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Phosphorus losses from a subdrained clayey soil as affected by cultivation practices

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Conservation tillage practices are included in the Finnish Agri-Environmental Program as phosphorus (P) loss control measures, but only few experiments have been performed to check their effectiveness in the local conditions. We studied surface and subsurface losses of P from a clayey underdrained field (Jokioinen/Kotkanoja: Vertic Cambisol/Typic Cryaquept), with 2% mean slope, during two separate experimental periods. Primary tillage treatments of the first experimental period of three years were moldboard ploughing (to 20–23 cm depth) vs. no autumn tillage (wintertime stubble). During the second experimental period of five years, the treatments were moldboard ploughing (20–23 cm) vs. shallow (to 5–8 cm) autumn tillage. The stubble treatment of the first experimental period produced higher dissolved reactive P (DRP) losses (104–259 g ha^{-1} yr^{-1}) than autumn ploughing (77–96 g ha^{-1} yr^{-1}), and equally high particulate P (PP) losses (mean 660, 235–1300 g ha^{-1} yr^{-1}). During the second experimental period, shallow autumn tillage produced 28% higher DRP losses (mean 120, 107–136 g ha^{-1} yr^{-1}) than ploughing (83–117 g ha^{-1} yr^{-1}) and 11% higher PP losses (mean 1090, 686–1336 g ha^{-1} yr^{-1}) than ploughing (783–1253 g ha^{-1} yr^{-1}). Surface runoff made up 28% and 16% of the total flow from the ploughed soil during the first and the second experimental period, respectively, as compared to 50% for the stubble and 44% for the shallow autumn tillage. Routing of flow between surface and subsurface pathways had a major influence on the P losses. In the relatively flat landscapes of the main agricultural areas of southern Finland, the potential for decreasing agricultural P losses by reduced tillage appears limited.

Key-words: Phosphorus, eutrophication, conservation tillage, moldboard ploughing, runoff, drainage

Introduction

Practices that leave at least 30% cover on the soil surface by plant residues after primary tillage are considered beneficial in areas where erosion, surface sealing and crusting, or poor soil structure adversely affect plant growth and/or result in environmental degradation (Wendt and Corey 1980, Cassel et al. 1995). Conservation tillage is a general term that embraces a variety of practices that may incorporate some of the plant residues to the soil, or (in no-till) leave the soil surface entirely intact until the next sowing.

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Erosion and phosphorus (P) losses are intimately related, and particulate P (PP) usually makes up a major share of the total P transport from the fine-textured soilscapes prevailing in South and Southwest Finland (e.g. Turtola and Paajanen 1995, Puustinen et al. 2005). The soils of these areas are mainly utilized in the production of annual crops, and traditionally moldboard ploughed to 20–25 cm depth after harvest in autumn. Most of the PP transport takes place during the autumn-winter flow period (Puustinen et al. 2007). Reducing tillage intensity might in these circumstances be a mean to abate erosion and nutrient losses (Puustinen et al. 2005, Alakukku et al. 2006); thus, reduced tillage has been adopted as a part of the Finnish Agri-environmental Programme.

As compared to conventionally ploughed soils, lower erosion rates and PP losses, but higher losses of dissolved molybdate-reactive P (DRP), have been recorded from fields under conservation tillage (Sharpley and Smith 1994, Gaynor and Findlay 1995, Puustinen et al. 2005). Lower erosion rates and PP losses from soils under reduced tillage are attributed to the protection by crop residues of the soil surface against the dispersing effect of raindrop impact, and to increased aggregate stability. On the other hand, when tillage depth is reduced, plant residues accumulate, and added P enriches, in a few centimeter part on soil surface (Ellis and Howse 1980, Duiker and Beegle 2006). Enriching soil surface layer with P tends to increase dissolved P concentrations in surface runoff (Römkens et al. 1973, Sharpley and Smith 1994), and in the worst case, transition from ploughing to conservation tillage may increase the losses of algal-available P (Sharpley et al. 1992, Gaynor and Findlay 1995).

While surface runoff is often emphasized in soil management studies, subsurface drainflow may constitute a major share of water discharge from tile-drained fields (e.g., Turtola and Paajanen 1995). Then, a complete picture of tillage effects on P losses requires monitoring both surface runoff and subsurface drainflow (Sims et al. 1998). This is emphasized in tillage studies, because changes in tillage practices may affect surface runoff volumes and routing of flow between surface and subsurface pathways (Lal 1976, Hill 1990).

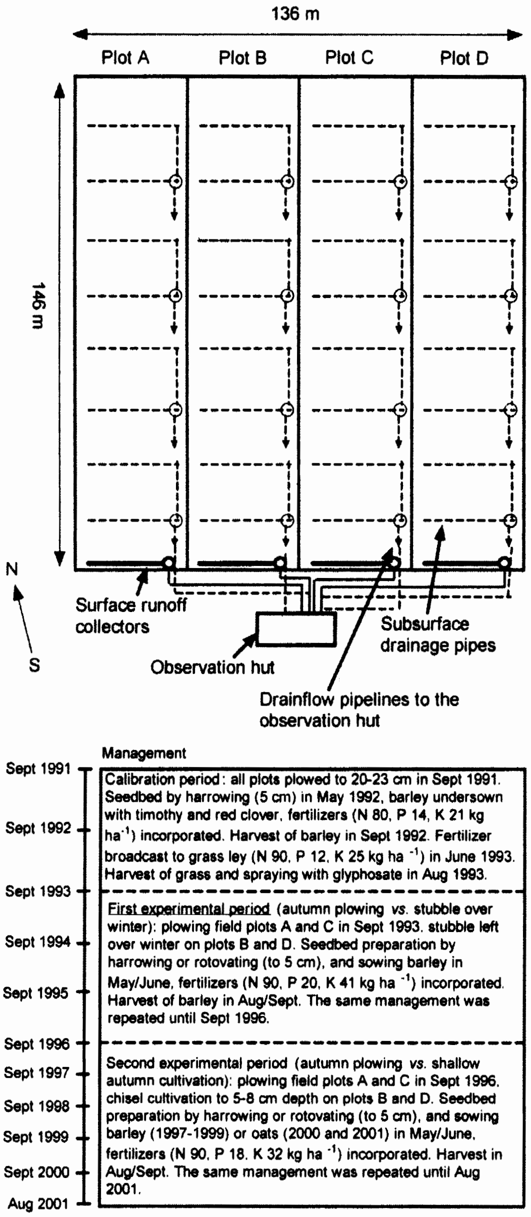
The objective of this study was to evaluate how reducing tillage intensity affects P transport from a typical – relatively flat, clayey, subdrained – field of southwest Finland. We report results collected during ten years (1991–2001), including a two-year calibration period (1991–1993), followed by a first experimental period of three years and a second experimental period of five years. During the experimental periods, two types of conservation tillage: (i) no autumn tillage (i.e., stubble over winter; 1993–1996) and (ii) autumn tillage with reduced (to 5–8 cm) depth (1996–2001) were applied. Moldboard ploughing (to 20–23 cm) in autumn served as a control treatment during the both experimental periods. Losses of P via surface and subsurface pathways were monitored, and the losses of potentially bioavailable P (the sum of dissolved P and potentially bioavailable particulate P) were estimated.

Material and methods

The soil

The study was conducted on the Jokioinen/Kotkanoja experimental field (2 ha), located in Southwest Finland (60°48.94' N, 23°30.84' E). The clayey soil was classified as a Vertic Cambisol according to the WRB classification (FAO 1998), or a very fine, mixed Typic Cryaquept according to the classification of U.S. Soil Taxonomy (Soil Survey Staff 1998). A detailed profile description has been given by Peltovuori et al. (2002).

Agronomic P status of the soil was "fair" according to the Finnish national criteria; i.e., at a level at which yield responses to annual P additions are becoming unlikely (see Saarela et al. 2006). The concentration of soil test P (P_{Ac}, ammonium acetate-extractable P; Vuorinen and Mäkitie 1955) in the surface layer (0–20 cm, Ap horizon) has slowly increased over the years, from 2–5 mg P_{Ac} l^{-1} in 1991 and 4–6 mg P_{Ac} l^{-1} in 1996 to 6–7 mg P_{Ac} l^{-1} in 2001, because P balances have been slightly positive. Concentration of about 6 mg kg^{-1} water-extractable P (1:50 soil-water ratio, 21 h extraction) was measured in plough-layer soil samples taken in 1997, whereas the concentration of $NaHCO_3$-extractable P (pH 8.5; Olsen and Sommers 1982) was 31–45 mg kg^{-1}, and the degree of soil P saturation, estimated by relating non-apatite inorganic P fractions (mol P kg^{-1}) to oxalate-extractable Al and Fe (mol Al_{ox} + Fe_{ox} kg^{-1}), was 8–9% (Peltovuori et al. 2002).



Calibration period: all plots plowed to 20-23 cm in Sept 1991. Seedbed by harrowing (5 cm) in May 1992, barley undersown with timothy and red clover, fertilizers (N 80, P 14, K 21 kg ha^{-1}) incorporated. Harvest of barley in Sept 1992. Fertilizer broadcast to grass ley (N 90, P 12, K 25 kg ha^{-1}) in June 1993. Harvest of grass and spraying with glyphosate in Aug 1993.

First experimental period (autumn plowing *vs.* stubble over winter): plowing field plots A and C in Sept 1993, stubble left over winter on plots B and D. Seedbed preparation by harrowing or rotovating (to 5 cm), and sowing barley in May/June, fertilizers (N 90, P 20, K 41 kg ha^{-1}) incorporated. Harvest of barley in Aug/Sept. The same management was repeated until Sept 1996.

Second experimental period (autumn plowing *vs.* shallow autumn cultivation): plowing field plots A and C in Sept 1996, chisel cultivation to 5-8 cm depth on plots B and D. Seedbed preparation by harrowing or rotovating (to 5 cm), and sowing barley (1997-1999) or oats (2000 and 2001) in May/June, fertilizers (N 90, P 18, K 32 kg ha^{-1}) incorporated. Harvest in Aug/Sept. The same management was repeated until Aug 2001.

Fig. 1. Layout and management of the Jokioinen/Kotkanoja field during the study (September 1991–August 2001).

The field and study layout

Cultivation of the Jokioinen/Kotkanoja experimental field was done on four 0.5-ha plots (Fig. 1), hydrologically isolated from the surroundings and from each other (see Turtola and Paajanen 1995). Flow measurement was arranged with data loggers connected to a tipping bucket equipment. Flow was separately measured and sampled from drainage pipes (8 drainflow pipelines per field plot) and surface runoff collectors (one per plot). A constant 0.1-% fraction of the flow was conducted from the collectors into polyethene containers, and this flow fraction was sampled for laboratory analyses.

When discussing the results, the 10 years covered (Sept 1991–Aug 2001) is divided into three periods (Fig. 1). Calibration of the field was done under uniform management of the four field plots during two years (Sept 1991–Aug 1993), after rebuilding the pipe drainage of the field in June 1991. Barley (*Hordeum vulgare* L.) was harvested in the autumn of 1991, and all plots were ploughed to 20–23 cm and left bare over winter. In the spring of 1992 barley was undersown with timothy (*Phleum pratense* L.) and red clover (*Trifolium pratense* L.). After the harvest of barley, no autumn tillage was done and the soil was covered by grass ley over the winter (1992–1993). The calibration period ended in the autumn of 1993, after the grass ley was harvested.

The first experimental period covered three annual cycles, from September 1993 to August 1996. Two of the field plots (in Fig. 1, plots A and C) were then ploughed (to 20–23 cm depth) each autumn, whereas no autumn tillage was done (but stubble was left over winter) on the two other plots (B and D). During the first winter (1993–1994), stubble was after timothy–red clover, the stand of which was in 20. August 1993 killed with glyphosate. Starting from spring 1994 onwards, barley was grown on the field.

During the second experimental period (Sept 1996–Aug 2001) ploughing was continued on the plots A and C. On the plots B and D, autumn cultivation was done to 5–8 cm depth using a Kværneland (Jæren, Norway) cultivator (in 1996 and 1999) and a Fibroflex (Kongskilde Industries A/S, Sorø, Denmark) cultivator. The crops grown were spring-sown barley, and spring-sown oats (*Avena sativa* L.).

Chemical analyses of water samples

The concentration of DRP was determined after filtration of a subsample through a 0.2-µm Nuclepore membrane (Whatman, Maidstone, UK) and that of total P (TP) after digestion of an unfiltered subsample by sulphuric acid and peroxodisulphate in an autoclave (120°C, 100 kPa, 30 min). A LaChat analyzer (LaChat Instruments, Milwaukee, WI, USA) equipped with a 880 nm wavelength filter was employed in all P analyses, determination being based on the molybdate colorimetry (Murphy and Riley 1962) modified for flow-injection analysis. Particulate P was taken as the difference between TP and DRP. Soil erosion was estimated through measurements of total suspended solids in surface runoff and drainflow samples and is reported by Turtola et al. (2007).

To estimate the amount of PP that could be transferred in a bioavailable form in aerobic and anoxic conditions of receiving waters, anion exchange resin (AER) and bicarbonate-dithionite (BD) extractions were conducted for a set of runoff samples (see Uusitalo et al. 2003). Anion exchange resin was used as a sink for P to promote desorption of PP. A 40-ml subsample of runoff was equilibrated with 1 g of AER (Dowex 1×8, Fluka Chemica, Neu Ulm, Germany), AER being enclosed in a mesh bag and presaturated with HCO_3^-. After 20 h shaking end-over-end at 37 rpm, the AER bag was removed from the runoff sample and washed with deionized water. The P sorbed by the AER was eluted by washing (shaken for 4 h) with 0.5 M NaCl solution, followed by determination of P concentration of the NaCl solution by molybdate colorimetry. To obtain an estimate of the AER-extractable particulate P (AER-PP) concentration in a runoff sample, DRP was subtracted from the AER-extractable P.

The use of a reductant, such as dithionite, mimics the conditions in severly reduced sediments that may leak P in the water phase. In the BD extraction, some Fe- and Mn-oxide dissolution takes place, leading to reduced P sorption capacity of the sediment matter and an increase in solution P concentration. Dithionite was used as a reducing agent and bicarbonate was added to buffer the decline in solution pH; in 40 ml of runoff, 1 ml of 0.298 M $NaHCO_3$ and 1 ml of 0.574 M $Na_2S_2O_4$ were pipetted (dithionite was dissolved in water just before the extraction). The BD-spiked runoff sample was placed on an orbital shaker, and immediately after shaking (15 min total reaction time, shaking at 120 rpm) passed though a 0.2 µm Nuclepore membrane, followed by digestion with an oxidant in acidic pH (as in TP analysis). Digestion was done to oxidize dithionite and Fe^{2+} that would interfere with colorimetric P determination, and acidity of the digest prevented Fe(III) hydroxide precipitation that, in turn, could strip soluble P. The concentration of BD-PP in runoff was calculated as the difference between BD-P and DRP.

Calculations and statistics

As stated above, all of the runoff samples taken during the study period were not analysed for AER- and BD-extractable P, but 213 AER and 76 BD extractions were made. Because the concentrations of AER-PP and BD-PP closely followed the PP concentration in runoff, extrapolation over all the samples taken during this study was done by utilizing the measured PP concentrations and the following equations (Uusitalo et al. 2003):

$$\text{AER-PP (mg l}^{-1}) = 0.081 \times \text{PP (mg l}^{-1}) - 0.005; \quad R^2 = 0.859, p < 0.0001 \qquad \text{[Eq. 1]}$$

$$\text{lg(BD-PP) (mg l}^{-1}) = 0.764 \times \text{lg(PP) (mg l}^{-1}) - 0.51; \quad R^2 = 0.885, p < 0.0001 \qquad \text{[Eq. 2]}$$

Annual losses of P forms were summed up after multiplying the measured flow volumes by the P concentrations of the corresponding flow fractions.

Water samples for the AER and BD extractions were collected between 1997 and 2001, and most of the samples originated from the ploughed plots. Because sampling for these analyses was done during the second experimental period, the equations 1 and 2 most accurately represent the runoff PP characteristics during the latter part of this study. The sizes of the two PP pools were 50–55 mg AER-PP and 730–820 mg BD-PP in a kilogram of suspended sediment (TSS). In a rainfall simulation study of 15 clayey soils of south Finland, Uusitalo and Aura (2005) estimated mean changes of 3.2 mg AER-PP and 8.2 mg BD-PP in a kilogram of TSS when soil test P concentration changed by 1 mg P_{Ac} l^{-1}. If we assume that these relationships between P_{Ac} vs. AER-PP/TSS and BD-PP/TSS are applicable for our present data, an increase of about 3 mg P_{Ac} l^{-1} in soil test P from 1991 to 2001 would correspond to an increase of about 20% in AER-PP (10 mg AER-P kg^{-1} TSS), but only 3% in BD-PP (25 mg BD-P kg^{-1} TSS). Thus, the AER-PP losses during the first experimental period may be slightly overestimated, wheras the estimates for BD-PP losses would be practically unaffected by the observed increase in soil P_{Ac} concentration.

The statistical tests on differences in flow, and concentrations and losses of DRP and PP between the treatments was made by using the two-way repeated measures ANOVA and the Bonferroni post test. The testing was based on monthly flow-weighted concentrations, or monthly losses and flow volumes, and the tests were performed using the Graph Pad Prism 4.03 software (Graph Pad

Table 1. Calibration period: surface (surf.), subsurface (subs.) and total flow, and losses of dissolved molybdate-reactive P (DRP) and particulate P (PP) from the four 0.5-ha field plots of the Jokioinen/Kotkanoja field during four six-month periods, and the sum flow and P losses during the two calibration years.

	Field plot A (to be pooled with C)			Field plot C (to be pooled with A)			Field plot B (to be pooled with D)			Field plot D (to be pooled with B)		
	surf.	subs.	total	surf.	subs.	total	surf.	subs.	total	surf.	subs.	total
Sept 1991–Feb 1992, precipitation 325 mm												
Flow, mm	11	131	142	7	136	144	9	132	140	15	142	157
DRP, g ha^{-1}	9	43	52	3	40	43	3	45	49	9	40	49
PP, g ha^{-1}	52	557	610	33	392	425	50	509	560	92	572	664
Mar 1992–Aug 1992, precipitation 277 mm												
Flow, mm	23	148	171	13	149	163	22	149	171	24	150	174
DRP, g ha^{-1}	11	38	49	4	35	39	5	38	44	6	31	37
PP, g ha^{-1}	26	192	218	15	142	157	33	156	189	42	166	208
Sept 1992–Feb 1993, precipitation 292 mm												
Flow, mm	47	119	167	32	135	167	51	120	171	64	116	180
DRP, g ha^{-1}	35	31	66	24	31	55	40	30	70	42	28	70
PP, g ha^{-1}	79	313	392	51	234	285	84	261	345	130	253	384
Mar 1993–Aug 1993, precipitation 358 mm												
Flow, mm	60	95	155	53	102	155	68	89	156	78	81	159
DRP, g ha^{-1}	52	36	89	58	34	93	63	32	94	75	30	105
PP, g ha^{-1}	245	403	649	171	363	534	231	304	536	284	286	570
Calibration period (Sept 1991–Aug 1993), precipitation 1251 mm												
Flow, mm	142	493	635	106	523	628	150	489	639	181	489	670
DRP, g ha^{-1}	108	148	256	90	140	230	112	145	257	132	129	261
PP, g ha^{-1}	402	1466	1868	270	1131	1401	398	1231	1629	549	1277	1826

Software Inc., San Diego, CA, USA). Prior to ANOVA, all data were logarithm transformed to obtain normally distributed data; normality was tested by the D'Agostino and Pearson omnibus test.

Results and discussion

Calibration period

When the data collected during the two calibration years were analyzed as nested pairs (A+C and B+D), there weren't any statistically significant differences (at the $\alpha = 0.05$ level; two-way repeated measures ANOVA) in flow-weighted concentrations of DRP nor PP between the field plot pairs; this holds for both the "treatment" (plot pairs under uniform treatment during the calibration period) and the "interaction" (treatment×time) terms. In surface runoff, the average (±standard error of the mean) monthly flow-weighted DRP concentrations were 0.068 (±0.009) vs. 0.056 (±0.008) mg DRP l^{-1} for the nested pairs A+C vs. B+D. The mean PP concentrations equaled 0.264 (±0.032) vs. 0.291 (±0.039) mg PP l^{-1} for A+C vs. B+D.

In subsurface drainflow, that delivered 70–80% of the total flow (summed surface and subsurface flow) during the calibration period (Table 1), the average monthly DRP and PP concentrations were essentially same for the both field plot pairs (A+C vs. B+D): 0.028 (±0.002) vs. 0.029 (±0.002) mg DRP l^{-1}, and 0.240 (±0.038) vs. 0.241 (±0.039) mg PP l^{-1}.

Also total flow was equally high from all of the four plots: the average (surface + subsurface) sum flow for the whole two-year calibration period was 643 mm, and the maximum relative deviation for the individual plots from that value was just 4%, or 27 mm. Similar P concentrations and flow conditions resulted in similar P losses from all field plots (Table 1). The somewhat lower PP loss during the whole calibration period from the plot C (15–25% lower than from the others) was largely attributable to the modest PP loss during the autumn of 1991; flow-weighted PP concentrations were then generally high after rebuilding the pipe drainage (in June 1991).

Autumn ploughing vs. stubble over winter

Omitting autumn ploughing had an effect on P concentrations that could be expected from the data reported in the litterature (Sharpley and Smith 1994, Gaynor and Findlay 1995, Puustinen et al. 2005, 2007). Namely, stubble produced substantially higher DRP concentrations and lower PP concentrations in surface runoff than autumn ploughing (Fig. 2); for the ploughed vs. stubble treatments, average monthly concentrations in runoff equaled 0.059 (±0.008) vs. 0.105 (±0.017) mg DRP l^{-1}, and 0.438 (±0.097) vs. 0.303 (±0.040) mg PP l^{-1}, respectively. The overall treatment effects were not statistically significant at the the $\alpha = 0.05$ level, but the interaction (treatment×time) term had p-values of 0.0006 (for DRP) and 0.0017 (for PP). The highest DRP concentrations and the most pronounced differences in DRP concentrations between the treatments were observed during the first autumn-winter period, after application of glyphosate on grass ley in the autumn. Besides decaying plant material being left on the surface in the stubble treatment, a fertilizer dressing on the soil surface (including 12 kg P ha^{-1}) given in June 1993 also contributed to the DRP losses from the stubble. In the ploughed plots, plant residues and fertilizer P had been incorporated in the plough layer in September and the concentrations of DRP in surface runoff were more moderate than in the stubble treatment.

As for subsurface drainflow, the differences in P concentrations between the treatments were less pronounced (Fig. 2) and the treatment effects were not statistically significant. However, the concentration of PP in subsurface drainflow was periodically higher in water draining from the ploughed plots, with a highly significant p-value (<0.0001) for the interaction term as a result. Even then, the mean flow-weighted monthly concentrations of both DRP and PP were at a fairly similar level for the ploughed plots and the plots left on stubble: 0.039 (±0.005) vs. 0.043 (±0.007) mg DRP l^{-1} and 0.267 (±0.030) vs. 0.231 (±0.029) mg PP l^{-1}, respectively.

By the end of the first experimental period, accumulated DRP loss in surface runoff from the stubble treatment was more than three times the

DRP loss from the ploughed soil, and the overall difference (treatment effect) was statistically significant (Table 2). In addition to the higher DRP concentrations in surface runoff from the plots under stubble as much as 50% of the flow was in the stubble treatment delivered via surface pathway, as compared to just 28% of the ploughed soil. On the contrary, subsurface losses of DRP were somewhat higher from the ploughed soil, as a result of the higher subsurface drainflow volumes. Summing the surface and subsurface losses, the plots left on stubble over winter produced during the 3 years accumulated DRP losses that were 1.8 times the losses from the ploughed control treatment.

Even though the concentrations of PP were generally lower in the stubble treatment than in the ploughed soil (Fig. 2), the losses of PP during the first experimental period were practically the same for the both tillage options (Table 2). A higher share of the flow occurred as surface runoff from the stubble treatment, and surface runoff had higher PP concentrations than drainflow. Also, soil losses (with associated PP) occuring in the course of the first experimental period for the most part took place in the summer months (May–August) when all of the field was either disturbed by seed-bed preparation or already vegetated. Runoff volumes in the wintertime, when stubble would have prevented soil loss, were small. The rainfall and flow patterns during the first experimental period were thus such that our results don't necessarily show the potential of the

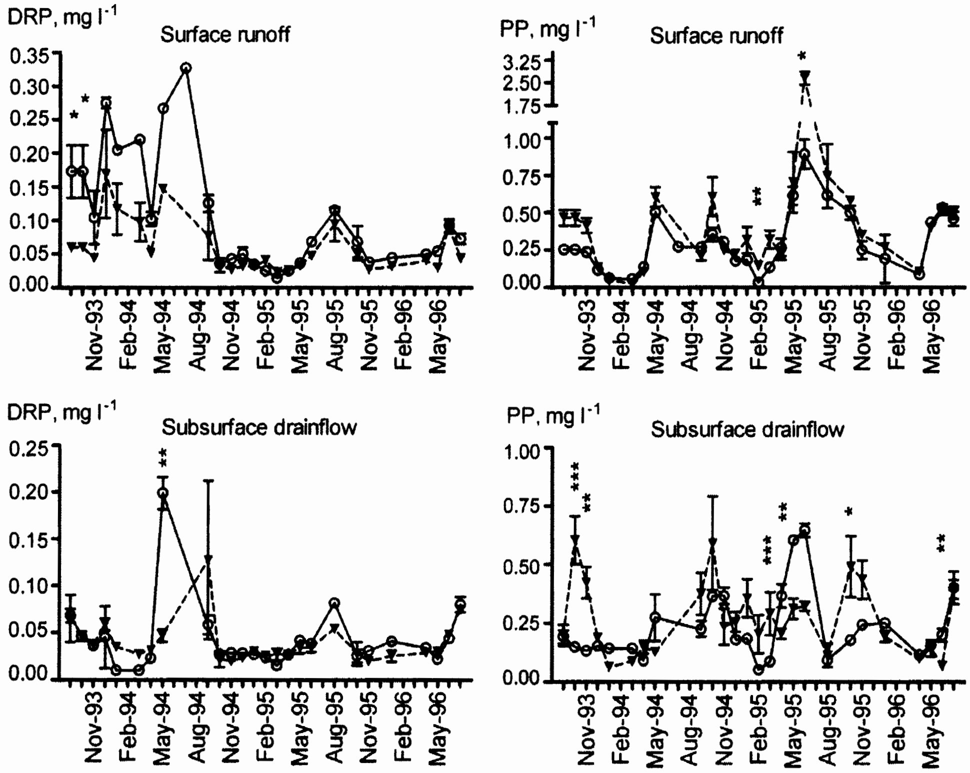


Fig. 2. Average monthly flow-weighted concentrations of dissolved reactive P (DRP) and particulate P (PP) in surface runoff and subsurface drainflow during the first experimental period (September 1993–August 1996). Dotted lines with triangle markers represent the ploughed plots and solid lines with circle markers represent the field plots left on stubble over winter; error bars indicate the range of the two replicate field plots. The asterisk markers show the significant differences in the average monthly concentrations (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; Bonferroni test).

Table 2. Surface, subsurface and total flow, and losses of dissolved molybdate-reactive P (DRP) and particulate P (PP) during the first experimental period as averaged over the two replicate field plots under autumn ploughing, or left on stubble over winter.

	Ploughed			Stubble over winter		
	surface	subsurface	total	surface	subsurface	total
Sept 1993–Aug 1994, precipitation 423 mm						
Flow, mm	71	98	169	157	34	191
DRP, g ha^{-1}	48	34	82	247	12	259
PP, g ha^{-1}	66	191	257	194	41	235
Sept 1994–Aug 1995, precipitation 777 mm						
Flow, mm	95	233	328	132	231	363
DRP, g ha^{-1}	33	63	96	38	74	112
PP, g ha^{-1}	649	651	1300	315	976	1291
Sept 1995–Aug 1996, precipitation 538 mm						
Flow, mm	26	175	201	93	112	206
DRP, g ha^{-1}	10	67	77	51	53	104
PP, g ha^{-1}	51	399	450	168	279	447
First experimental period (Sept 1993–Aug 1996), precipitation 1739 mm						
Flow, mm	192	506	698	382*	377	760
DRP, g ha^{-1}	91	164	255	336*	139	475**
PP, g ha^{-1}	766	1241	2007	677	1296*	1973

Significant overall treatment effects (the significantly higher value of the treatment–flow pathway combinations) are indicated by * and ** markers (for $p < 0.05$ and 0.01, respectively; two-way repeated measures ANOVA).

stubble to prevent soil and PP losses. Especially high PP losses from ploughed soil would be expected to occur in a rainy and warm winter when bare soil surface thaws several times (Puustinen et al. 2005, 2007).

Autumn ploughing vs. shallow autumn cultivation

During the second experimental period, stubble was replaced by a shallow (to 5–8 cm depth) autumn cultivation. The shallow cultivation produced significantly higher DRP concentrations in surface runoff than was observed for the ploughed soil (Fig. 3; treatment effect $p = 0.0145$), with average monthly concentrations of 0.049 (±0.004) vs. 0.066 (±0.007) mg DRP l^{-1}. Somewhat surprisingly, but in line with measured soil losses (Turtola et al. 2007), also PP concentrations were higher in surface runoff from the plots under shallow autumn cultivation than in runoff from the ploughed plots, 0.356 (±0.030) vs. 0.466 (0.047) mg PP l^{-1}. This time the overall effect of cultivation was non-significant ($p > 0.05$), but the treatment×time interaction had a p-value of less than 0.0001.

When averaged over the whole second experimental period, flow-weighted DRP concentrations in subsurface drainflow were equal for the both treatments (ploughing vs. shallow cultivation), 0.041 (±0.004) vs. 0.042 (±0.002) mg DRP l^{-1}. Similarly, the average PP concentrations in drainflow were close to each other, with averages of 0.359 (±0.043) for the ploughed plots vs. 0.330 (±0.035) mg PP l^{-1} for the plots under shallow autumn cultivation. However, there were periodical differences in the concentrations of DRP and PP (Fig. 3), and the interaction terms were highly significant for the both P forms.

During the second experimental period, the total flow volumes for the two treatments were again the same (Table 3). However, surface runoff volumes for the plots under shallow autumn cultivation were much higher than the runoff volumes for the ploughed plots: ploughed soil delivered on average 16% of the flow via surface pathway (between 8 and 28% during the individual annual cycles), whereas the share of surface runoff from the shallow autumn cultivation was as high as 44% (38–66% in individual years). High surface runoff peaks during snowmelt in March-April were observed in the plots under shallow cultivation (see Turtola et al. 2007). Such runoff peaks were more moderate in the ploughed soil with a higher depressional water storage capacity, because mechanically loosened surface layer of ploughed soil could accumulate excess water during periods of rapid snowmelt (and also during autumn storms). High surface layer storage capacity apparently increased percolation of water and hence also increased subsurface drainflow, in agreement with the concept presented by Horton (1937).

On the basis of surface runoff data only, the practice of shallow cultivation would have appeared as a total failure as far as P loss abatement is concerned: the P losses in surface runoff from the plots under shallow autumn cultivation were 3.5 times those from the ploughed plots (Table 3). Even when the both flow pathways were

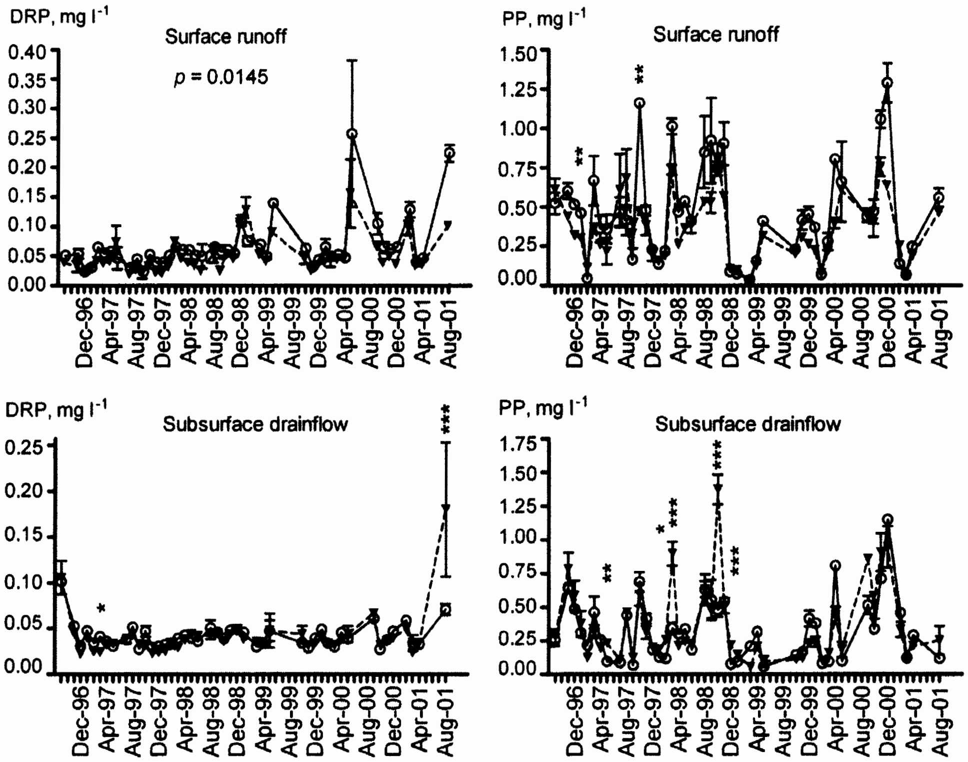


Fig. 3. Average monthly flow-weighted concentrations of dissolved reactive P (DRP) and particulate P (PP) in surface runoff and subsurface drainflow during the second experimental period (September 1996–August 2001). Dotted lines with triangle markers represent the ploughed plots and solid lines with circle markers represent the field plots under shallow autumn cultivation; error bars indicate the range of the two replicate field plots. The given *p*-value indicates a significant overall cultivation effect (two-way repeated measures ANOVA), and the asterisk markers show the significant differences in the average monthly concentrations ($*p < 0.05$, $**p < 0.01$, $***p < 0.001$; Bonferroni test).

Table 3. Surface, subsurface and total flow, and losses of dissolved molybdate-reactive P (DRP) and particulate P (PP) during the second experimental period as averaged over the two replicate field plots under autumn ploughing, or under shallow (5–8 cm depth) autumn cultivation.

	Ploughed			Shallow autumn cultivation		
	surface	subsurface	total	surface	subsurface	total
Sept 1996–Aug 1997, precipitation 708 mm						
Flow, mm	19	228	247	102	157	259
DRP, g ha^{-1}	7	80	87	60	73	133
PP, g ha^{-1}	66	1017	1083	351	778	1129
Sept 1997–Aug 1998, precipitation 654 mm						
Flow, mm	28	219	248	101	147	248
DRP, g ha^{-1}	12	71	83	59	55	114
PP, g ha^{-1}	132	672	804	574	476	1050
Sept 1998–Aug 1999, precipitation 496 mm						
Flow, mm	80	201	281	169	89	258
DRP, g ha^{-1}	43	74	117	102	34	136
PP, g ha^{-1}	119	874	993	346	340	686
Sept 1999–Aug 2000, precipitation 694 mm						
Flow, mm	27	248	275	93	168	261
DRP, g ha^{-1}	11	91	102	47	72	119
PP, g ha^{-1}	76	707	783	485	753	1238
Sept 2000–Aug 2001, precipitation 598 mm						
Flow, mm	46	188	234	90	145	235
DRP, g ha^{-1}	18	70	88	49	58	107
PP, g ha^{-1}	134	1119	1253	388	948	1336
Second experimental period (Sept 1996–Aug 2001), precipitation 3150 mm						
Flow, mm	200	1084*	1284	555	706	1261
DRP, g ha^{-1}	91	386**	477	317**	292	609
PP, g ha^{-1}	527	4389*	4916	2144*	3295	5439

Significant overall treatment effects (the significantly higher value of the treatment–flow pathway combinations) are indicated by * and ** markers (for $p < 0.05$ and 0.01, respectively; two-way repeated measures ANOVA).

taken into account, the total P losses were greater from the shallow cultivation than from ploughed plots. Surface runoff was more voluminous from the plots under shallow cultivation and, at the same time, the DRP concentrations were higher in surface runoff than in subsurface drainflow. As calculated for the whole second experimental period, both pathways taken into account, DRP losses were on average 28% (annually 16–53%) higher and the PP losses 11% higher from the plots under the shallow cultivation treatment than from the ploughed plots (Table 3).

Losses of potentially bioavailable P forms

The loss estimates for readily bioavailable (DRP) and potentially bioavailable (AER-PP and BD-PP) P forms that occurred during this study are summarized in Table 4. In addition, Fig. 4 shows the cumulative losses of DRP and BD-PP for the individual field plots during the whole 10-y study; in Fig. 4, BD-PP is shown because it was the variable more robust than AER-PP against the changes in soil P status.

Table 4. Surface, subsurface and total losses of dissolved molybdate-reactive P (DRP), and the loss estimates for bioavailable particulate P: anion exchange resin-extractable PP (AER-PP), and bicarbonate-dithionite-extractable PP (BD-PP) from the Jokioinen/Kotkanoja field. The values represent averages over the two replicate plots that were ploughed or under conservation management (stubble over winter/shallow autumn cultivation) during the experimental periods.

	Ploughed			Stubble or shallow cultivation		
	surface	subsurface	total	surface	subsurface	total
Calibration period (Sept 1991–Aug 1993)						
DRP, g ha^{-1}	99	144	243	122	137	259
AER-PP, g ha^{-1}	21	80	101	30	77	108
BD-PP, g ha^{-1}	135	524	659	189	503	691
First experimental period (Sept 1993–Aug 1996)						
DRP, g ha^{-1}	91	164	255	336	139	475
AER-PP, g ha^{-1}	53	75	128	37	86	123
BD-PP, g ha^{-1}	246	512	758	286	491	776
Second experimental period (Sept 1996–Aug 2001)						
DRP, g ha^{-1}	91	386	477	317	292	609
AER-PP, g ha^{-1}	33	301	334	147	232	378
BD-PP, g ha^{-1}	209	1576	1785	758	1162	1920
September 1991–August 2001						
DRP, g ha^{-1}	281	694	975	775	569	1343
AER-PP, g ha^{-1}	107	457	564	214	395	609
BD-PP, g ha^{-1}	591	2611	3202	1232	2155	3387

The total losses of potentially bioavailable P from the four field plots were uniform during the calibration years (on average about 120–130 g DRP ha^{-1} yr^{-1}, 50–55 g AER-PP and 330–350 g BD-PP ha^{-1} yr^{-1}), but they differentiated as soon as the different tillage treatments were applied (Fig. 4). The surface runoff losses of DRP were very high from the plots under stubble (at the beginning of the first experimental period), and even if the difference between the treatments was less spectacular later on, surface pathway losses of DRP were all the time higher from the plots under conservation tillage than from the ploughed plots. During the two experimental periods (Sept 1993-Aug 2001), about 350 g more DRP was lost from the plots under conservation tillage than from the ploughed plots (Table 4), and the 8-yr mean annual difference between the treatments was 44 g ha^{-1} yr^{-1}.

The losses of potentially bioavailable PP were initially unaffected by the omission of autumn cultivation, but during the second experimental period AER-PP and BD-PP losses were cosistently higher from the plots under shallow autumn cultivation than from the ploughed plots (Fig. 4). The 8-yr P loss sums show that, in addition to the average 44 g ha^{-1} higher annual DRP loss, slightly more bioavailable PP (between 5 and 19 g ha^{-1} based on AER-PP and BD-PP losses, respectively) was annually lost from the plots under the conservation practices than from the ploughed plots (Table 4).

Conclusions

The studied conservation tillage practices applied in our study were at this site more detrimental than beneficial in eutrophication control point of view. This was because of the higher DRP losses from the plots under conservation tillage, attributed to the

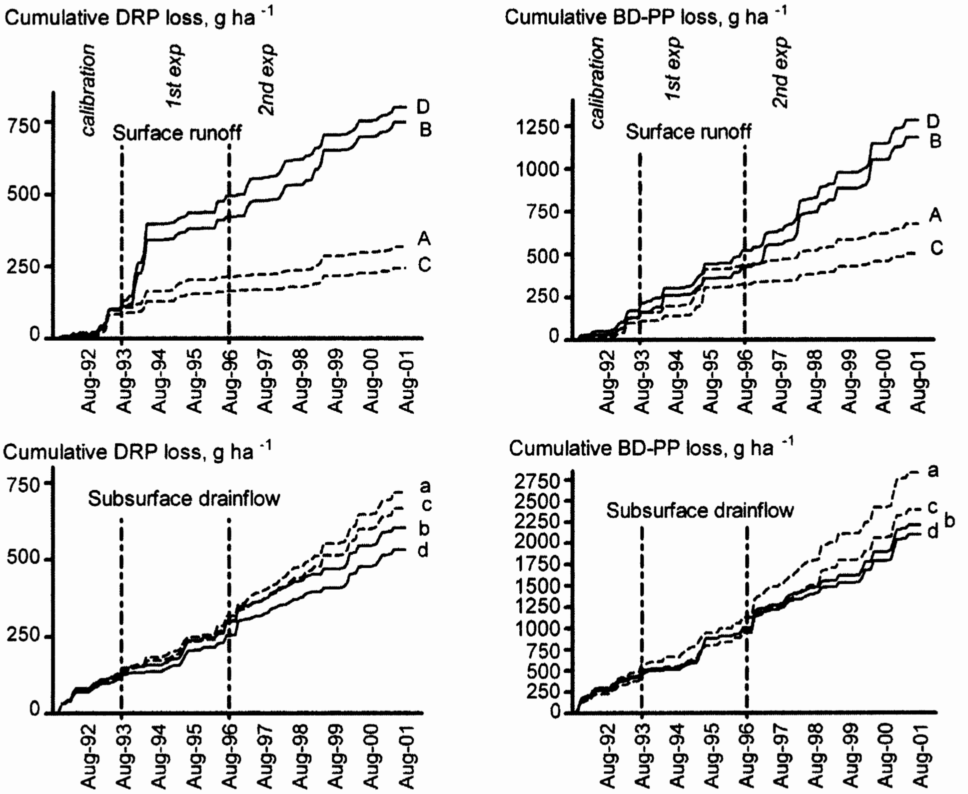


Fig. 4. Cumulative surface and subsurface losses of dissolved molybdate-reactive P (DRP, lefthand figures) and redox-labile PP (BD-PP, righthand figures) from the Jokioinen/Kotkanoja field during the 10-year study (September 1991–August 2001). The plots A and C (dotted lines) were ploughed, and the plots B and D (solid lines) were under conservation tillage during the experimental periods (labels for surface runoff capitalized, subsurface drainflow indicated by lower case letters). Vertical lines indicate the calibration period and the two experimental periods.

high share of surface runoff and to the higher DRP concentrations in runoff from the soil under conservation tillage than in runoff from the ploughed soil. Furthermore, PP losses were not reduced when autumn ploughing was omitted, because erosion rates from the relatively flat Jokioinen/Kotkanoja field were relatively low regardless of the tillage treatment. During the latter part of the study, shallow autumn cultivation also tended to produce higher PP losses than ploughing. As the main part of the Finnish cultivated soils are located in relatively flat landscapes, the potential of conservation tillage as a mean to reduce agricultural P losses appears limited in our conditions, especially if the conservation practices include some type of autumn cultivation.

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SELOSTUS

Fosforin kulkeumat käytettäessä kevennettyjä muokkausmenetelmiä loivasti viettävällä savimaalla

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MTT Kasvintuotannon tutkimus

Kevennettyä syysmuokkausta sovelletaan Suomessa ja muuallakin menetelmänä, jonka tarkoituksena on pienentää eroosiota ja ravinnekulkeumia pelloilta vesistöihin. Kaltevilla ja eroosioalttiilla pelloilla, joilla pääosa valunnasta on pintavirtailua, muokkauksen keventäminen on osoittautunut tehokkaaksi menetelmäksi pienentää fosforin kokonaiskuormitusta. Tällöin on erityisesti erodoituneeseen kiintoainekseen kiinnittyneen fosforin kuorma vähentynyt, kun taas veteen liuenneen fosforin kuorma on saattanut kasvaa. Koska rehevöittävä fosfori muodostuu sekä liuenneesta fosforijakeesta että osasta kiintoaineksen mukana kulkeutuvaa fosforia, on kevennetyn syysmuokkauksen kuitenkin joissakin tapauksissa epäilty lisäävän rehevöittävää fosforikuormaa vaikka kokonaiskuorma hieman pienentyisikin. Näin voisi tapahtua etenkin tasaisilla mailla, joiden valumasta pääosa tulee salaojien kautta ja joilla eroosio on suhteellisen vähäistä.

Tässä tutkimuksessa seurattiin fosforipitoisuuksia ja fosforin kuormaa Jokioisten Kotkanojan koekentällä. Kenttä on topografialtaan varsin tasainen (keskimääräinen vietto 2 %), ja pääosa valumasta poistuu pellolta salaojien kautta. Seurantajakso oli 10 vuotta, johon sisältyi kahden vuoden kalibrointijakso (syyskuusta 1991 elokuuhun 1993) ja kaksi muokkauskoejaksoa. Ensimmäisellä muokkausjaksolla (syyskuusta 1993 elokuuhun 1996) koekenttä jätettiin talven yli sängelle tai kynnettiin syksyllä, kun taas toisella muokkauskoejaksolla maa muokattiin syksyllä matalaan (5–8 cm:iin) kultivaattorilla sänkikäsittelyn sijaan.

Sänkikäsittely aiheutti suuremman liuenneen fosforin kuorman kuin kyntö. Koska sademäärä oli kasvukauden ulkopuolella hyvin pieni, sänkikäsittelyn kiintoainesfosforin kuormaa vähentävä vaikutus ei tullut koejaksolla esiin lainkaan. Syksyllä tehty kultivointi (5–8 cm:n muokkaussyvyys) aiheutti yksiselitteisesti suurempia fosforikuormia kuin kyntö (20–23 cm:n muokkaussyvyys); liuenneen fosforin kuorma oli 28 % suurempi ja kiintoainesfosforin 11 % suurempi. Muokkauskäsittelyt vaikuttivat valunnan suuntautumiseen pinta- tai salaojavalunnaksi. Valuntareittien muutokset puolestaan aiheuttivat eniten eroja kuormitukseen. Sänkipeitteisiltä ja matalaan muokatuilta ruuduilta tuli huomattavasti enemmän pintavaluntaa kuin kynnetyiltä ruuduilta, vaikka kokonaisvalunta oli samansuuruinen. Koska fosforipitoisuudet olivat pintavalunnassa suurempia kuin salaojavalunnassa, kevennetysti muokattujen koeruutujen kuorma muodostui selvästi suuremmaksi kuin kyntökäsittelyssä. Tasaisilla lohkoilla kevennetyn muokkauksen ei voi odottaa vähentävän rehevöittävän fosforin kulkeumaa pellolta vesistöön. Koska viljelymaidemme valtaosa sijaitsee suhteellisen tasaisilla mailla, yksinään muokkaustapojen muutoksilla ei voida vähentää maataloudesta vesistöihin päätyvää rehevöittävää fosforikuormaa.