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Surface runoff, subsurface drainflow and soil erosion as affected by tillage in a clayey Finnish soil

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Conservation tillage practices were tested against autumn mouldboard ploughing for differences in physical properties of soil, surface runoff, subsurface drainflow and soil erosion. The study (1991–2001) was performed on a gently (2%) sloping clayey soil of southern Finland, with two replicates of the tillage treatments on 0.5 ha plots. The annual shares of surface runoff of the total flow (surface runoff + subsurface drainflow) were 8–42% for ploughing (depth 20–23 cm), 36–66% for shallow autumn stubble cultivation (depth 5–8 cm) and 36–82% for soil left untilled over winter. Surface runoff increased with decrease in the tillage intensity, and in line with the values of depressional water storage, macroporosity and saturated hydraulic conductivity. Erodibility of this gently sloping soil was at highest after autumn and spring tillage operations and decreased with time. Shallow autumn tillage produced erosion as high as mouldboard ploughing (407–1700 kg $ha^{-1}yr^{-1}$), but 48% and 12% lower erosion levels were measured from plots left untilled in autumn, covered by grass or barley residues, respectively. Eroded soil particles moved relatively freely to the subsurface drains, which carried 37–94% of the annual soil losses from the field. The study shows that even on the relatively flat clayey soils typical for southern Finland, tillage has a great influence on soil losses. The frequency of tillage needs to be reduced rather than the depth of tillage on clayey soils with poor water conductivity and structural stability if soil loss is to be diminished by conservation tillage.

Key-words: Clay, drainage water, grass, hydrology, physical properties of soil, ploughing, reduced tillage, soil erosion, soil macroporosity, stubble, stubble cultivation, surface runoff

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Introduction

In the cultivation of annual crops in Finland, autumn mouldboard ploughing to a depth of 20–25 cm is the conventional method for primary tillage. However, the combination of annual cropping and conventional soil tillage has long been acknowledged as unfavourable in terms of soil erosion (e.g. Stoltenberg and White 1953, Römkens et al. 1973). In Finnish conditions, autumn ploughing leaves the soil surface bare for 7–8 months, from September/October to late April/May. This practice may thus have a strong influence on erosion levels in southern Finland, because most soil erosion occurs during autumn and spring runoffs (Puustinen et al. 2007).

Since 1995, when Finland joined the EU, both farm economics and environmental regulations have encouraged farmers to replace ploughing with conservation tillage methods. The most frequently used methods in Finland have been (1) stubble cultivation to a depth of 10–15 cm in autumn and (2) postponing the primary tillage until spring, i.e. leaving the soil under stubble over winter. In recent years, these methods have covered roughly 20% and 5% of the field area of southern Finland, respectively, whereas the share of autumn ploughing has been around 60% (MMM 2004). Annual crops occupy 75–85% of the field area in southern Finland, leaving 15–25% for perennial cropping such as grass, set-aside grass and pastures. Further, clayey soils make up 55–66% of the total field area, and the median field slope is around 1%.

For conservation tilled fine-textured soils, many investigations have found lower saturated hydraulic conductivity and infiltration rates compared to conventional tillage (Gantzer and Blake 1978, Tebrügge and Düring 1999, van Es et al. 1999, Lipiec et al. 2006). In several studies, conservation tillage has, however, been reported to increase the water infiltration rate and saturated hydraulic conductivity (Logsdon et al. 1993, McGarry et al. 2000, Buczko et al. 2006). The variability in these two properties can be associated with differences in soil surface sealing (e.g. Tebrügge and Düring 1999), the temporal water storage capacity of wet soil (Alakukku 1998, Lipiec et al. 2006) and flow-active macropores made by soil fauna (Ehlers 1975, Pitkänen and Nuutinen 1998). Ploughing, in turn, increases temporal water storage capacity by creating a rough surface structure, large voids, and pores (Zobeck and Onstad 1987, Hansen et al. 2000, Pitkänen 1999). This increases infiltration and, consequently, reduces the risk of surface runoff, especially on relatively flat soils.

In southern Finland, soil erosion from autumn ploughed clayey soils planted with annual crops varies from 700 to 4700 kg ha^{-1}yr^{-1}, depending on the soil type, slope and annual precipitation patterns, with 30–70% lower erosion rates measured from perennial grassland (Turtola and Paajanen 1995, Turtola and Kemppainen 1998, Koskiaho et al. 2002, Puustinen et al. 2005, Paasonen-Kivekäs and Koivusalo 2006). Also, plant residue cover and shallow tillage have been shown to reduce soil losses on relatively steep slopes: compared with autumn ploughing, Puustinen et al. (2005) reported 32–62% reductions in erosion by surface runoff, and Koskiaho et al. (2002) reported 55% reduction in erosion by total runoff from two clayey soils (8–9% and 4–6% slopes, respectively) which were either under shallow stubble cultivation (5–15 cm) in autumn or left as stubble. Studies on clayey soils of Norway and Sweden showed 55–99% reductions in soil erosion when left untilled under stubble and 26–62% when the soil was stubble cultivated in autumn (Skøien 1988, Lundekvam 1993, Ulén 1997, Lundekvam 1998).

In many studies cited above, the erosion is accounted for by surface runoff only. Without a doubt, surface runoff is the main water flow pathway on steep slopes, which also have the highest erosion rates. However, on gentle slopes, as are typical in Finland, the share of total runoff as subsurface drainflow may be considerable, at 40–90% of total runoff, and drainflow may also carry substantial amounts of eroded material from clayey soils (Turtola and Paajanen 1995, Uusitalo et al. 2001, Koskiaho et al. 2002, Paasonen-Kivekäs and Koivusalo 2006). Thus, the subsurface flow pathway can have a large impact on total erosion and should not be neglected when estimating the effects of different cultivation practices on soil erosion.

Erosion and associated phosphorus losses from steeply sloping fields are well recognised problems. While gentle slopes predominate in Finland, their role in water quality deterioration due to soil loss is also substantial, at least in southern part of the country with clayey soils. On the other hand, despite the environmental rewards of conservation tillage practices, the effects of these practices on erosion in both surface runoff and drainflow has seldom been examined in long-term field experiments. The present study was initiated to test the potential of autumn stubble cultivation or stubble to reduce total soil erosion on the gently sloping heavy clay soils of southern Finland. The second aim was to quantify the changes in physical properties of the soil due to conservation tillage and thereby estimate the effects of conservation tillage on water flow routes (surface runoff or subsurface drainflow) and erosion via the different flow pathways.

Material and methods

The Jokioinen/Kotkanoja field

This study was conducted on a clayey soil at Jokioinen, southwest Finland (60°49'N, 23°30'E) with a mean slope of 2% (1–4%). The Jokioinen/Kotkanoja experimental field is divided into four 0.5-ha plots, which are hydrologically isolated by plastic sheet curtains that extend 1 m below the soil surface, by open ditches and by 20–30 cm high barriers of mounded soil (Turtola and Paajanen 1995).

The soil of the experimental field was classified as a Vertic Cambisol according to the FAO (1998) classification system, and as a very fine, mixed Typic Cryaquept according to the U.S. Soil Taxonomy scheme (Soil Survey Staff 1998). A detailed profile description has been given by Peltovuori et al. (2002). Soil texture (by wet sieving and pipetting, Elonen 1971) was heavy clay (at least 60% of the particles in the clay fraction), the surface layer (0–25 cm) being partly silty clay (Table 1). The content of total C in 0–20 cm depth, 2.5–3.0%, considered to be organic C [measured using a LECO CN-2000 analyzer (St. Joseph, MI, USA)] and soil pH, 6.0–6.5 [measured in 1:2.5 (v/v) water suspension with a glass electrode] were typical for the soil type in the area.

Soil tillage and cropping practices

A brief summary of the tillage treatments and cropping practicess for 1991–2001 is given below. The study is presented in three sections, consisting of the calibration period (two years), and two experimental periods (three and five years, Table 2).

Calibration period

The study was preceded by reconstruction of the subsurface drainage system and construction of the hydrological barriers in June 1991 (Turtola and Paajanen 1995). In the following autumn (Sep 1991), all plots [A, B, C and D (for the field layout, see Uusitalo et al. 2007)] were ploughed to 23 cm

Table 1. Particle size distribution, pH (1:2.5 v/v in water) and content of total C in the Jokioinen/Kotkanoja experimental field at the start of the experiment.

Depth,	Particle size distribution, %			pH_w	Total C,
cm	<0.002	0.002–0.02	0.02–0.2 μm		%
0–20	61	16	23	6.0	2.7
20–40	83	8	9	6.1	0.6
40–80	90	6	4	6.4	0.4

Table 2. Soil tillage and other management practices for the experimental plots (A, B, C, D) during the calibration period and the two experimental periods.

Date	Soil tillage and cropping practices
Calibration period, Sep 1991–Aug 1993	
Sep 1991	(Barley), mouldboard ploughing (20–23 cm depth)
May 1992	Seedbed by harrowing (5 cm depth), barley undersown with timothy and red clover, NPK fertilizer with combisowing
Aug 1992	Harvest of barley
Jun 1993	NPK/fertilizer broadcast to grass ley
Aug 1993	Grass cutting, spraying with glyphosate
First experimental period: autumn ploughing vs. stubble over winter, Sep 1993–Aug/Sep 1996	
Sep/Oct 1993–1995	Mouldboard ploughing, plots A + C Left untilled over winter, plots B + D
May/June 1994–1996	Seedbed by harrowing or rotary harrowing (5 cm), sowing barley, NPK fertilizer with combisowing
Aug/Sep 1994–1996	Harvest of barley
Second experimental period: ploughing vs. shallow autumn stubble cultivation, Sep 1996–Aug 2001	
Sep/Oct 1996–2000	Mouldboard ploughing, plots A + C Stubble cultivation (5–8 cm), plots B + D
May/June1997–2001	Seedbed by harrowing or rotary harrowing, sowing barley (1997–1999) or oats (2000–2001), NPK fertilizer with combisowing
Aug/Sep 1997–2001	Harvest of barley/oats

depth up and down the slope, and in the next spring (May 1992) they were sown with barley (*Hordeum vulgare* L.), with simultaneous undersowing with timothy (*Phleum pratense* L.) and red clover (*Trifolium pratense* L.). NPK fertiliser (N 80, P 14, K 21 kg ha^{-1}) was applied during combisowing. The barley stand was harvested in August 1992, whereas the timothy-red clover ley was left growing for another year. Fertiliser was broadcast onto the grass ley in June 1993 (N 90, P 12, K 25 kg ha^{-1}). This two-year period (Sep 1991–Aug 1993) was considered to be a calibration period, during which it was determined whether flow volumes and the shares of surface and subsurface flow were similar for all four plots. At the end of the calibration period, on August 20, 1993, all plots were treated with glyphosate. During the calibration period, the total precipitation was near the average for 1980–2001 (Table 3). The winters were rather mild, and the maximum amount of water as snow was less than average.

First experimental period

During the following three years (Sep 1993–Aug 1996), nutrient losses were studied on plots that were, after harvest, either ploughed in autumn (plots A+C) or left untilled (plots B+D) as grass (autumn 1993–spring 1994) or stubble over the winter. In the spring of 1994, the seedbed was prepared by rotary harrowing to a depth of 5 cm, and thereafter spring barley was sown (NPK fertiliser, N 90, P 20, K 41 kg ha^{-1}, applied during combisowing) on field plots. These same cultivation practices were followed during the next two annual cycles, barley being grown in all plots (Table 2). The barley was sown in early May to early June, with the exception of the year 1995, when the sowing was delayed until June 22 (plots A + C) and June 26 (plots B + D) due to heavy rains in May and early June. The harvest was between mid-August and late September and plots A and C were ploughed to a depth of 23 cm between mid-September and early October.

Table 3. Precipitation, number of days with more than 20 mm precipitation in 24 hours, maximum amount of water in snow in spring, dates of snow cover and frost, number of periods without snow between the first and last dates of snow (total snowmelts) and maximum frost depth during the experimental years (year: 1 Sep–31 Aug).

Year (Sep–Aug)	Precipitation, mm	Days with > 20 mm precipitation in 24 h	Max. water in snow, mm	Dates of snow cover	Number of total snowmelts before the final snowmelt	Dates of frost	Max. frost depth, cm
1991–1992	602	1	57	19 Nov –28 Apr	1	5 Dec –12 Mar	25
1992–1993	650	4	44	30 Oct –18 Apr	2	23 Oct –28 Apr	42
1993–1994	423	0	84	14 Nov –13 Apr	0	22 Oct –28 Apr	57
1994–1995	777	5	73	18 Nov –22 Apr	1	4 Nov –18 Apr	28
1995–1996	538	3	113	3 Nov –22 Apr	0	1 Nov –22 Apr	48
1996–1997	708	4	80	12 Dec –25 Apr	0	14 Dec – 2 May	30
1997–1998	654	4	45	24 Nov –30 Mar	1	23 Oct –30 Apr	45
1998–1999	496	0	118	6 Nov –10 Apr	0	8 Nov –16 Apr	35
1999–2000	694	1	86	15 Nov –18 Apr	1	15 Nov –18 Apr	25
2000–2001	598	2	35	18 Dec –19 Apr	1	21 Dec –27 Apr	45
Average 1980–2001	643		94	24 Nov –14 Apr	0.6	17 Nov –21 Apr	39

During the first experimental period, the average dry matter yield of barley grains was 4050 kg $ha^{-1}yr^{-1}$ from the autumn ploughed plots and 30% lower from the plots which were left untilled over winter. There were two years with less than average total precipitation and relatively hard winters (1993–1994 and 1995–1996) and one year with above average total precipitation and a mild winter (1994–1995).

Second experimental period

From September 1996 to August 2001, plots A and C were kept under ploughing, whereas the autumn tillage of plots B and D was changed to shallow autumn stubble cultivation (chisel ploughing, one pass to 5–8 cm depth). The stubble cultivation was done using a Kværneland Turbo2 (Jæren, Norway) cultivator (in 1996 and 1999) or a Kongskilde Fibroflex (Kongskilde Industries A/S, Sorø, Denmark) cultivator (in 1997, 1998 and 2000) between mid-September and early October. Both ploughing and stubble cultivation were done up and down the slope. From 1996 to 1999, barley was grown in the field, whereas in 2000 and 2001, oats (*Avena sativa* L.) replaced barley. NPK fertiliser was applied during combisowing (N 90, P 18, K 32 kg $ha^{-1}yr^{-1}$) and the cereal crops were harvested between mid-August and early September. During the second experimental period the average dry matter yields were very similar from ploughed and stubble cultivated plots, giving 3300 kg $ha^{-1}yr^{-1}$ for barley and 4500 kg $ha^{-1}yr^{-1}$ for oats. The annual precipitation did not differ much from the long-term average and the winters were mild except for the third year (1998–1999, Table 3), when there was less total precipitation and no total snowmelts before the final snowmelt in early April.

Surface conditions and physical properties of soil

During the second experimental period, surface conditions and physical properties of soil were examined. The average area covered by crop residues was estimated by taking photographs from above the soil surface throughout the winter of 1996–1997, with two additional measurements in autumn 1997 and spring 1998. The photographs were taken perpendicularly to the soil surface from 1 m height (area 0.65 m^2) with eight replicates per surface runoff plot. Slides of the photos were reflected on a background with 100 randomly placed circles (Ø 3 mm) and the residue cover was estimated as the average of three countings of the covered circles on different backgrounds. Simultaneously with the residue cover determinations, depressional water storage was estimated through surface roughness measurements by a pinrelief (cell size 25 × 25 mm, Kamphorst et al. 2000), with four replicate measurements representing an area of 4 × 1 m^2 per each surface runoff plot A–D.

To study hydraulic conductivity and macroporosity after eight years of different tillage treatments, undisturbed soil cores, with a diameter of 15 cm and length of 60 cm, were taken using PVC pipes with a tractor driven soil auger (Pöyhönen et al. 1997) at the end of the experiment (Nov 19–21, 2001). The total number of samples was 32, with eight cores taken from each of the four field plots (two replicates for each drainage plot). From each soil core, stored at +4–5°C between sampling and analyses, three subsamples representing functional layers of the soil, were separated: plough layer (0–20 cm), plough pan (20–35 cm), and the subsoil (35–50 cm). The depth limits of these subsamples also approximately correlate with the depths of the three uppermost genetic horizons of the Jokioinen/Kotkanoja soil: Ap (0–24 cm), Bw1 (24–32 cm), and 2Bw2 (32–56 cm) (Peltovuori et al. 2002). To obtain a broken surface with open macropores, cut surfaces were prepared by removing smeared or damaged soil with a knife and a vacuum cleaner. The number of cylindrical pores larger than 2 mm in diameter were classified as earthworm burrows and were counted. The prepared, cleaned sections of the soil cores were saturated with water, which had been boiled and cooled, starting from the bottom to avoid air entrapment, and soaked for five days. Saturated hydraulic conductivity (K_{sat}) was measured using the constant head method (Youngs 1991), and macroporosity (pores larger than 0.3 mm in diameter) was determined according to Alakukku (1996).

Runoff sampling

Surface runoff was collected at the lower ends of the four field plots A–D whereas subsurface drainflow was separately collected from each plot by 4 pairs of pipe drains laid at about 1 m depth. The original subsurface drainage system with tile pipes was established in 1962, but the system was reconstructed using plastic pipes in June 1991 (Turtola and Paajanen 1995). Surface runoff and subsurface drainflow flowed through PVC pipes to an observation hut where the volume of water was measured by a tipping bucket arrangement equipped with a data logger. A constant 0.1% fraction from the tippings of the collector buckets was emptied into polyethene containers, which were sampled for laboratory analyses. Runoff fractions were taken for analysis at different intervals depending on runoff volumes (on average, each flow collector was sampled 2.7 times a month during the 10 years of the study (1991–2001), and kept at +4–5°C in the dark until analysed.

All individual samples were analyzed for total suspended solids (TSS). TSS concentration was measured by weighing the evaporation residue of 40–80 ml of runoff and used as a measure of soil erosion. Annual soil losses were summed up after multiplying the measured runoff volumes by the TSS concentrations of the corresponding runoff fractions. Monthly average flow-weighted TSS concentrations were calculated for the surface runoff and the subsurface drainflow of each plot by summing up the TSS losses in the individual water samples for the month and dividing the monthly loss by the amount of water flow. The concentrations and losses of phosphorus in surface runoff and subsurface drainflow were also measured, and they are reported separately by Uusitalo et al. (2007).

Statistical analyses

The statistical tests on differences in surface runoff, subsurface drainflow, and concentrations of TSS were made using the two-way repeated measures ANOVA for finding significant treatment (tillage) effects, and the Bonferroni post test for finding significant interactions of tillage and time. The testing was based on monthly flow-weighted concentrations, or monthly flow volumes, and the tests were performed using the Graph Pad Prism 4.03 software (Graph Pad 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. The nonparametric Mann-Whitney U-test (Sokal and Rohlf 1995) was used in between-treatment comparisons of medians of soil physical properties.

Results

Surface conditions and physical properties of the soil

Soil surface conditions were characterised in the second experimental period by estimating the residue cover and the depressional water storage of the soil surface. The residue cover after autumn tillage operations was considerably higher in the shallow stubble cultivated plots than in the mouldboard ploughed plots (Table 4). The amount of residue cover of the stubble cultivated plots, in particular, depended on the straw yield, which was much higher in 1997 (3160 kg ha^{-1}) than in 1996 (1470 kg ha^{-1}). The simultaneous estimation of depressional water storage values showed higher values for the ploughed plots than for the plots under shallow autumn stubble cultivation. There was a decline in the depressional water storage of the ploughed plots between autumn 1996 and spring 1997, whereas the change was smaller in the plots under shallow stubble cultivation (Table 4).

After the second experimental period, the macroporosity of the ploughed plots in the 0–20 cm layer was significantly greater than that of stubble cultivated plots (Table 5), despite the macroporosity being measured before the autumn ploughing so that the soil had settled for one year after the previous ploughing. In agreement with the macroporosity values, the saturated hydraulic conductivity in the 0–20 cm layer was significantly less in the stubble cultivated plots than in the ploughed plots In the stubble cultivated plots, earthworm burrows were observed only at depths of 20 and 35 cm, and at 35 cm depth, only in three out of eight sampled sections of the plots. In contrast, earthworm burrows were found at each examined depth of the ploughed plots (Table 5), although at 60 cm depth only in three out of eight sampled sections.

Surface runoff and subsurface drainflow

Calibration period

The average total flow volumes (surface runoff + subsurface drainflow) during the two calibration years were 316 mm (1991–1992) and 328 mm

Table 4. Mean values of crop residue cover on the soil surface (n = 16) and depressional water storage (n = 8) on plots with autumn ploughing and shallow autumn stubble cultivation with range in the parenthesis.

	Residue cover, %		Depressional storage capacity, mm	
Date	Ploughed	Stubble cultivated	Ploughed	Stubble cultivated
3 Oct 1996	15 (11–22)	48 (40–57)	14 (9–24)	5 (4–9)
9 Dec 1996	11 (5–19)	44 (33–54)	11 (8–15)	6 (5–9)
17 Mar 1997			9 (6–12)	5 (3–7)
13 May 1997	9 (4–14)	40 (27–57)	7 (5–9)	4 (3–6)
23 Oct 1997			11 (7–15)	9 (7–12)
12 May 1998	11 (2–15)	66 (45–79)	6 (4–8)	6 (5–7)

Table 5. Medians (Md) and quartile deviations (QD) of soil macroporosity, number of earthworm burrows and saturated hydraulic conductivity (K_{sat}) in 2001 in ploughed plots and autumn stubble cultivated plots (stubble cultivated in 1996–2000, left on stubble over winter in 1993–1995), $n = 8$.

Determination*	Ploughed		Stubble cultivated	
Depth, cm	Md	QD	Md	QD
Macroporosity >0.3 mm (m^3 100 m^{-3})				
0–20	6.8^a	1.2	4.3^b	1.7
20–35	0.6	0.3	0.6	0.1
35–60	0.3	0.05	0.2	0.04
Number of earthworm burrows m^{-2}				
23	113	25	71	32
38	28	28	0	14
60	0	14	0	0
K_{sat} (cm h^{-1})				
0–20	33^a	45	8^b	7
20–35	1.6	1.0	0.8	0.5
35–60	0.005	0.03	0.003	0.01

*Limits recommended for good structure of clay soils in Finland: K_{sat} in topsoil ≥ 30 cm h^{-1}, in subsoil ≥ 1 cm h^{-1} (Aura 1990); number of earthworm burrows in subsoil ≥ 100 m^{-2} (Aura 1990, Alakukku 1996).

^{ab} Median macroporosity or K_{sat} values between two treatments with a different letter are significantly different according to the nonparametric Mann-Whitney U-test ($p < 0.05$).

(1992–1993) with ranges for the four plots of 307 to 331 mm and 322 to 339 mm, respectively. Maximum differences in area-specific total flow from the individual field plots during the first and second calibration years were only 4.9 and 3.5%, respectively. There was no statistically significant difference between the plot pairs A+C and B+D in subsurface drainflow (cumulative drainflow during the calibration period 508 vs. 490 mm) or in surface runoff (124 vs. 166 mm, respectively, Table 6), except for a few months in spring 1993 (Fig. 1).

First experimental period: Ploughing vs. untilled over winter

During the three-year period (Sep 1993–Aug 1996), total runoff was 9% higher from the untilled plots (B+D) than from the ploughed plots (A+C) (Table 6). Omitting autumn tillage changed the flow such that the plots produced much more surface runoff ($p = 0.04$, Fig. 1) and less subsurface drainflow as compared to the ploughed plots. The plots B+D had already, during the calibration period, delivered 33% more surface runoff than the plots A+C, but now the difference was much greater. During the three consecutive years of the first experimental period, surface runoff from the untilled plots was 2.2, 1.4, and 3.6 times the surface runoff from the ploughed plots. As a result, 36–82% of the total runoff from the untilled plots was surface runoff, as compared to 13–42% for the ploughed plots. The untilled plots either produced surface runoff in times when the ploughed soil did not (especially winter 1993–94), or then the (springtime) surface runoff peaks were sharper than those in the ploughed soil (Fig. 1).

Second experimental period: ploughing vs. shallow stubble cultivation

The total flow from the stubble cultivated plots was slightly less (2%) than that from the ploughed plots (Table 6). As before, there was a clear difference in the flow distribution between surface and subsurface pathways according to the tillage treatments ($p = 0.01$ for the difference in subsurface

Table 6. Water flow as surface runoff, subsurface drainflow, and total runoff (mm) from the experimental plots of the Jokioinen/Kotkanoja field during the calibration period and the two experimental periods.

Date	Plots A + C			Plots B + D		
	Surface runoff	Subsurface drainflow	Total	Surface runoff	Subsurface drainflow	Total
Calibration period						
Sep 1991–Aug 1992	28	282	310	35	287	322
Sep 1992–Aug 1993	96	226	322	131	203	334
Σ Calibration period	124	508	632	166	490	656
First experimental period	Plots ploughed in autumn			Plots left untilled over winter		
Sep 1993–Aug 1994	71	98	169	157	34	191
Sep 1994–Aug 1995	95	233	328	132	231	363
Sep 1995–Aug 1996	26	175	201	93	112	205
Σ First experimental period	192	506	698	382	377	759
Second experimental period	Plots ploughed in autumn			Plots stubble cultivated in autumn		
Sep 1996–Aug 1997	19	228	247	102	157	259
Sep 1997–Aug 1998	28	219	248	101	147	248
Sep 1998–Aug 1999	80	201	281	169	89	258
Sep 1999–Aug 2000	27	248	275	93	168	261
Sep 2000–Aug 2001	46	188	234	90	145	235
Σ Second experimental period	200	1084	1284	555	706	1261
Σ First + second experimental period	392	1590	1982	937	1083	2020

drainflow, Fig. 1), and the shares of surface runoff and drainflow were very similar to those from the same plots during the first experimental period. Subsurface drainflow was always the main pathway (with an 84% share, annual variation between 72 and 92%) for water flow from the ploughed plots, whereas the stubble cultivated plots delivered 56% of the total flow via subsurface drains (annual variation 34–64%) (Table 6). Again, the most pronounced differences in the flow patterns occurred in springtime, with a much higher share of the total flow as subsurface drainflow from the ploughed plots (Fig. 1).

Soil erosion

Calibration period

The concentrations of total suspended solids (TSS) were highest during autumn and spring, and very similar in surface runoff and subsurface drainflow (Fig. 2). There were no statistical differences between the field plots in monthly averaged TSS concentrations in the flows. In surface runoff, median concentrations of 0.335 and 0.300 g l^{-1} were measured for plot pairs A+C and B+D, respectively, whereas the respective median values for subsurface drainflow were 0.376 and 0.354 g l^{-1}. Average annual soil losses from the field plot pairs A+C and B+D during the two-year calibration period were 1346 and 1405 kg ha^{-1}, respectively, giving a 4% difference between the pairs (Table 7). As a result of greater subsurface drainflow volumes, the losses of TSS were dominated by subsurface transport: drainflow carried 88–93% and 60–72% shares of the summed TSS losses in the first and second years, respectively. With regard to soil losses, the field thus behaved very uniformly during these two years, and the only difference between the pooled plot pairs was the tendency for the plots B+D to

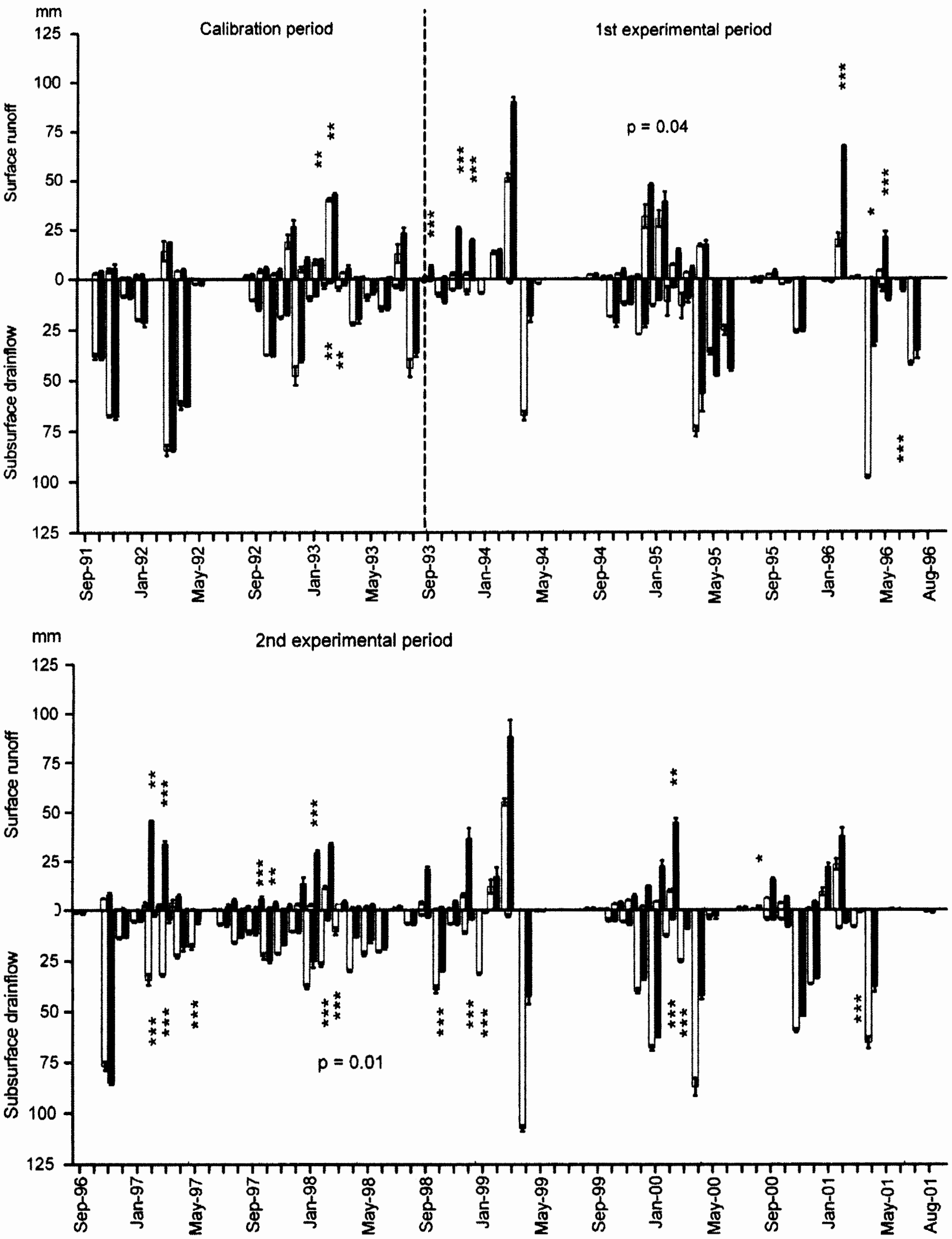

Fig. 1. Monthly values of surface runoff and subsurface drainflow in the Jokioinen/Kotkanoja field during the two-year calibration period (Sep 1991–Aug 1993) and the first three-year experimental period (Sept 1993–Aug 1996) (above) and the second five-year experimental period (Sep 1996–Aug 2001) (below). The columns present average values for the two 0.5-ha plots under the same autumn tillage treatments (white: plots (A+C) autumn ploughed in 1991 & 1993–2000, untilled in autumn 1992; black: plots (B+D) autumn ploughed in 1991, untilled in autumn 1992–1995, stubble cultivated to a shallow depth in autumn 1996–2000; error bars show the range. Given *p*-values refer to the two-way repeated measures ANOVA with significant tillage effects for the experimental periods in question and asterisks (*, **, ***) refer to the Bonferroni post tests with significant tillage effect for the months in question. Analyses were performed using logarithmically transformed data.

Table 7. Losses of total suspended solids (TSS, kg ha^{-1}) in surface runoff, in subsurface drainflow, and in total runoff from the experimental plots of the Jokioinen/Kotkanoja field during the calibration period and the two experimental periods.

Date	Plots A + C			Plots B + D		
	Surface runoff	Subsurface drainflow	Total	Surface runoff	Subsurface drainflow	Total
Calibration period						
Sep 1991–Aug 1992	100	1157	1257	145	1251	1396
Sep 1992–Aug 1993	454	982	1436	529	885	1414
Σ Calibration period	554	2139	2693	674	2136	2810
First experimental period	Plots ploughed in autumn			Plots left untilled over winter		
Sep 1993–Aug 1994	107	300	407	135	78	213
Sep 1994–Aug 1995	797	903	1700	335	1093	1428
Sep 1995–Aug 1996	67	596	663	223	423	646
Σ First experimental period	971	1799	2770	693	1594	2287
Second experimental period	Plots ploughed in autumn			Plots stubble cultivated in autumn		
Sep 1996–Aug 1997	81	1198	1279	430	849	1279
Sep 1997–Aug 1998	153	940	1093	647	703	1350
Sep 1998–Aug 1999	126	1074	1200	370	382	752
Sep 1999–Aug 2000	85	979	1064	508	838	1346
Sep 2000–Aug 2001	161	1338	1499	421	948	1369
Σ Second experimental period	606	5529	6135	2376	3720	6096
Σ First + second experimental period	1577	7328	8905	3069	5314	8383

deliver a somewhat higher share of the surface runoff as presented above.

First experimental period: Ploughing vs. untilled over winter

Median values for TSS concentrations in surface runoff from the ploughed and untilled plots were 0.335 and 0.236 g l^{-1}, and in subsurface runoff they were 0.377 and 0.309 g l^{-1}, respectively. In runoff from the ploughed plots, TSS concentrations often peaked in October after ploughing, and after ploughing in 1993 the differences in TSS concentrations between the ploughed and grass covered plots were statistically significant both in surface runoff and in drainflow (Fig. 2). Similarly, statistically significant differences were found between ploughed and stubble plots during spring 1995 (Fig. 2).

In February and March 1995, the differences in surface characteristics resulted in more ice formation on the surface of the stubble plots during snow melt episodes, and the stubble plots were covered by snow and ice to a later date than the ploughed plots. The ice cover was further associated with low turbidity of the surface runoff. Once ice disappeared from the stubble surface, the TSS concentration in surface runoff increased.

Annual erosion rates were very low during the first year of the first experimental period, with a 48% difference between the ploughed (410 kg ha^{-1}) and the grass covered (210 kg ha^{-1}) plots (Table 7). During the next year, when erosion was at about the same level as during the calibration period, the difference between the ploughed (1700 kg ha^{-1}) and barley stubble (1430 kg ha^{-1}) treatments was 16%. During the third year, intermediate soil losses were measured, giving only a 2% difference between the field plot pairs (660 and 650 kg ha^{-1}). Summing the soil losses for this three-year experimental period, we measured

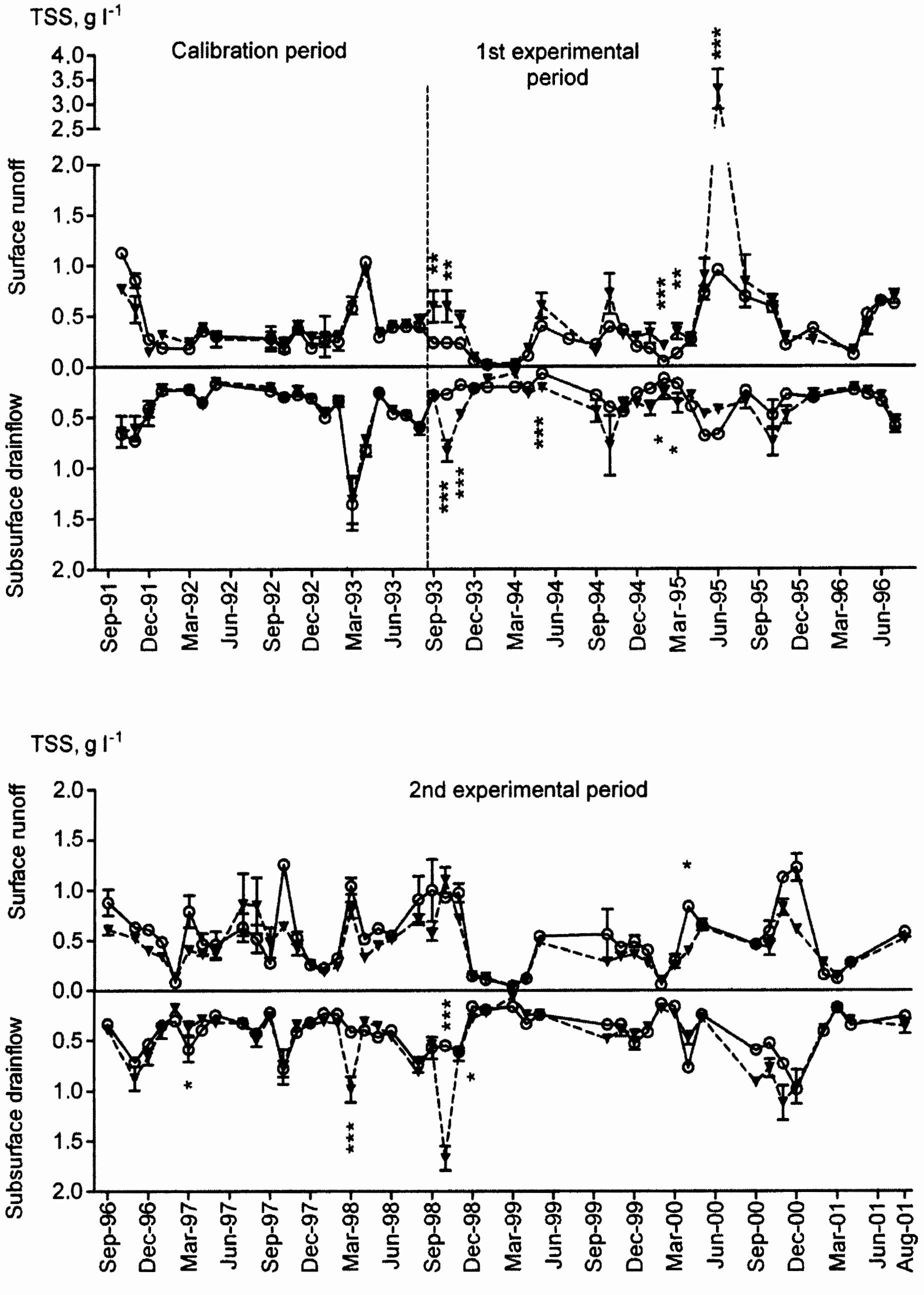

Fig. 2. Monthly concentrations of total suspended solids (TSS) in surface runoff and subsurface drainflow in the Jokioinen/Kotkanoja field during the two-year calibration period (Sep 1991–Aug 1993) and the first three-year experimental period (Sep 1993–Aug 1996) (above) and the second five-year experimental period (Sep 1996–Aug 2001) (below). The lines present average values for the two 0.5-ha plots under the same autumn tillage treatments (dashed: plots (A+C) autumn ploughed in 1991 & 1993–2000, untilled in autumn 1992; solid: plots (B+D) autumn-ploughed in 1991, untilled in autumn 1992–1995, stubble cultivated to a shallow depth in autumn 1996–2000); error bars show the range. Asterisks (*, **, ***) refer to the Bonferroni post tests with significant tillage effect for the month in question. Analyses were performed using logarithmically transformed data.

17% lower erosion rates from the untilled field plots (2290 kg ha^{-1}) than from the ploughed plots (about 2770 kg ha^{-1}).

In general, more soil particles were detached from the ploughed soil surface than from the untilled plots covered by grass or barley straw and stubble, and with the exception of May-June 1995, further routing of the water into subsurface drainflow did not have any marked influence on the particle concentrations. The TSS concentrations in drain flow were, however, always somewhat higher in the lower end of the field, reflecting the different backfill material in the drain frenches, wood chips in the lower and topsoil in the upper end of the field (Turtola and Paajanen 1995). For ploughing, this difference was 22% (5–36% in the individual years) and for stubble it was 32% (21–54%).

In June 1995, surface runoff contained clearly higher concetrations of TSS than subsurface drainflow (Fig. 2). In the ploughed plots, spring tillage practices had been started before an exceptionally rainy episode. The newly tilled soil surface of the autumn ploughed plots was sealed, and the surface of the ploughed plots was heavily eroded. Meanwhile, the stubble covered plots had not yet been tilled but there, in turn, the TSS concentrations in the subsurface drainflow water were substantially higher than in the ploughed plots (Fig. 2). This was accompanied by open cracks in the stubble plots which were formed in the preceeding dry summer 1994 (crack width up to 5 cm, depth more than 70 cm, and at their largest above the pipe lines of the subsurface drainage system) and which remained partly open in April 1995. In contrast, the crack system from the surface of the ploughed plots disappeared during the tillage operations in autumn. It is obvious that in June 1995 the cracks conducted water from the surface to the subsurface drainage system; on the untilled plots the TSS concentration was only slightly reduced upon water passage through the soil, from about 1 g l^{-1} in surface runoff to about 0.7 g l^{-1} in subsurface drainflow. The respective concentrations for the ploughed plots, 3.5 and 0.5 g l^{-1}, indicate, in contrast, considerable sieving of the soil particles from water while moving to the subsurface drains.

The TSS losses were smaller in the cold winter 1995–1996 than in the mild and rainy winter of 1994–1995, when there was subsurface drainflow throughout the winter and continuous surface runoff starting from February (Fig. 1). Moreover, the successive rains in late spring and early summer 1995 caused exceptionally large TSS losses. In May-June alone, about 860 kg ha^{-1} of soil was eroded from the ploughed plots and about 830 kg ha^{-1} from the stubble plots, representing 50% and 58% of the annual TSS loss, respectively.

Second experimental period: ploughing vs. shallow stubble cultivation

In contrast to the first experimental period, surface runoff from the plots under stubble cultivation now contained more TSS than surface runoff from the ploughed plots (Fig. 2). The median TSS concentrations were higher in the stubble cultivated plots both in the surface runoff (0.395 for ploughing vs. 0.520 g l^{-1} for stubble cultivation) and in the subsurface drainflow (0.365 vs. 0.395 g l^{-1}, respectively). However, the concentration differences were seldom statistically significant, even occasionally showing significantly higher TSS concentrations in drainflow from ploughed plots (Fig. 2). The actual soil losses were often determined by some months with very high TSS concentrations and voluminous flows. Exceptionally high monthly TSS concentration, for example, was recorded in subsurface drainflow from ploughed plots in October 1998 (Fig. 2).

The median TSS concentrations had so far been higher in subsurface drainflow than in surface runoff, but during the second experimental period the median TSS concentrations in surface runoff were higher than those in subsurface drainage water. As with the first experimental period, the TSS concentrations in subsurface drainflow were always higher in the lower end of the field. For ploughing the difference was 42% (22–74% in the individual years), and for stubble cultivation it was 47% (42–55%).

The erosion rates were relatively high throughout this second experimental period (Table 7). As compared to the stubble cultivated plots, the ploughed plots had clearly higher erosion rates in the third year (1998–1999) and slightly higher erosion in the fifth year (2000–2001) and lower erosion in the second and fourth year, with no difference in erosion in the first year. In the stubble cultivated plots, the highest TSS losses were often recorded in spring through surface runoff, while in the ploughed plots they were often largest in October through subsurface drainflow. For example, in October 1998 alone, about 61% of the annual soil loss of 1998–1999 was transported via subsurface drainflow from the ploughed plots, which were tilled just before a rainy period. The shallow stubble cultivation, in turn, had been done 8–11 days before the ploughing, thus leaving time for the surface soil to dry before the rains started. In 1998–1999, the difference in the tillage dates in autumn was thus an additional factor behind the recorded difference in erosion, in favour of the shallow stubble cultivation. Summed soil losses during the whole five-year period were practically the same for the both treatments, 6140 kg ha^{-1} for ploughing and 6100 kg ha^{-1} for stubble cultivation, with less than 1% difference between the tillage practices; this difference equals the difference in total runoff (2%).

Discussion

Physical properties of the soil as affected by tillage

Compared to conventional mouldboard ploughing, reduced tillage affected the physical and hydrological properties of the soil in several ways. As indicated by the roughness measurements, the surface of the stubble cultivated soil was more even than that of the ploughed soil, reducing the depressional water storage capacity, in agreement with the results of Zobeck and Onstad (1987), Pitkänen (1999) and Hansen et al. (2000). The low depressional water storage reduces the time available for water infiltration into the soil and increases the risk of surface runoff, as was evident from the results. While neither plant residue cover nor the depressional water storage were estimated in the field during the first experimental period, it is reasonable to assume that for the ploughed plots, surface characteristics were very similar to those of the second experimental period. Respective measurements for soil left as stubble in 1996–1998 in a nearby field in Jokioinen gave average residue cover values of slightly less than 100% and average depressional water storage values of less than 1 mm (Pitkänen 1999).

In agreement with the concept of Horton (1937), both the temporal water storage capacity of the surface layer (0–20 cm) and the saturated hydraulic conductivity of the same layer were smaller in the stubble cultivated than in the ploughed soil. The smaller values for macroporosity in the topsoil in the plots under reduced tillage also indicated lower temporal water storage capacity. Our result agrees with that Lipiec et al. (2006) and with earlier results for Finnish clay soils which had been stubble cultivated for 5 to 10 years (Pitkänen and Nuutinen 1995, Alakukku 1998). In addition, in other studies concerning fine-textured soils, the infiltration rate or saturated hydraulic conductivity was found to be lower under zero tillige (Gantzer and Blake 1978, Tebrügge and Düring 1999) than under ploughing. In the subsoil (below 35 cm) of the present study the saturated hydraulic conductivity was equally low in both treatments.

During the first experimental period, macroporosity of the soil was not measured. However, there were certainly fewer large (>0.3 mm) pores in the surface layer of the untilled stubble plots than in the ploughed plots, especially during late autumn and spring runoff, because ploughing increases the amount of large macropores in the tilled layer of clayey soils (e.g. Alakukku 1998). The ice formation on the surface of the stubble plots during snow melt episodes in spring was probably due to low macroporosity of the surface.

In contrast to the results presented above, several researchers have reported enhanced infiltration capacity and hydraulic conductivity for conservation and zero tillage (e.g. Logsdon et al. 1993, Pitkänen and Nuutinen 1998, McGarry et al. 2000). The inconsistencies could be associated with pore functioning. In a soil under conservation tillage, in particular, continuous earthworm burrows are regarded as essential for rapid water flow in saturated conditions, and preferential flow along biopores or other macropores is more important for water passage through the soil than in ploughed soil (Ehlers 1975, Riley et al.1994, Pitkänen and Nuutinen 1998). In the present study, there were no clear indications of such differences between the tillage treatments. The number of earthworm burrows was low in subsoil and, according to an earlier study by Nuutinen et al. (2006), there was a low density of *L. terrestris,* which makes deep, vertical burrows in soil. At this point our results also differ from earlier studies on Finnish fine textured soils (Pitkänen and Nuutinen 1997, 1998, Alakukku 1998) that have shown higher average numbers of earthworm burrows in subsoil (below 20 cm depth) both under autumn ploughing and stubble cultivation.

At the beginning of our study the soil was rather impermeable, and within the profile the conductivity fell off sharply, indicating a high tendency towards surface and near-surface runoff instead of deep percolation (Turtola and Paajanen 1995). The number of earthworms was also low. Thus, at the starting point, the soil conditions were not favourable to reduced tillage according to local practical experience. The subsurface drainage system was, however, reconstructed just before the field experiment was established, improving the expectations for success in managing the soil with reduced tillage. Indeed, during the experiment, the physical properties of the soil improved and there were signs of increased earthworm activity, although by the end of the 10-yr experiment the values were still low for both the saturated hydraulic conductivity below 35 cm depth and the number of earthworms (unpublished data by Dr. Visa Nuutinen). It is probable, however, that these values will continue to increase along with proper functioning of the subsurface drainage system and deeper rooting depth of the cultivated crops.

Water flow pathways and their contribution to erosion

Averaged over the years, the share of surface runoff was about 20% of the total water flow from autumn ploughed soil, about 40% from soil covered by stubble or stubble cultivated in autumn and about 60% from soil covered by grass. The soil physical properties measured at the end of the 10-yr experiment were in line with the measured proportions of surface runoff and subsurface drainflow. There was a higher tendency towards surface runoff in untilled or stubble cultivated plots than in ploughed plots. Thus, in this heavy clay soil with a relative dense structure and low earthworm activity, these factors contributed to altered water flow routing when the tillage system was changed from autumn ploughing to reduced autumn tillage. The subsurface drainflow from ploughed plots was probably enhanced further by horizontal water flow near the bottom of the ploughed layer (above untilled subsoil), leading the water towards drain trenches and through backfill to the subsurface drains.

Our results are in agreement with the findings of Børresen and Uhlén (1991) and Skøien et al. (1995). In contrast to our results, Lal et al. (1989) found that the share of surface runoff was very similar in ploughed and zero tilled treatments, 24 and 26%, respectively, and e.g. Shipitalo and Edwards (1998) measured less surface runoff in zero tillage. Pitkänen and Nuutinen (1998) found in a rainfall simulation study that surface runoff from spring stubble cultivated, silty clay soil was significantly less than from autumn ploughed or stubble cultivated soil. The inconsistencies could be associated with differences in soil, weather and topography conditions.

In this study, 65–90% and 61–70% of erosion from plouged and unploughed plots, respectively, was carried by subsurface drainflow. This was in agreement with previous results from the same field (Turtola and Paajanen 1995) and from other Finnish experimental fields on clayey soils equipped to record both surface runoff and subsurface drainflow (Koskiaho et al. 2002, Paasonen-

Kivekäs and Koivusalo 2006). Furthermore, Uusitalo et al. (2001) found that the origin of most eroded material in subsurface runoff from these experimental fields was probably the soil surface layer. Relevant to this, in Norway, Øygarden et al. (1997) found that erosion via preferential flow to a subsurface drainage system was considerable. The tillage of clay soil increased the particle concentration of subsurface runoff water indicating that the particles eroded from the plough layer. High sediment losses via a subsurface drainge system have also been measured in other studies on loamy (Grant et al. 1996) and clayey soils (Uhlén and Mattson 2003).

The remarkably similar concentrations of TSS in surface runoff and in subsurface drainflow in the present study indicate only a marginal sieving of the eroded particles while moving from the surface layer to the subsurface drainflow. The previously mentioned study of Uusitalo et al. (2001), conducted in the same experimental field, showed that although the clay percentage of the surface soil was high, there was still an enrichment of clay-sized particles both in surface runoff and in subsurface drainflow. The smallest particles probably move rather freely in the tilled surface layer and have only limited possibilities to become flocculated or bound in the drain trenches of the experimental soil. Only when the erosion amount is exceptionally high, as in June 1995, and the erosion material probably includes larger particles than during normal erosion events, sieving occures during water passage to the subsurface drains.

Erosion as affected by tillage

During the whole study period (1991–2001), the highest total erosion amounts (1500–1700 kg ha^{-1}) were recorded from the ploughed plots when the autumn was rainy and mild or the winter was mild and the early summer exceptionally rainy. The lowest erosion levels (210–750 kg ha^{-1}), on the other hand, were measured from grass covered or stubble cultivated plots when the precipitation was clearly less than average and the winter was relatively cold. These results are in agreement with results reported by Puustinen et al. (2007), who found that erosion from autumn ploughed sloping clay soil was twice as high in winter periods with a wet autumn followed by a mild and rainy winter than in average winters with less rain and lower temperatures. In that study, reduced tillage practices and no-till diminished the fluctuation in erosion between the different years.

When the annual erosion rates were summed for the whole second 5-yr experimental period, there was no difference between the ploughing and shallow stubble cultivation treatments. Only in two years out of five, the TSS losses from the stubble cultivated plots were less than those from the ploughed plots. In both cases, the difference was due to large TSS losses from ploughed plots in rainy and warm autumn months. In contrast, on clayey fields with lower clay contents and steeper slopes than in the present study, Puustinen et al. (2005) measured a reduction in erosion by surface runoff and Koskiaho et al. (2002) by total runoff due to shallow stubble cultivation. Likewise, studies on clayey soils of other Nordic countries showed large reductions in soil erosion when left untilled under stubble and considerable reductions when the soil was stubble cultivated in autumn (Skøien 1988, Lundekvam 1993, Ulén 1997, Lundekvam 1998).

For our soil, a typical TSS concentration after soil tillage, both ploughing and stubble cultivation, was about 1 g l^{-1}. In extreme cases with recent tillage, successive rains and water logging of the soil, the concentration peaked at 3–4 g l^{-1}. Stubble cover over winter, and the associated absence of soil tillage in autumn, somewhat reduced the average TSS concentrations while grass cover (with at least 1.5 years since the most recent soil tillage) kept the TSS concentrations at less than 0.5 g l^{-1}.

Dexter et al. (1983) showed that changes in soil macrostructure with rainfall occurred most rapidly immediatelly after tillage, causing a process of internal erosion where detached material reduced void continuity. With Finnish clay soils, Aura (1990) found that the water stability of soil aggregates was clearly improved by air drying. In the present study, the highest TSS concentrations and subsequent soil losses occurred when soil tillage was soon followed by rains. If the tilled surface was able to dry before the rains, susceptibility to erosion decreased. Our result may even imply that, under the prevailing climatic conditions and from the point of view of erosion, it might often be more favourable to do the autumn tilling in mid-September rather than in mid-October, to increase the probability of drying of the tilled soil surface.

When a surface cover, such as stubble or perennial grasses as in the present experiment, is associated with a lower frequency of tillage, then the soil surface can be gradually stabilised by drying cycles and age-hardening (Dexter et al. 1988). A more stable and firm surface develops during summer also due to rainfall which causes surface sealing and a decrease in roughness. Therefore, during the first experimental period, the surface conditions between the autumn ploughed soil and the untilled soil differed considerably during winter. Whilst ploughing incorporated most of the crop residues, turned the surface soil, and exposed fresh surfaces to raindrop and runoff impact, the soil surface of untilled plots was relatively firm and covered by straw and stubble over the winter. During the winter of 1993–1994, the surface was probably even more firm and stable than during the next two winters with barley stubble, due to the presence of grass, which was established in spring 1992.

It is impossible to know the relative impacts of the two inter-connecting factors, the absence of tillage and the residue/crop cover of the surface, that decreased erosion by rain and runoff on the stubble or grass covered soil surface. However, the slightly higher TSS concentrations in surface runoff from the plots under shallow autumn tillage than from the ploughed plots suggest that the straw residue cover alone was not capable of reducing the vulnerability of the soil to erosion. It is most probable that in our soil the absence of tillage, along with a gradual stability increase of the topmost soil layer in the stubble and grass covered plots as discussed earlier, had a greater impact on soil erosion than the crop cover alone. In our conditions, with rather low rainfall intensities, a gentle slope and a heavy clay soil, the relative impact of surface cover on the risk of erosion may thus be lower than in areas with higher rainfall intensities, different types of clays or steeper slopes.

It seems that the clay type found in the soil of our experimental field is quite easily dispersed when already wet at the start of rain or snowmelt. This may be due to the presence of mica or illite in the coarse clay fraction (0.2–2 µm), which has a negative impact on the stability of such clays (see Tan 1993, p.144 or review by Amézketa 1999). Mica or illite is typically found in both the fine (< 0.2 µm) and coarse clay fractions of Finnish heavy clay soils, with average shares of 37% and 33%, respectively, in subsoil (Sippola 1974). The mineral has a high negative charge (2/structure unit), and this, along with runoff waters of low ionic strength, such as snowmelt waters, may reduce the stability of soil aggregates and increase dispersion of the clay particles. While ice cover seems to protect the untilled soil surface from erosion, ice melting may cause stability changes, with a consequent increase in the TSS concentration of surface runoff, as observed in the present study.

Conclusions

By breaking the prevailing surface structure, and exposing fresh, unstable surfaces to shear forces from raindrops and runoff, soil tillage is one of the most important factors behind soil erosion and associated losses of nutrients from fields. To mitigate soil and associated nutrient losses during winter, optional measures such as conservation tillage and crop cover were introduced in the Finnish Agri-Environment Programme in 1995.

The results of the present study show that erosion from gently sloping clayey soils can be substantially reduced by permanent grass cover or leaving the soil untilled over winter. As time passes after tillage operations, soil surfaces respond with decreased soil erodibility but may, at the same time, show an increasing tendency towards surface runoff. However, merely changing the autumn tillage method to one that leaves more cereal straw residue to cover the soil seems to be an uncertain way to reduce the concentration of suspended soil particles in runoff from clayey soils with characteristics similar to the soil of the present study. If soil pore structure is initially poor and clay content high, erosion may not be reduced, at least in 5–10 years, even if the drainage system is improved before adopting the conservation tillage practices. Instead, on similar clayey soils with gentle slopes under typical climatic conditions for southern Finland, autumn stubble cultivation may lead to both soil losses that are just as high as for autumn ploughing and considerably greater surface runoff. This result challenges the method of shallow autumn stubble cultivation as a definite means for controlling water pollution from clayey fields in southern Finland.

Large quantities of soil matter from the surface layer may be transported via the subsurface drainage system from clayey soils. Depending on the pore system along the route of the subsurface drainflow and the backfill material in the drain trenches, variable amounts of the eroded particles are sieved out in the soil profile. However, in extreme circumstances, such as after dry summers, there may be no sieving of the eroded soil particles. The results emphasise the need to intervene during the first step of the erosion process on the soil surface and thereby restrict the transport of soil particles, phosphorus and various agrochemicals adsorbed to surface-derived soil material. This may be achieved by omission of soil tillage in autumn or by soil management which improves the structural properties of the clayey soils.

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SELOSTUS

Muokkauksen vähentämisen vaikutus savimaan rakenteeseen, pinta- ja salaojavaluntaan ja eroosioon

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Etelä-Suomen viljeltyjen savimaiden eroosio aiheuttaa huomattavaa sisävesistöjen samentumista, ja lisää myös niiden sekä Itämeren rannikkoalueen rehevöitymistä. Vaikka maa-ainesta irtoaa eniten jyrkiltä rinteiltä, myös loivasti viettävien peltojen eroosio on merkittävää niiden suuren pinta-alaosuuden vuoksi. Etelä-Suomessa eroosiohaitat korostuvat, koska valtaosa pelloista on talvisin muokattuina, ja kasvipeitteisten nurmien, viherkesantojen ja laitumien osuus on vain 15–25 % peltoalasta. Eroosion vähentämiseksi maatalouden ympäristötuessa on suosittu toimenpiteitä, joilla peltojen syysmuokkausta joko kevennetään kyntöön verrattuna tai siitä luovutaan kokonaan, jolloin pelto jää talven yli sängelle. Tässä tutkimuksessa verrattiin eriasteisen maanmuokkauksen vaikutuksia eroosioon ja tutkittiin eroosion taustatekijöitä, kuten maan pintakerroksen ominaisuuksia ja vedenjohtokykyä sekä taipumusta tuottaa pinta- ja salaojavaluntaa.

Tutkimus toteutettiin loivasti viettävällä (2 %) Jokioisten Kotkanojan huuhtoutumiskentällä, jonka pintamaan savespitoisuus on 61 %. Kentän salaojitus oli uusittu kesällä 1991 ennen kokeen aloittamista. Kahden vuoden kalibrointijakso (1991–1993) osoitti kentän olevan riittävän tasalaatuinen valunnan jakautumisen ja eroosion suhteen. Varsinaisella koejaksolla (1993–2001) kentän neljästä vierekkäisestä ruudusta kaksi kynnettiin syksyisin 23 cm syvyyteen ja kaksi muuta joko jätettiin syksyllä muokkaamatta sängelle (1993–1996) tai sänkimuokattiin kultivaattorilla 5–8 cm syvyyteen (1996–2001).

Muokkauksen vähentäminen madaltamalla syysmuokkausta tai luopumalla syysmuokkauksesta kokonaan lisäsi pintavalunnan osuutta kokonaisvalunnasta. Pintavalunnan osuus vuosittaisesta kokonaisvalunnasta (169–363 mm) oli kynnetyillä koeruuduilla 8–42 %, matalaan kultivoiduilla ruuduilla 36–66 % ja muokkaamatta jätetyillä sänki- ja nurmiruuduilla 36–82 %. Matalaan kultivoidussa maassa valunta suuntautui kynnettyä maata enemmän pintavalunnaksi, koska maan pintakerroksen vedenjohtokyky oli heikompi ja maan hetkellinen kyky varastoida vettä oli pienempi sekä maan pinnalla että pintakerroksen suurimmissa huokosissa. Myöskään lierokäytäviä ei ollut riittävästi, jotta niillä olisi ollut merkitystä pintavalunnan torjunnassa. Nämä samat tekijät lisäsivät myös muokkaamattoman maan pintavaluntaa.

Kultivoidulta maalta tulleiden pintavaluntavesien eroosioainespitoisuus oli korkea, eikä menetelmä vähentänyt eroosiota. Olki peitti 40–66 % matalaan kultivoidun ja vain 9–15 % kynnetyn maan pinnasta, mutta tällä erolla ei näyttänyt olevan merkitystä eroosion kannalta. Sen sijaan maan rikkominen muokkauksella lisäsi eroosioalttiutta, joka oli suurimmillaan heti muokkauksen jälkeen syksyllä ja keväällä. Eroosio olikin sitä pienempää, mitä harvemmin maata muokattiin: ohran sänki vähensi eroosiota 12 % (edeltävästä muokkauksesta 0,5–1 vuotta) ja nurmen sänki vastaavasti 48 % (muokkauksesta 1,5–2 vuotta) kynnettyyn maahan verrattuna (407–1700 kg ha^{-1}). Maan pinta stabiloitui muokkauksen jälkeen vähitellen mm. kuivumisen vaikutuksesta. Koekentän savimaa dispergoitui helposti pinnalla virtaavaan veteen, mikä saattoi johtua savihiukkasten ominaisuuksista ja virtaavan veden ajoittain pienestä ionivahvuudesta.

Äskettäin uusittu salaojasto kuljetti 18–92 % savimaan vuosittaisesta kokonaisvalunnasta ja 37–94 % eroosioaineksesta. Vain murto-osa pinnalta irronneesta eroosioaineksesta suodattui maan huokostossa ennen päätymistään salaojiin. Jos salaojakaivannoissa oli peitemateriaalina puuhake, pinnasta irronnut maa-aines kulkeutui verrattain vapaasti salaojiin, kun taas pintamaalla täytetyt salaojakaivannot suodattivat maahiukkasia hieman paremmin. Joissakin tapauksissa edeltävänä kuivana kesänä maahan syntyneet suuret halkeamat johtivat eroosioainesta suoraan salaojiin vielä seuraavana keväänä. Tulokset osoittavat, että tämänkaltaisten savimaiden eroosiontorjunta edellyttää salaojituksen kunnossapidon lisäksi muokkaustiheyden radikaalia pienentämistä ja/tai muita toimenpiteitä maan pintarakenteen lujittamiseksi.