and PP but increases DRP losses (e.g., Sharpley and Smith, 1994; Puustinen et al., 2005; Smith et al., 2015a).

The higher DRP concentrations in discharge from our no-till plots were probably driven by enrichment of the uppermost soil layer with readily soluble P. Soil P stratification within 0 to 30 cm was measured twice during our study, in 2007 (Year 5 of the grass period) and 2012 (Year 4 of the treatment period). In 2012, the soil-test P concentration in the top 2.5-cm layer of no-till plots was about threefold higher than that in the corresponding layer in plowed plots (Supplemental Fig. S5). From the start of the grass period, translocation of P by plants from deeper in the root zone and freezing- and thawing-induced P release from crop residues left over winter on the soil surface of no-till plots probably contributed P, not only directly to DRP concentration of runoff water (Roberson et al., 2007; Elliott, 2013), but also to P stratification of the no-till soil (Lozier et al., 2017).

In the present study, conducted on a relatively level field, subsurface drainflow was equally important as a DRP loss pathway as surface runoff, contributing 48 and 64% of cumulative surface and subsurface DRP losses in the no-till and plowed treatments, respectively. For PP losses, the importance of drainflow was even higher, as subsurface losses contributed on average 71 (no-till) and 82% (plowed) of the PP discharged from the field. For both treatments, subsurface TP losses were consistently higher than losses via surface runoff.

A noteworthy finding was the increasing DRP concentrations in subsurface drainflow from no-till plots during the latter half of the treatment period. The increase was substantial, and by 2016, the DRP concentration in drainflow approached the levels measured in surface runoff from the same plots during the final years of the study. A similar trend was not seen for plowed plots, so it is unlikely that the increase stemmed from weather patterns alone. A plausible explanation is the formation of a continuous pore and crack structure typical of no-till soils (Shipitalo et al., 2004).

In this study, continuity of the macropore structure in no-till soil manifested itself in high DRP concentrations in drainflow, rather than in increased subsurface flow volumes or lower surface runoff volumes otherwise associated with conservation tillage practices (Langdale et al., 1985; Shipitalo et al., 2000). On the contrary, our no-till plots discharged greater surface runoff volumes and less subsurface drainage water than the plowed soil. A delayed start to drainage water discharge from no-till plots in spring, due to prolonged frost in the soil profile in the start of the main discharge period, was decisive for the differences in flow routing via surface and subsurface pathways. Compared with a plowed soil, the substantially smaller temporary water storage in the surface layer of a no-till soil provides little capacity to delay overland flow when percolation deeper in soil profile is restricted by frozen subsurface soil (Horton, 1937).

Drainage discharge quality is affected by chemical properties of the soil layers along the path of the percolating water (Andersson et al., 2015), provided there is contact and reaction time between percolating water and soil. Hence, DRP concentration in subsurface drainage discharge may not always be elevated despite P stratification (Djodjic et al., 2002; Smith et al., 2015a; Zhang et al., 2017). However, if a permanent macropore structure with connective biopores develops with time under no-till management, this would serve as a rapid flow path from surface soil to the subsurface drainage system (Shipitalo and Gibbs, 2000; Shipitalo et al., 2004; Smith et al., 2015b). Additionally, a gradual increase in P sorption saturation of the soil along the flow paths within the soil profile might occur.

As has been pointed out repeatedly (Williams et al., 1980; Gerdes and Kunst, 1998; Ellison and Brett, 2006), use of TP as an indicator of likely water quality impacts may be problematic when comparing management practices that have contrasting effects on DRP and PP losses. Total P is often taken as the primary indicator of success or failure of a mitigation method, but mainly due to a lack of other readily accessible data and because of the convenience of TP analysis (Correll, 1998). The proportion of PP in TP that might be effective in supporting algae growth has also received much attention over recent decades. A number of methods have been used to estimate the bioavailable share of PP, including algal assays (Williams et al., 1980; Sharpley, 1993; Ekholm, 1994), bacterial growth tests (Nakajima et al., 2006), P sinks driving desorption of PP (Hanna, 1989; Ekholm and Yli-Halla, 1992; Sharpley, 1993), and chemical extractions (Dorich et al., 1985; James et al., 2002; Uusitalo and Turtola, 2003).

The bioavailability of PP using 2- to 3-wk algal assays has been determined for various land use types. Values ranging from 10 to 55% have been recorded for storm runoff from agricultural areas (Dorich et al., 1985), urban runoff (Cowen and Lee, 1976), and stream sediment matter (Cowen et al., 1978). In studies involving soil–water suspensions and simulated runoff, algal assays indicate similar ranges of bioavailable PP (17–50% of PP) (Huettl et al., 1979; Ekholm and Krogerus, 2003), as do P sinks (Andraski et al., 1985). Extraction of sediment matter with NaOH sometimes yields higher ranges (e.g., 27–93% of PP) (Dorich et al., 1985; Sharpley et al., 1992; James et al., 2002).

In the present study, no-till produced 9-yr cumulative total losses of 4.3 kg DRP and 5.6 kg PP ha^{-1}, compared with 1.4 kg DRP and 12.3 kg PP ha^{-1} from plowed soil. If TP was used to indicate water quality effects of these tillage systems, no-till with its TP losses of 10.0 kg ha^{-1} would be preferable to plowing, with its TP losses of 13.7 kg ha^{-1}. However, if PP bioavailability was <100% of PP, the conclusion might be different. At our study site, conversion to long-term no-till management would be beneficial for water quality only if PP bioavailability exceeded 43%. No-till decreased PP losses by 6.7 kg ha^{-1} (12.3 − 5.6 kg PP ha^{-1}), and then PP bioavailability needs to be 43% or higher to compensate for the 2.9-kg increase in DRP loss due to transition from plowing to no-till (4.3 − 1.4 kg DRP ha^{-1}). This is a greater PP bioavailability rate than found in many of the studies cited above. Sequential P fractionation of the soil at our study site (Peltovuori et al., 2002) suggests that a substantial share of soil P is present in apatite and refractory P pools. It thus remains an open question whether adoption of no-till as an eutrophication control measure at the study site is justified.

The site of our study is characterized by moderate erosion rates. For autumn-plowed plots, Turtola et al. (2007) reported average annual total (surface and subsurface) erosion of 1100 kg ha^{-1}, of which erosion load via surface runoff was just 200 kg ha^{-1}. This can be compared with 2100 kg ha^{-1} annual erosion via surface runoff reported by Puustinen et al. (2005) for their plowed clay soil with 8 to 9% slope in Southwest Finland. The more sediment and associated PP losses can be decreased by adopting no-till, the more it would compensate for the effects of increased DRP loss that follows from P stratification. No-till would thus remain a useful P mitigation option for highly erodible (sloping) soils. However, occasional inversion tillage would be needed to undo P stratification (Smith et al., 2007; Baker et al., 2017). Such intermittent tillage is a vehemently debated measure (Kleinman et al., 2015), because it is feared to include long-term weakening of macroaggregate stability in the soil surface layer and decreased C sequestration (Grandy et al., 2006). It is difficult to imagine other practical means to undo stratification of readily soluble P in the surface soil, and the question is then how often soil mixing should be done. In the present study, no-till followed a period of long-term grass, and we are not confident to assess the pace of P stratification due to no-till based on the material presented here, but the assessment is to be done using greater data. There are also ready simulation tools, such as the Annual P Loss Estimator (APLE; Vadas et al., 2012), that can be useful in assessing mixing interval.

Conclusions

A period of ley before this tillage study equalized P concentrations after previous experiments at the field site. When the treatment period comparing no-till and annual plowing started, no-till produced substantially lower PP losses than autumn plowing in both surface runoff and subsurface drainflow. A drawback was a concomitant increase in DRP losses. Halfway through the treatment period, DRP concentrations and losses via drainflow from no-till plots started to increase, probably because of formation of flow channels that facilitated rapid percolation to subsurface drains, possibly assisted by increased P saturation of the active flow paths. Total P losses in surface runoff were, in most years, higher from no-till, whereas TP losses in subsurface drainflow were clearly higher from plowed soil. Calculated as the sum of surface runoff and drainflow losses during the 9-yr treatment period, the no-till treatment discharged 27% less TP than plowed soil. However, no-till as a measure to mitigate eutrophication of receiving waters at the study site is only justified when PP bioavailability exceeds 43%. According to earlier P fractionation results, a large share of soil P is firmly bound in the clay soil at the site, and the bioavailability of PP transported is unknown. This unknown piece of data would be needed for proper evaluation of water protection potential of no-till and other methods that have contrasting effects on DRP and PP losses.

Supplemental Material

The supplemental material includes a short description of past management of the study site, data tables on annual and quarter-year P losses, and figures showing flow-weighted P concentrations in surface and subsurface waters during the grass and treatment periods.

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