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Strategic tillage of no-till decreased surface and subsurface losses of dissolved phosphorus

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Abstract

Enrichment of soluble P on the surface layer of long-term no-till (NT) soils, and consequent increase in dissolved P losses, is a concern for which occasional plowing has been suggested as a remedy. We measured the effect of such strategic tillage (ST) on surface and subsurface P losses from 0.5-ha field plots on clay soil for 4 years. Two NT plots had discharged threefold dissolved molybdate-reactive P (DRP) losses compared to annually plowed soil conventional tillage (CT). ST by plowing to 20-cm depth was applied on one of the NT plots, whereas the other remained under NT. ST done in July was sown with canola (*Brassica napus* ssp. *oleifera*) to establish plant cover before winter. Summed 4-year DRP loss from ST treatment was 60% lower compared to NT (0.78 vs. 1.96 kg ha^{-1}), accompanied with 11% higher particulate P (PP) loss (4.39 vs. 3.97 kg ha^{-1}). CT plots produced slightly lower DRP losses (0.53–0.76 kg ha^{-1}) than ST, but higher PP losses (6.02–7.96 kg ha^{-1}). Bioavailable P (BAP) losses from ST were lower than from the other treatments if >7% of PP turns bioavailable. After ST, soil P stratification first vanished, but started to develop again when NT was resumed. Occasional tillage of NT soils mitigates DRP losses over several years, and it was at the study site the preferred mitigation option in reducing BAP losses.

Plain Language Summary

No-till is a very effective erosion control option and therefore a widely recommended water protection measure. However, categorical application of no-till, at sites that are not very erosion-prone, may be more detrimental than beneficial in eutrophication point of view, because dissolved P losses from no-till tend to be higher than in regular inversion plowing. This study showed that occasional plowing of no-till helps controlling dissolved P losses for several years, and it would be the preferred eutrophication control measure at the site of this study.

Abbreviations: BAP, bioavailable P; CT, conventional tillage; DRP, dissolved molybdate-reactive P; NT, no-till; PP, particulate P; ST, strategic tillage; TP, total P.

1 | INTRODUCTION

Among other contributions to soil health, no-till (NT) is recommended instead of annual soil plowing to minimize wind and water erosion (Christianson et al., 2016; Gaynor & Findlay, 1995; Puustinen et al., 2005). However, NT is associated with higher dissolved molybdate-reactive P (DRP) losses than plowing, and this may compromise the use of NT as a water protection measure in landscapes with inherently modest erosion (Jarvie et al., 2017; Sharpley & Smith, 1994; Uusitalo et al., 2018a). If NT as a soil conservation practice is categorically recommended over large land areas, an increase in DRP losses, that is, the P form readily available for utilization by algae and aquatic vegetation, may eventually fuel eutrophication of surface waters (Iho et al., 2023; Jarvie et al., 2017). As a remedy to DRP losses, strategic tillage (ST) of long-term NT has been advocated (Baker et al., 2017; Kleinman et al., 2015; Smith et al., 2007).

There is no consensus on the effects of ST on soil functions and productivity, but they likely vary in different environments (Dang et al., 2015; Peixoto et al., 2020; Stavi et al., 2011). Some authors recommend caution in breaking up continuous NT because it may be pernicious to soil fauna, arbuscular mycorrhizae, offset soil carbon accumulation, and disturb aggregate structures developed in topsoil (Bono et al., 2008; Garcia et al., 2007; Grandy et al., 2006). However, detrimental effects are not always found (Baan et al., 2009; Calvelo-Pereira et al., 2022; Fang et al., 2022; Quincke et al., 2007; Schlegel et al., 2020), and sometimes plant productivity may benefit from occasional tillage (Kettler et al., 2000; Peixoto et al., 2019). One outcome is still common: ST of NT soils decreases vertical stratification of nutrients and C within the mixed soil layer (Garcia et al., 2007; Kettler et al., 2000; Quincke et al., 2007).

Elevated DRP losses in NT are due to the enrichment of readily soluble P to the topmost soil layer that seeks to equilibrate with rain and snowmelt waters (Ahuja et al., 1982; Sharpley et al., 1978; Yang et al., 2015). Mixing the P-enriched top layer with soil that has lower soluble P content is a practical solution that reduces the risk for P mobilization. Several rainfall simulation studies have proved the concept. In their review, Blanco-Canqui and Wortmann (2020) listed five rainfall simulation studies on ST that addressed specifically water quality parameters (DeLaune & Sij, 2012; Melland et al., 2017; Quincke et al., 2007; Smith et al., 2007; Warnemuende et al., 2007). Generally, the studies showed variable effects on surface runoff generation, a tendency for increased sediment and thus particulate P (PP) losses, but decreased DRP loss or concentration in runoff. Blanco-Canqui and Wortmann (2020) concluded that occasional tillage could mitigate total P (TP) loss as far as erosion is effectively controlled, for example, by establishing a new canopy before intense rains. Then, an increase in PP loss would be only temporary.

Core Ideas

- No-tilled clay soil was plowed to 20 cm and P losses compared to those of continuous no-till and annual plowing.
- Over 4 years, strategic tillage lowered dissolved reactive P loss by 60% and increased particulate P loss by 11% compared to continuous no-till.
- Strategic tillage was associated with lower bioavailable P losses than no-till or annual plowing.
- We assessed that under no-till soil P stratification returns to the initial level in 7 years after one-time plowing.

Our 4-year field study on the effects of ST under natural precipitation follows a 9-year study that compared P losses from two 0.5-ha plots under NT with two identical plots that were annually plowed. Water discharges and P losses during the 9-year study were similar in the duplicate plots allocated to these managements (Uusitalo et al., 2018a). In the summer of 2018, one of the NT plots was plowed to about 20-cm depth after 10 years of NT management and 16 years from the previous soil mixing. After that, NT management was resumed. The other NT plot remained under continuous NT. The two remaining plots served as annually plowed control treatment. We monitored surface and subsurface water and P discharges from these field plots and measured how soil P stratification developed after the one-time plowing of the other NT plot.

2 | MATERIALS AND METHODS

2.1 | Study site and soil sampling

The study site of Kotkanoja, in Jokioinen community, SW Finland (60°48′56.5″ N, 23°30′39.5″ E, 100 m asl), has fine-textured soil with 50%–60% clay-sized (<2 μm) particles in the topsoil and increasing clay content with depth. Organic C content of the Ap horizon is 2%–3% and pH 6.3 (5.9–6.5). Topography is relatively flat with about 2% mean slope. According to WRB classification, the soil is a (clayic and cutanic) Protovertic Luvisol (M. Yli-Halla, personal communication, July 18, 2018). A detailed soil profile description, with P fractionation and soil mineralogy, is found in Peltovuori et al. (2002).

Cracks extending to about 40-cm depth appear regularly in dry summers and the subsoil has a prismatic structure with pressure faces on the ped surfaces and some clay linings. These indicate a potential for preferential flow and material transport from topsoil. Earlier Cs^{137} analysis of soil profiles and suspended sediments also suggests that particles carried by subsurface drainage waters originate from topsoil (Uusitalo et al., 2001).

The field setup is described in Uusitalo et al. (2018a); see also Figure S1. Weather data (rain and temperature) for the study period are given in Tables S1–S4.

All four 0.5-ha field plots (labeled A, B, C, and D) were sampled for P analyses in May 2018 (before ST of plot D later in the summer), August 2021, and September 2022. The NT and ST treatments (plots B and D, respectively) were additionally sampled in 2019 and 2020. Soil sampling was done with slotted 5-cm diameter steel cylinders that allowed layer-wise separation at predetermined depths of 0–2.5, 2.5–5, 5–10, and 10–18 cm. From each field plot and depth, 4 separate samples for the laboratory were combined from 6–10 subsamples.

The soil samples retrieved in 2018, 2020, and 2021 were analyzed for Mehlich3-P (M3-P; Mehlich, 1984) and all samples for P-Ac according to the Finnish national agronomic method involving extraction with pH 4.65 ammonium acetate-acetic acid solution at 1:10 volumetric soil-to-solution ratio for 1 h (Vuorinen & Mäkitie, 1955). For Mehlich3 extracts, P was determined with an inductively coupled plasma emission spectrometer (iCAP 6500 Duo, Thermo Fisher Scientific). P-Ac determination was done using the molybdate colorimetric method with a Skalar San++ continuous flow analyzer (Skalar Analytical B.V.).

2.2 | Cropping and treatments

From autumn 2008 onward, plots A and C had, for the 10 years previous to this study, been plowed each autumn, while plots B and D were under NT. Cereal crops have been grown in all plots, with identical crops and fertilization. Crop rotation and fertilizer management are typical practices for the region. Tillage, crops, and fertilizer applications during the study period are summarized in Table 1 (data for the control period are detailed in Uusitalo et al., 2018a, 2018b).

In May 2018, barley (*Hordeum vulgare*, L.) was sown over all plots, in plots B and D by direct drilling (Table 1). Only in plot A, Italian ryegrass (at 10 kg ha^{-1} rate) was undersown as a catch crop. For all plots, fertilization was done with NPK (23-3-8) compound mineral fertilizer supplying N 90, P 12, and K 31 kg ha^{-1}.

In July 2018, one of the previous NT plots (plot D) and one of the conventional tillage (CT) plots (plot C) were harvested for whole crop silage, followed by inversion plowing to about 20-cm depth. A week later, these plots were sown with canola (*Brassica napus* ssp. *oleifera*) that was given N 50, P 14, and K 29 kg ha^{-1}. The other two plots (i.e., the non-disturbed NT plot B and the other CT plot A) were harvested in September, after which plot A was plowed to 20 cm in October.

In spring 2019, canola (plots C and D) received supplemental N fertilizer at 110 kg ha^{-1} rate, but no P or K. Plots A and B were sown with barley (plot B direct-drilled), plot A again with the ryegrass as catch crop, and supplied with the same NPK rates as previously (Table 1).

From autumn 2019 onward, plots A and C were always plowed, whereas plots B and D were left with stubble, to be direct-drilled in the following spring. Spring barley or oat was grown on all plots with the same fertilization (Table 1).

The input of fertilizer P during the 4-year period summed 60–62 kg ha^{-1}, the 2 kg ha^{-1} difference being associated with P given for canola. Fertilizers were always placed in the soil at 3- to 4-cm depth simultaneously with sowing.

2.3 | Water sampling and analyses

Surface runoff was collected at the lower end of the plots, in about 30-m long trenches filled with a layer of 30- to 50-mm pebbles (one collection trench per plot), under which a drainage pipe has been laid to conduct water to collection wells and further to an observation hut. Movement of surface runoff between the plots is prevented by about 30-cm high barriers of mounded soil around the plot margins. Belowground the plots are separated from each other with plastic curtains that extend from the soil surface over the about 1-m drainage depth. Subsurface drainage water from each 0.5-ha field plot is collected with eight plastic drainage pipes (with 16 m spacing) and conducted with four collection pipes separately to the observation hut (Figure S1).

Inside the observation hut, water volume was recorded with 4.5-L tipping buckets equipped with magnetic counters. A fraction of 0.1% of the flow was diverted to 30-L plastic containers using small funnels placed under the tipping buckets (Figure S1). Water samples for laboratory analyses were retrieved from the field on a daily to fortnightly basis, depending on flow. Some changes in P speciation due to longer sampling intervals are possible, but longer sampling frequency was restricted to periods with low flows in summer and winter. Sampling containers were also then regularly checked and sampled if the accumulated water volume was about 2 L or more; 2 L volume corresponds to <1mm of discharge.

The laboratory analyses included the determination of dissolved molybdate-reactive P (DRP) and TP, PP being calculated as their difference. Subsamples used for DRP determination were passed through 0.2-μm Nuclepore membrane (Whatman) within 24 h of sampling. The filtered samples were refrigerated and DRP analysis was conducted within a few days. For total P analysis, unfiltered subsamples were digested with hydrogen peroxide and peroxodisulfate (120˚C, 120 kPa for 30 min). Water sample P analyses were performed

TABLE 1 Primary tillage for the years 2008–2017 (preceding this study) and cropping during the study years.

	Plot A, CT	Plot B, NT	Plot C, CT	Plot D, ST 2018
2008–2017	Annually plowed	No-till	Annually plowed	No-till
2018				
Crop	Barley/ryegrass	Barley	Barley/canola	Barley/canola
N-P-K, kg ha^{-1}	90-12-31	90-12-31	90-12-31/50-14-29	90-12-31/50-14-29
Tillage	Plowed in October	None	Plowed in July	Plowed in July
2019				
Crop	Barley/ryegrass	Barley	Canola	Canola
N-P-K, kg ha^{-1}	90-12-31	90-12-31	110-0-0	110-0-0
Tillage	Plowed in October	None	Plowed in October	None
2020				
Crop	Barley	Barley	Barley	Barley
N-P-K, kg ha^{-1}	90-12-31	90-12-31	90-12-31	90-12-31
Tillage	Plowed in October	None	Plowed in October	None
2021				
Crop	Oat	Oat	Oat	Oat
N-P-K, kg ha^{-1}	90-12-31	90-12-31	90-12-31	90-12-31
Tillage	Plowed in October	None	Plowed in October	None
2022				
Crop	Oat	Oat	Oat	Oat
N-P-K, kg ha^{-1}	90-12-31	90-12-31	90-12-31	90-12-31

Abbreviations: CT, conventional tillage; NT, no-till; ST, strategic tillage.

using a LaChat 8000 Quickchem flow injection analyzer (Hach Company).

2.4 | Statistical analyses

For statistical analyses, water and P discharge data (surface runoff, subsurface drainflow, and their sum) were calculated to quarter-year sums (Tables S5–S8). Because ST treatment was applied on one of the two plots under NT for the previous 10 year (2008–2017), data collected during this preceding period was utilized as a control period, using the logic of before-after-control-impact (BACI) study design, and paired watersheds (e.g., Clausen & Spooner, 1993). This allowed us to study if the discharge or P loss accumulation rate (i.e., slope) for the field plots differed before (the control period) and after (the study period). These models also allowed us to compare slopes within the periods. Data covering the study period are shown in Tables S5–S8, and data for the control period are found in Uusitalo et al. (2018b).

First, to see whether the one-time plowing of plot D had an impact on the cumulative water and P discharges, a generalized linear mixed model (GLMM) was fitted to the data collected during control (September 2008–June 2018) and study (September 2018–August 2022) periods. The slopes of cumulative water discharges and P losses were modeled in each field plot (A, B, C, and D) in both periods (see Table S9). Field plot, period, time as a continuous variable, and all of their interactions were used as fixed effects. In addition, the observed substantial shift in 2020 (due to weather) was accounted for in the model by a fixed interaction effect of a shift (coded as 1 during a shift and 0 otherwise) and field plot. The structure of the design was taken into account by using year and quarter of a year as categorical random effects, and the covariance structure of cumulative sums within a field plot by using a compound symmetry (CS) covariance structure.

Second, we tested whether the one-time plowing of plot D had an impact on the partitioning of water and P discharges via surface and subsurface pathways during the study period. A GLMM was fitted for the proportion of surface runoff or surface pathway P losses to the summed surface and subsurface discharges, and for the proportion of DRP to TP using a beta distribution with a logit link function. Field plot and time, identified as a quarter of a year, and their interaction, were used as fixed effects. Time within a year was also used as a random effect having homogeneous or heterogeneous (CS and CS_H) or unstructured (UN_r) covariance structure within a year. The Akaike information criterion was used to select the most suitable covariance structure. The same model was used for mean DRP concentrations, except that time was used as a continuous fixed effect instead of a quarter of a year.

In pairwise comparison, p-values were adjusted with the Holm method to account for the error rate using a significance level of 0.05. The comparison between the slopes was made during the whole timeline as usual in the BACI models ($n_{adj} = 6$), but we also conducted the six comparisons between field plots in both periods and the four comparisons between the periods for each field plot ($n_{adj} = 16$). The first comparison, during the whole timeline, allowed us to see whether the slopes of the control and study periods differed from each other. The Kenward–Roger method was used for degrees of freedom. The restricted maximum likelihood estimation method was used for the BACI models and the residual pseudo-likelihood estimation method for the beta models. Diagnostic plots were used to evaluate the normality of residuals. Statistical analyses were made using SAS software, Version 9.4.

Statistical analyses on water discharge or P loss accumulation reported are based on subsequent quarter-years as input. In addition, water discharge and P loss sums, and their routing via surface and subsurface pathways, are reported for the whole 4-year study period to illustrate the differences between treatments.

3 | RESULTS

For illustration of data covering both 10-year calibration and 4-year study periods, Figure 1 shows field plot-wise discharges 2008–2022, thus including the years when field plots B and D were both under NT and plots A and C were annually plowed (see Uusitalo et al., 2018a). We first report here within-plot analysis of flow and P loss accumulation differences between the control and study periods (9/2008–7/2018 vs. 8/2018–8/2022). The comparisons between plots in the two periods are reported in more detail under separate subheadings.

Within any given field plot, no significant differences were found in the summed surface and subsurface water discharges between the control and study periods (adj. $p > 0.72$). As 14 years sums, water discharges from the four plots varied between 3456 and 3804 mm, thus within 10%.

For DRP losses, within-plot differences between control and study periods were clearly non-significant for plots A and C (adj. $p > 0.88$), and non-significant also for plot B (adj. $p > 0.90$). Plot D, which during the control period was under NT, was plowed once in 2018, and then returned to NT, had significantly different DRP accumulation slopes during the two periods (adj. $p = 0.015$); a clear turn in DRP loss accumulation after ST is shown in Figure 1.

With reference to PP and TP losses, there were no statistically significant differences between control and study periods, but comparisons yielded adj. $p > 0.16$ for PP and adj. $p > 0.47$ for TP.

3.1 | Water discharge

Between-plot comparison of the slopes showed that during the calibration period water flow was significantly different in all comparisons (adj. $p < 0.001$). In the study period, water discharges of plot A (CT) increased more than in plots C and D (adj $p < 0.02$; Table S9). Total flow sums were not widely different between plots (Figures 1 and 2), but the small differences produced statistically significant differences because the discharges remained relatively similar between plots throughout the study. For the most interesting pair of plots B (NT) and D (ST), total 4-year water discharges were 1179 and 1174 mm, respectively, while plots A and C (CT) produced 1170 and 1074 mm total flow.

Most of the water discharged from the field via subsurface drains; 64%–77% of the summed flow for the individual field plots. Surface runoff during the study period was most voluminous from the NT treatment (plot B), with the 4-year runoff reaching 423 mm, or 36% of the total (summed surface and subsurface) flow. Surface runoff of ST (plot D) was 285 mm, or 24% of the flow sum. The plowed plots discharged 400 and 244 mm of surface runoff, or 34% and 23% (plots A and C, respectively) of the total 4-year flow sums.

There were two larger increments in flow accumulation during the study (Figure 2), the first occurring in winter 2019/2020, which was mild with hardly any snow cover in SW Finland (Figure S2). In mid-February, nine successive days of ambient air temperature above zero coincided with 67 mm of rain, and subsurface drainage flow continued almost without interruptions throughout the winter. The other large flow increment was in 2022 when snow depth peaked at the start of April. Warming April days melted snow, but nighttime temperatures still dropped below the freezing point, slowing down the disappearance of ground frost and resulting in an increase in surface runoff.

3.2 | Dissolved reactive P

During the control period, there were no differences in DRP loss accumulation between no-tilled plots B and D (Table S10), or between plowed plots A and C (for both groups, adj. $p > 0.17$; Table S11), but the treatments differed significantly from each other (A/C vs. B/D $p < 0.001$). During the study period, accumulation of DRP loss from the ST plot D increased less than those of the other plots (adj. $p < 0.001$; Table S9). DRP loss of plot D was significantly different from that of the NT plot B (D vs. B adj. $p < 0.001$) but not different from the CT plots (D vs. A/C adj. $p > 0.60$). The difference between NT and CT plots was highly significant (B vs. A/C adj. $p < 0.001$). During the 4-year study period, DRP losses from NT (plot B) summed 1.96 kg ha^{-1}, whereas ST (plot D) discharged

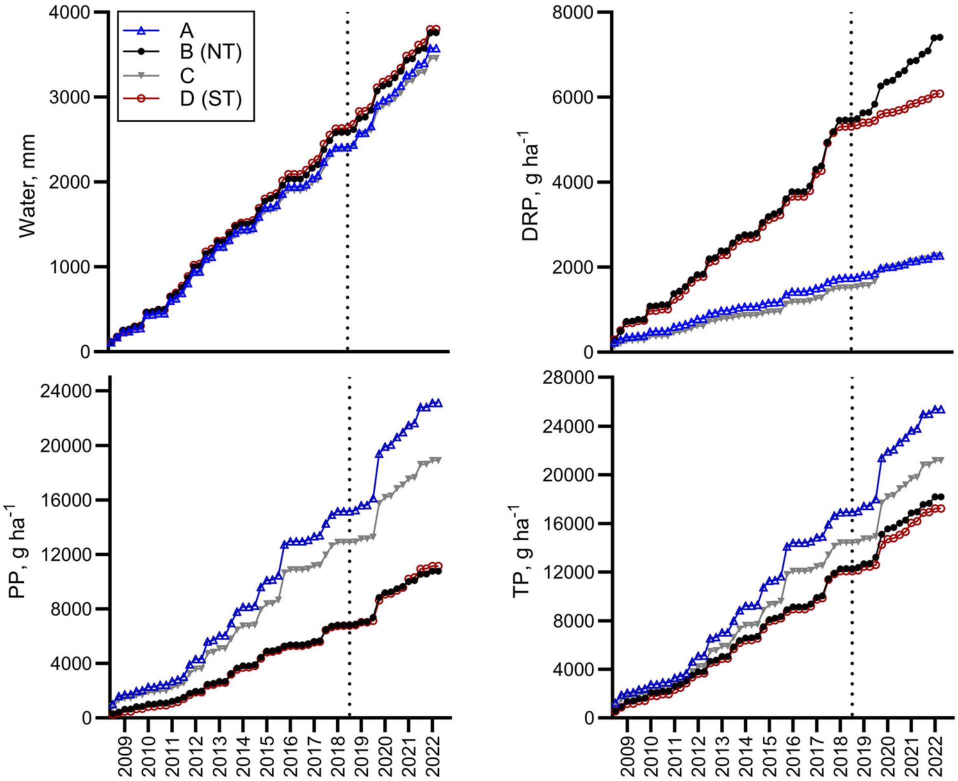

FIGURE 1 Field plot-wise water and P discharges (sum of surface and subsurface) for the period July 2008-August 2022, that is, 10 years before and 4 years after strategic tillage of plot D (red open circles). Vertical dotted line indicates the start of the study period in July 2018. DRP, dissolved molybdate-reactive P; NT, no-till; ST, strategic tillage.

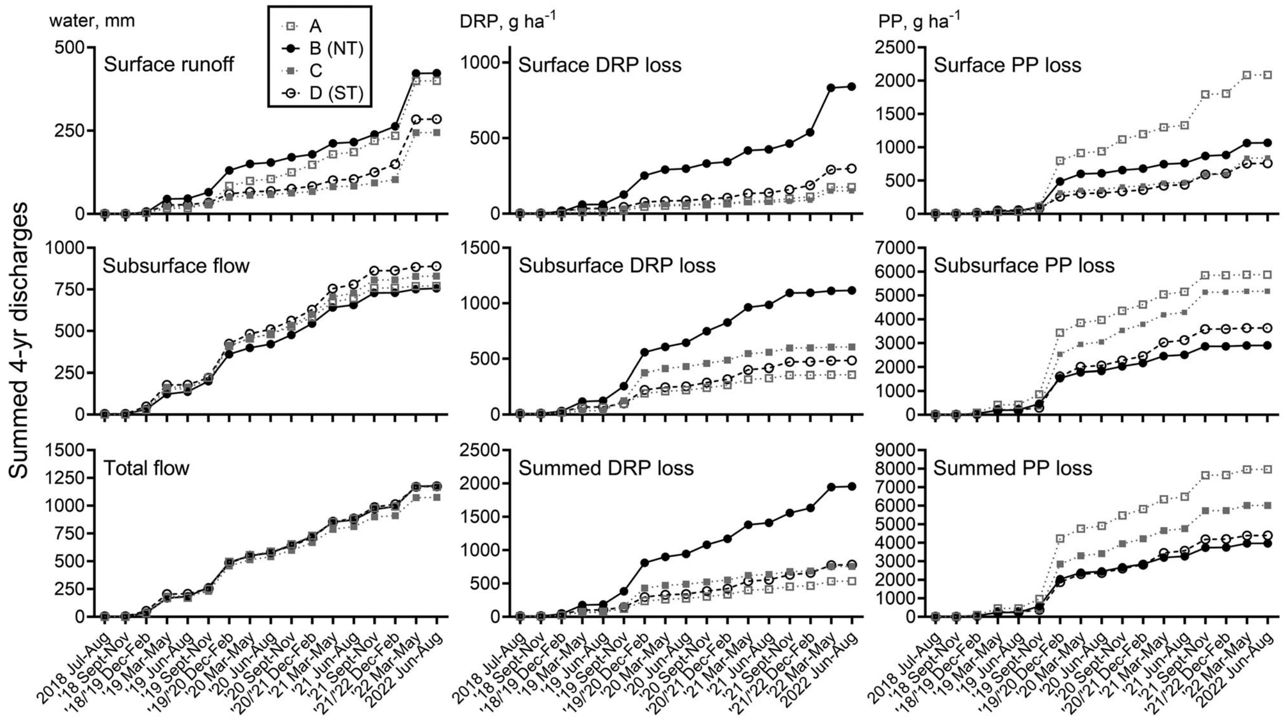

FIGURE 2 Cumulative water (left), dissolved molybdate-reactive P (DRP) (middle), and particulate P (PP) (right) discharges in surface runoff (top), subsurface drainage (center row), and their sums (bottom) during the study period (July 2018–August 2022). Plots A and C were annually plowed (conventional tillage [CT]; gray squares, dotted lines), plot B under continuous no-till (NT; black circles, solid line), and plot D (strategic tillage [ST]; open circles, dashed line) was plowed one time (in July 2018) to about 20-cm depth.

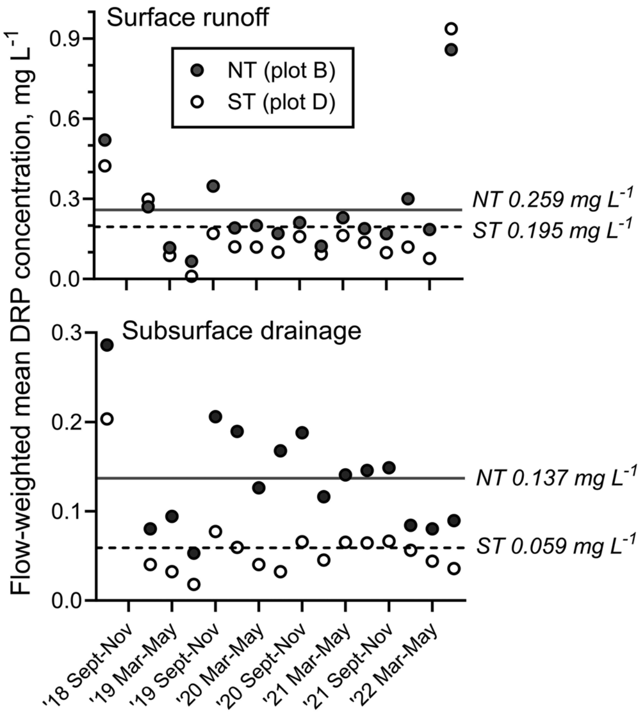

FIGURE 3 Quarter-year flow-weighted mean dissolved molybdate-reactive P (DRP) concentrations in surface and subsurface waters of the no-till (NT, filled circles) and strategic tillage (ST, open circles) plots during the study period. Horizontal lines and inset values indicate mean over the 4-year study, solid line for NT, and dashed line for ST.

0.78 kg ha^{-1}, and CT (plots A and C) 0.53 and 0.76 kg ha^{-1} (Figure 2).

Like water flow, DRP losses were routed mostly (by 57%–80%) via subsurface drains. The share of surface pathway DRP losses for NT was 43% and for ST 38% of the summed surface and subsurface DRP losses. For the CT plots, surface runoff delivered 33% and 20% (plots A and C, respectively) of the DRP discharges. In comparisons between the field plots, no statistically significant differences in DRP routing as surface and subsurface losses were found.

Flow-weighted DRP concentrations for NT and CT remained at the level of those measured for the NT plot B and the CT plots (A and C) before this study. After ST of plot D, however, the mean DRP concentrations of both surface runoff and subsurface drainage waters became significantly lower for ST ($p < 0.05$) than for NT. The difference for surface runoff was 25%, but for subsurface drainage water mean DRP concentration of the ST plot D was less than half of that of the NT plot B (Figure 3). In the start and end of the study, high concentrations in surface runoff were associated with very low (<1 mm) runoff volumes during those quarter-years (Table S5).

The highest DRP share of summed TP loss during the study period was measured for NT, 44% for surface, and 28% for subsurface P losses. Compared to NT, the DRP/TP share was significantly ($p < 0.001$) lower in ST, 28% in surface runoff and 12% in subsurface flow. During the 10-year control period before the present study, the difference between plots B and D had been non-significant ($p > 0.44$) for both flow pathways. The lowest shares of DRP/TP were measured for CT plots, for which surface runoff DRP made 8% and 15%, and subsurface flows 6% and 10% (A and C, respectively) of TP losses. Over the 4 years, DRP/TP trended (not shown) so that the highest shares were for surface runoff measured in March–May quarter and for subsurface drainage waters in June–August quarter. The lowest DRP/TP shares for both pathways were measured in September–November.

3.3 | Particulate P

Pairwise comparisons between plots showed that during the calibration period, all pairs but B versus D (NT plots) had significantly different PP losses; B and D had the lowest PP losses of all plots (Figure 1). During the 4-year study period, of all plots, the summed PP loss was lowest from NT (plot B), 4.0 kg ha^{-1} (Figure 2). Compared to plot B, significantly higher PP loss was recorded for the CT plot A at 8.0 kg ha^{-1} (B vs. A adj. $p < 0.001$), followed by plot C with 6.0 kg ha^{-1} loss (B vs. C adj. $p < 0.001$; A vs. C adj. $p = 0.158$). PP loss from the ST plot D, summing 4.4 kg ha^{-1}, was significantly lower than that of plot A ($p < 0.001$) but not different from plots B or C (adj. $p > 0.26$).

Subsurface tiles were the main loss pathway for PP, accounting for 73%–86% of the summed surface and subsurface PP losses on all plots; there was no significant difference between the field plots ($p > 0.05$) in the share of surface and subsurface pathway PP losses. It is noteworthy how much the warm weather of winter 2019/2020 increased subsurface PP losses, making this quarter-year responsible for 34%–41% of the summed 4-year subsurface PP losses.

3.4 | Total P

Like for PP, also TP loss accumulation during the control period significantly differed in comparisons between all plot pairs but the no-tilled plots B versus D (Table S11). During the study period, statistically highly significant differences in TP loss accumulation were found between plots A versus B (adj. $p = 0.011$) and A versus D (adj. $p = 0.003$), but not in other comparisons. The highest TP loss sum was recorded for the CT plot A at 8.5 kg ha^{-1} and the lowest for the ST plot D at 5.2 kg ha^{-1}; the NT plot B discharged 5.9 and the CT plot C 6.8 kg ha^{-1} TP (Figure S3).

The CT plot A also discharged the highest total P mass via the surface pathway (2.3 kg ha^{-1}, or 27% of the summed TP loss; 8% of this was DRP), followed by NT (plot B 1.9 kg ha^{-1}, 32% of TP sum; 44% being DRP). For plots C (CT) and D (ST), surface runoff discharged 1.0 (15% of TP sum) and 1.1 kg ha^{-1} (20% of TP sum) total P losses, respectively.

3.5 | Soil P stratification

In May 2018, after 10 years of NT on plots B and D, P stratification in the Ap horizon resulted in about a twofold difference in M3-P and P-Ac concentrations in the uppermost 2.5 cm soil layer samples as compared to the 0–18 cm plow layer. Once NT management of plot D resumed after ST in July 2018, stratification started to develop again; Figure 4a shows the development of M3-P for the years 2018, 2020, and 2021.

The P-Ac concentration ratio between the top 2.5-cm soil depth and the whole Ap horizon soil depth (Figure 4b), just prior to this study (2 months before ST), was 1.96 for plot B (NT) and 2.35 for plot D (ST). In soil sampling about one year after ST, in autumn 2019, the P-Ac concentration of the topmost soil layer of plot D was 1.12 times that of the whole Ap horizon. In the three succeeding years, P enrichment of the topmost layer increased to 1.27, 1.49, and 1.48 times the concentration of the whole Ap. During the study, P-Ac concentration of the topmost soil layer of NT (plot B) was 1.96-2.28 times that of the whole Ap horizon, without clearly trending. Assuming linear development of P enrichment at the same pace as in 2019–2022, an enrichment ratio of 2.0 in plot D would be attained in 7 years after the one-time plowing.

3.6 | Losses of bioavailable P

When assessing bioavailable P (BAP) losses, one needs to assume how much of the P load may become bioavailable in waters that receive field discharges. The DRP fraction is considered 100% available for uptake by organisms, whereas some of the P-associations included in the PP fraction solubilize very slowly, if at all (e.g., Ekholm & Krogerus, 2003). In Table 2, we have calculated BAP losses under the assumption that 6.6%, 45%, or 95% of PP may turn into a bioavailable form. Using the lowest 6.6% fraction, 4-year BAP losses of the CT plots A and C would on average equal the BAP losses of the ST plot D at 1.1–1.2 kg ha^{-1}. The NT plot B would produce twice as much BAP (2.2 kg ha^{-1}) compared to the others. If the bioavailable PP fraction was 45%, the CT plots A and C would produce equal mean BAP loss as the NT plot B, 3.7–3.8 kg ha^{-1}. The ST plot D would have the lowest BAP loss of 2.8 kg ha^{-1}. Finally, if nearly all (95%) of PP would ultimately become bioavailable, ST would again have the lowest BAP loss (5.0 kg ha^{-1}), followed by NT (5.7 kg ha^{-1}), and CT would produce the highest BAP losses (6.5 and 8.1 kg ha^{-1}).

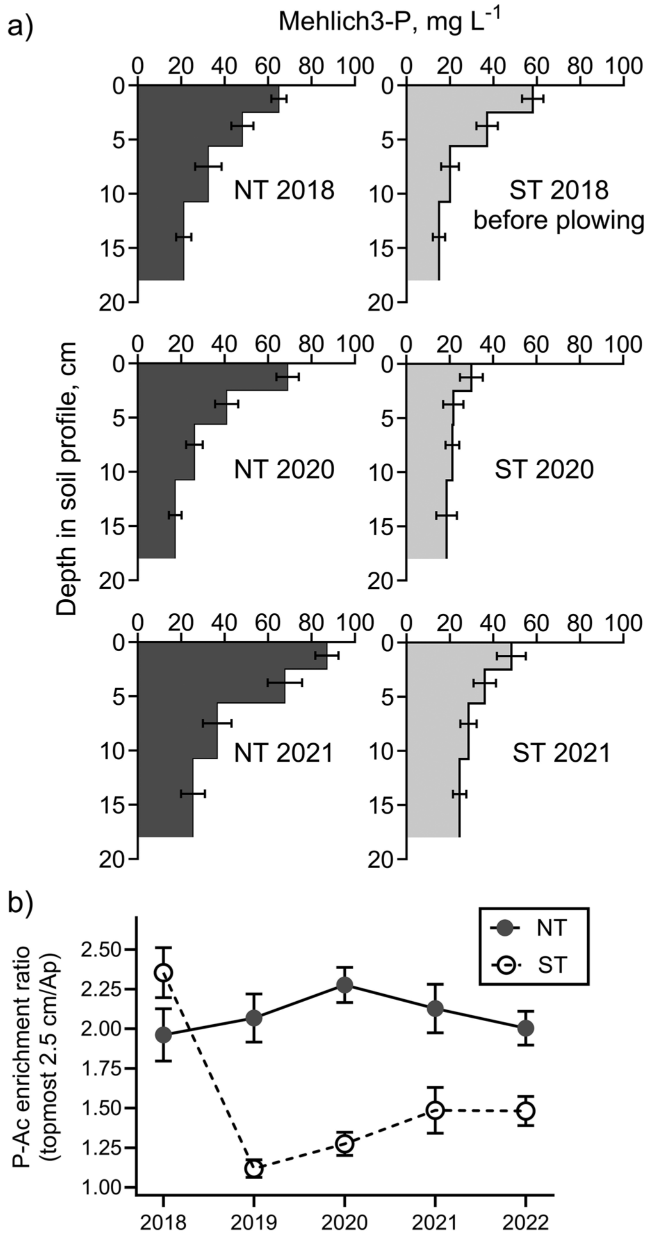

FIGURE 4 (a) Mehlich3-P profile of Ap horizon (plow layer) in continuously no-tilled plot B (NT, lefthand figures, dark gray) and one-time tilled plot D (strategic tillage [ST], righthand figures, light gray) in May 2018 (upper, before conducting ST in July 2018), and in autumn 2020 and 2021. Error bars show SEM ($n = 4$). (b) Enrichment of P-Ac in the topmost 2.5 cm relative to the whole (0–18 cm) plow layer.

4 | DISCUSSION

At our study site, P applications since 1991 have been moderate and the soil is considered P-responsive. Fertilizers are incorporated in the soil in combination with sowing, so these recommended measures have already been applied for a long time. We do not consider incidental P losses as a major problem, but P losses are rather associated with tillage practices

TABLE 2 Measured dissolved molybdate-reactive P (DRP) and particulate P (PP) losses (sums of surface and subsurface discharges) from the four field plots during the study and calculated bioavailable P (BAP) losses under assumptions that 6.6%, 45%, or 95% of PP becomes bioavailable in receiving waters.

	Plot A (CT)	Plot B (NT)	Plot C (CT)	Plot D (ST)
	g ha^{-1} during 4 year			
DRP	534	1956	756	782
PP	7960	3967	6015	4391
PP*6.6%	525	262	397	290
PP*45%	3582	1785	2707	1976
PP*95%	7562	3769	5714	4171
	Calculated 4-year BAP loss, g ha^{-1}			
BAP 6.6%	1060	2217	1153	1072
BAP 45%	4116	3741	3463	2758
BAP 95%	8096	5725	6470	4953

Abbreviations: CT, conventional tillage; NT, no-till; ST, strategic tillage.

and weather patterns that combined influence discharge water quality (Turtola & Paajanen, 1995; Uusitalo et al., 2007, 2018a).

Even though NT is a useful water protection measure for heavily erodible sites, especially if the proportion of PP that becomes algae-available is relatively high, it may also be a practice associated with a risk for accelerating eutrophication (Baker et al., 2017). This would happen at sites where erosion is a lesser problem and where eroded soil matter holds a high share of recalcitrant P that makes a minor contribution to the loading of BAP (Iho et al., 2023). Our study site has relatively modest annual erosion, and Uusitalo et al. (2018a) calculated that continuous NT would lessen BAP losses compared to annual plowing only if >43% of PP becomes algae-available in receiving waters. If the proportion is less than that, NT would in P-limited waters rather increase than decrease eutrophication compared with annual plowing due to high DRP loss. In the present study, we calculated nearly that same percentage (45%) as a cutoff value between NT and CT. Taking ST as an alternative management option in comparisons shows that it would be the preferred P-loss management at this site, regardless of PP bioavailability. Only in the case of a totally inert PP load would CT produce somewhat lesser BAP losses than ST.

In other studies, the duration of the effect on water quality after ST has been often assessed as short-lived. Schärer et al. (2007), who conducted irrigation experiments on pasture soil plots that were either untreated or tilled once, only found a year-long decreasing effect on DRP in surface runoff. Dodd et al. (2014), who mixed deeper low-P soils with the surface layer of pasture soils, found the decline in DRP losses in percolation water to last only a few weeks. However, data from ST effects on water quality conducted on a field scale and under natural rainfall has been lacking.

If P enrichment develops in the coming years at the same average pace as measured for P-Ac, extrapolation suggests that ST would reach a P-Ac enrichment ratio of 2.0 when 7 years have passed from plowing. Fertilization practices naturally affect the speed of P accumulation in the soil surface layer and shorter periods for P stratification have been reported (Rhoton, 2000; Scheiner & Lavado, 1998; Wortmann et al., 2010). The P management we used at our study site is typical for Finnish cereal farms, and it is this type of production where continuous NT is a management option that has gained popularity. Soil P stratification was again observable in our study's ST plot D after 4 years, but this did not yet translate into higher DRP concentrations or losses. Assuming that soil test P of the topmost soil layer is the main driver for DRP losses, DRP would thus be moderated for several years. If decaying plant material is the main source of DRP, a shorter duration would be expected. For example, in rainfall simulations, possibly rapid decay of plants may supply much DRP in the simulated runoff, but this effect likely evens out in longer studies involving year-round collection of water samples. Blanco-Canqui and Wortmann (2020) suggested that a 5–10 years interval between ST of NT fields would be associated with little risk of adverse effects on soil ecosystem services while reducing weed pressure and stratification of elements within the Ap horizon. This ST interval seems appropriate also in controlling DRP losses at our study site.

Regarding PP, elevated concentrations or losses after ST are typically reported in rainfall simulation studies (DeLaune & Sij, 2012; Melland et al., 2017; Quincke et al., 2007). We also measured somewhat higher subsurface PP discharges from ST than NT, and this difference came about gradually from the second year of the study. Admittedly, the growth of canola was delayed at first in this study due dry soil conditions, and green surface cover at the end of the growing season was modest. At that time, low discharge volumes also meant small PP losses. In a wet autumn, the results might have been different.

Having no direct measurements on aggregate stability, we cannot explicitly say if any weakening of aggregates due to ST took place. Yet, a comparison of flow and PP loss data shows that PP losses of ST and NT were about equal during the abnormally warm and wet quarter year December 2019–February 2020, which was alone responsible for about a third of all PP losses measured during the study. The other period with high discharge in spring 2022 shows a substantial surface runoff increment, especially for NT, without a corresponding jump in PP loss. However, the high flow was due to snowmelt on frozen ground and thus hardly tells anything about particle stability. Aggregate stability would merit attention, especially in the high latitudes, because of its great impact on P losses if the predicted warming of winter half-years is realized. Fennoscandian growing season has already moved 3.3 days earlier per decade from the 1950s, with an accelerating pace since 1990 (Aalto et al., 2022). The probability of thermal winter being absent in SW Finland has (in 1971–2000) been <5% but is projected to increase to 20%–40% during 2040–2069 (Ruosteenoja et al., 2020). This would mean an increasing frequency of winters that resemble the December 2019–February 2020 period, with subsurface flow continuing almost without interruptions throughout the year.

5 | CONCLUSIONS

Our field study under natural precipitation showed that ST is a viable option to decrease BAP losses from soils that have been under NT management for a longer time and therefore produce elevated DRP loads to surface waters. At our study site, the beneficial effect of mixing P-enriched topsoil within the plow layer lasted for the whole 4-year study period. Importantly, DRP concentrations in subsurface drainage waters, the main P loss pathway in this soil, remained at a much lower level after ST compared to continuous NT. No substantial increase in PP loss due to ST was observed, partly because of non-erosive weather conditions after the one-time plowing treatment, but we did not see any obvious signs of a collapse of soil aggregate structure during the study. Continuous NT is probably the correct management option for highly erodible soils with steep slopes, but soil mixing at 5–10 years interval to undo P stratification at sites with modest erosion can be recommended to control P losses that fuel eutrophication of surface waters.

AUTHOR CONTRIBUTIONS

Risto Uusitalo: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; writing—original draft; writing—review and editing. **Riitta Lemola**: Data curation; methodology; resources; writing—review and editing. **Mira Šuštar**: Formal analysis; methodology; validation; visualization; writing—review and editing. **Mika Kurkilahti**: Formal analysis; methodology; validation; writing—review and editing. **Janne Kaseva**: Formal analysis; methodology; visualization; writing—review and editing. **Eila Turtola**: Writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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