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Nutrient transport through tile drains on a clayey field

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Introduction

In Finland, subsurface drainage is a common practice in field cultivation. On average, almost 60% of the total agricultural field area (2.2 millions ha) is subsurface drained. The proportion is even 75% in southern and south-western Finland where the main crop cultivation areas are located. In this region, clayey soils (>30% clay fraction, 0.002 mm) account for 55-66% of the total field area. The agriculture induced water pollution in the region is evident and there is an urgent need to reduce nutrient loading from field cultivation and animal production.

In arable fields, subsurface drainage is regarded beneficial in controlling of erosion and phosphorus losses which is the main focus in water pollution control of Finnish watercourses. Drainage also enhances crop growth and nutrient uptake reducing potentially leachable nutrients in the root zone. However in low permeable soils, several studies reviewed e.g. by Nieber (2001) and Jarvis (2007) have demonstrated the ability of preferential flow via macropores to transport pollutants rapidly through the soil to drain lines leading to loading of surface waters. Transport of eroded soil and particulate phosphorus via tile drains has been discovered in several studies in Finland and the other Nordic countries (e.g. Grant et al. 1996; Øygarden et al. 1997; Ulén and Persson 1999; Djodjic et al. 2000; Uusitalo et al. 2001, 2007; Turtola et al. 2007).

The aim of this paper is to characterize seasonal and short-term transport of nitrogen, phosphorus and eroded soil via subsurface drainage on the field scale. The study was based on on-farm monitoring data representing cracking and swelling clay soil under relatively old subsurface drainage system in southern Finland. Potential pathways of water flow to tile drains and their impact on nutrient transport are discussed on the basis of these data and soil properties investigated by Alakukku et al. (2003, 2008). A 3-D model application of water flow at the field site is presented by Warsta et al. (2008) in this proceedings.

Field site and data

The data used in this study are from the Sjökulla experimental site located in southern Finland (60º15' N, 24º27' E). The site was run by Water Resources Laboratory at the Helsinki University of Technology in the 1990s to monitor runoff, erosion and nutrient transport. After the monitoring study, investigation of soil macroporosity and hydraulic conductivity and earthworm abundance on the field was conducted in relation to location of the tile drains by MTT Agrifood Research Finland (Alakukku et al. 2003, 2008). The hydrometeorological and water quality data used in this study covered different periods of time from January

1995 to April 1999. The average annual precipitation in southern Finland is 600-700 mm and evapotranspiration 400-500 mm. Snow forms about 30-40% of the annual precipitation.

The experimental site embodied a field section of 3.3 ha. The subsurface drainage system was installed in 1951, the drains being comprised of clay tiles. The distance between the drains is about 13 m and the drain depth 0.7-1.5 m. The drainage outlet discharged to a main ditch flowing to an adjacent lake.

The clay content of the soil varies from 38% to 90% increasing with the depth. The soil is prone to cracking and swelling. The topography of the field is undulating with the maximum slope of almost 5%. Detailed data on the texture, macroporosity (diameter > 0.300-0.450 mm) and other soil physical properties can be found in Alakukku et al. (2003, 2008). Mineralogical features of the soil layers have been presented by Peltovuori et al. (2002).

Small grain crops (wheat 1994, barley 1995, autumn rye 1995-1996, spring wheat 1997 and 1998) were grown in the field. Mineral fertilizers were applied with a rate of 95-120 kg N ha^{-1} and 9-20 kg P ha^{-1} by placement technique. Ploughing (depth 23-25 cm) or stubble cultivation (depth 15 cm) was used in autumn and seedbed preparation (depth 5 cm) in spring and in autumn 1995.

Tile drain flow from a field section of 3.14 ha was measured by using a v-notch weir and a pressure transducer at the drainage outlet. Surface runoff was measured from two subcatchments (0.63 ha and 2.04 ha) within the field. Depth of groundwater table was monitored with several observation tubes along a single hillslope. Precipitation and other meteorological was available on-site. Hourly values of the hydrometeorological variables were calculated from the measurements recorded every 15-30 minute. Snow water equivalent (SWE) and frost depth were measured manually on several points within the field.

An autosampler (EPIC 1011 Portable Water Sampler) was used to study short-term variation of subsurface drainage water quality in May/June – October/November 1995 and 1998. Grab samples of tile drain flow were collected at irregular intervals during spring and late autumn in 1995 and 1998, and throughout the year 1996. Samples of surface runoff during the study periods were always collected manually.

The water quality data comprised of concentrations of total nitrogen (total N), sum of nitrite and nitrate nitrogen (NO_2+NO_3-N), and total suspended solids (TSS) in subsurface and surface runoff samples through the study periods. Nitrite nitrogen (NO_2-N) was measured in April 1995−December 1996. Total phosphorus (total P) was analysed from September 1997 to April 1999 and dissolved orthophosphate phosphorus (DP) in April 1995−December 1996 and September 1997−April 1999. The analytical methods are described by Paasonen-Kivekäs et al. (1999) and Paasonen-Kivekäs and Koivusalo (2006).

Drain flow, and concentrations and losses of nutrients and TSS were studied over three seasons: winter-spring (January-April), summer/growing season (May-August), and autumn (September-December). The division was done on the basis of hydrometerological conditions and cultivation practice.

When calculating the estimates of nutrient and TSS losses, the hourly/daily runoff volumes were multiplied by the measured or estimated concentrations. Annual and seasonal flow weighted concentrations were calculated using these losses and measured discharges.

Results and discussion

Drainage discharge

The measured runoff and precipitation values for each season in the study years are shown in Table 1. Data was occasionally missing in surface runoff of the winter-spring season due to malfunction of the instruments. In 1998, drain flow existed almost throughout the year due to exceptionally high rainfall. Whereas, in the other years long periods without drain flow and surface runoff existed.

Table 1. Rainfall and subsurface drain flow and surface runoff in different seasons, at Sjökulla experimental site.

Year	Precipitation, mm			Subsurface drain flow, mm			Surface runoff, mm		
	Jan-April	May-Aug	Sep-Dec	Jan-April	May-Aug	Sep-Dec	Jan-April	May-Aug	Sep-Dec
1995	208	203	281	15	24	37	90 1)	0.4	4
1996	91	245	359	20	20	84	64	3.0	58
1998	142	395	262	42	55	57	83	0.6	88
1999	186			57			116		

1) No observations from 1January to 24 February

Subsurface drainage flow constituted about half of the annual measured total runoff (drainage+surface runoff). In real terms, the proportion was likely lower due to the unmeasured part of surface runoff.

In May-August, almost all the runoff discharged through the tile drains. Surface runoff appeared only occasionally and remained negligible even in the rainy summer 1998. Drain flow accounted for 90% of the total runoff in autumn 1995. In autumn 1996 the proportion was 59%, and 39% in autumn 1998.

Examples on short-term dynamics of drainage discharge to rainfall in summer and autumn are shown in Fig. 1a and in Fig. 2a, respectively. Antecedent soil moisture conditions of these time points differed before the first flow event. In June the surface soil was slightly cracking, but in October the tilled soil was wet and no cracks were visible.

The share of subsurface drainage flow of the annual total runoff (drain flow + surface runoff) has largely varied in Finnish experimental sites in clayey soils (Seuna 2004, Puustinen et al. 2006, Turtola and Paajanen 1995, Turtola et al. 2007). A clear reason is the age of the subsurface drainage system, but the weather conditions and cultivation practice have also impact. At the Kotkanoja site in south-western Finland, drainage water constituted 10-40% of the total runoff, but after the renewal of the drainage system 18-92% (Turtola and Paajanen 1995, Turtola et al. 2007). A long-term study at the same site showed that 13-42% of the total runoff from the ploughed plots was surface runoff. In the untilled plots the respective value was 36-82% (Turtola et al. 2007).

Nitrogen concentrations and losses in tile drainage water

The average seasonal flow weighted concentrations and estimated losses of total N in the tile drain outflow are presented in Table 2.

Table 2. Average flow weighted concentration and load of total nitrogen in tile drain outflow in different seasons.

Year	Total N concentration mg/l			Total N load kg/ha			
	Jan-April	May-Aug	Sep-Dec	Jan-April	May-Aug	Sep-Dec	Jan-Dec
1995	4.1	45.6	4.0	0.6	10.8	1.5	12.9
1996	7.1	7.1	5.5	1.4	1.6	5.2	8.2
1998	7.3	13.4	5.4	3.1	7.2	3.0	13.3
1999	2.9			1.6			

The results showed prominent variation of the total N loading via tile drains in respect to one season and different seasons. In some season, as in winter –spring 1996 and 1999, the seasonal loads were equal but the concentrations and drain volumes differed remarkably between the years.

Large variation of the total N loads via drain lines was discovered among growing seasons. High N losses were measured in the early growing season when the N concentrations increased sharply compared to the values before fertilization. The concentrations clearly decreased towards later summer and the losses generally remained lower in spite of higher runoff volumes. In autumn, the total N losses via tile drains varied from 1.5 to 5.2 kg ha^{-1}. The average flow weighted concentrations remained relatively stable between the autumns, thus, the variation was mainly attributed to flow volumes.

Proportion of NO_3-N of the total N loss in the drainage effluent showed evident temporal variation. In May-June after fertilization, NO_3-N accounted for 80-90% of the total N export, whereas about 30% of the total N load was as NO_3-N in the rainy autumn 1998.

The tile drain outflow was intensively sampled during storm events in 1998. Total N and NO_2+NO_3-N concentrations over the course of subsurface flow events in early summer is shown in Fig. 1b. An example of the variation in late autumn is shown in Fig. 2b. In June 1998, the total N transport varied from 0.6 to 2.3 kg ha^{-1} among the three drain flow events.

The estimated annual losses of total N (subsurface flow + surface runoff) at the Sjökulla site (14-21 kg ha^{-1}) corresponded well to the range measured in other Finnish experimental fields and small agricultural catchments in clayey soils (e.g. Turtola and Paajanen 1995, Vuorenmaa et al. 2002). At Sjökulla, subsurface drainage flow made up 60-90% of the estimated annual total N load.

Phosphorus and suspended solids concentrations and losses in tile drainage water

The total P and TSS concentrations on the Sjökulla field had clear seasonal variation. The highest concentrations and losses both in drain flow and surface runoff were measured in autumn after tillage. TSS concentrations and loads in the drainage outflow are show in Table 3.

Table 3. Average flow weighted concentration and load of suspended solids (TSS) in tile drain outflow for different seasons.

Year	TSS concentration mg/l			TSS load kg/ha			
	Jan-April	May-Aug	Sep-Dec	Jan-April	May-Aug	Sep-Dec	Jan-Dec
1995	116	203	106	18	48	39	105
1996	573	642	1750	114	140	1649	1903
1998	365	856	1664	153	461	937	1551
1999	269			154			

The measured concentrations of total P varied between 0.04 and 6.6 mg l^{-1} in tile drain outflow during the period from September 1997 to April 1999 when the parameter was analysed. The respective range in the surface runoff samples was 0.14 – 6.7 mg l^{-1}. The maximum measured DP concentration was 0.24 mg l^{-1} in drain flow and 0.41 mg l^{-1} in surface runoff. Major part of total P in drain flow was as particulate P which was assumed to be the difference of total P and DP. Accordingly, the concentrations of total P (and PP) and TSS were tightly correlated. The highest DP values were observed in spring 1996 when the soil was covered with autumn rye and after fertilization.

The average flow weighted concentration of total P in tile drain outflow was 0.32 mg l^{-1} in January-April 1998 and 0.35 mg l^{-1} in January-April 1999. In May-August 1998, the concentration was 0.80 mg l^{-1} increasing to 1.96 mg l^{-1} in September-December. The respective seasonal loads of total P through tile drains were 0.13, 0.43 and 1.11 kg ha^{-1}. The estimated losses via surface runoff were 0.65, 0.06 and 2.28 kg ha^{-1} for the sequential seasons in 1998.

In 1998, the average flow weighted DP concentrations for the sequential seasons were 0.045, 0.095 and 0.063 mg l^{-1}. The concentration value in January-April 1999 was 0.039 mg l^{-1}. Subsurface drainage flow carried the following seasonal DP loads in 1998: 0.02, 0.05 and 0.04 kg ha^{-1}.

Variation of TSS, total P and DP concentrations in subsurface drainage water under individual rainfall-runoff events in early summer is illustrated in Fig. 2c-d and in late autumn in Fig. 3c-d. Temporary elevated TSS and total P peaks were always observed in drain discharge, followed by a gradual decrease. TSS and total P concentrations increased clearly after tillage. In October, the TSS loss varied from 45 to 188 kg ha^{-1} and total P loss from 0.06 to 0.21 kg ha^{-1} between the drain flow events.

At the Sjökulla site, the estimated transport of eroded soil and total P was exceptionally high in 1996 and 1998 compared to the values measured in other experimental sites in southern and south-western Finland (e.g. Vuorenmaa et al. 2002, Puustinen et al. 2006, Turtola et al. 2007, Uusitalo et al. 2007). In the sloping fields of the Kotkanoja experimental site, subsurface drainage outflow carried 37-94% of the annual soil losses (Turtola et al. 2007). The annual loading (drain flow + surface runoff) varied from 407 to 1700 kg ha-^{1}. According to Uusitalo et al. (2003, 2007) P associated with eroded soil can form a significant loss of bioavailable P both in surface and subsurface runoff from clayey fields. In this study also runoff water samples from the Sjökulla site were analyzed.

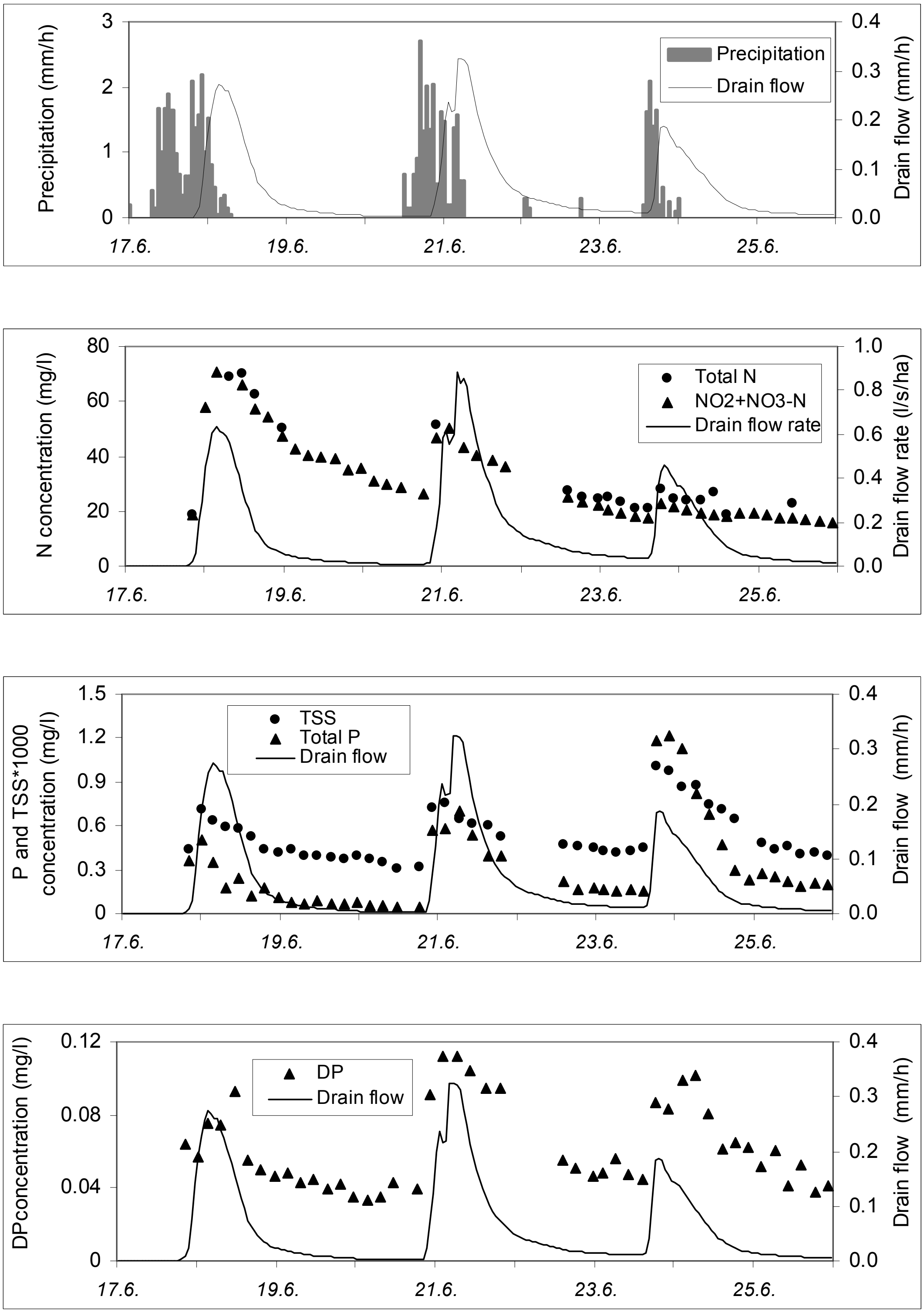

Fig. 1. Hourly rainfall and tile drain flow (a), total N and NO_2+NO_3-N concentration (b), total P concentration total suspended solids (TSS) (c), and dissolved P concentration (DP; d) in subsurface drainage outflow on 17–26 June 1998. Seeding (spring wheat) and fertilisation (117 kg N ha^{-1}) were carried out on May 16. Rainfall was 53 mm, subsurface drainage outflow 12.2 mm and surface runoff 0.3 mm during the period. Total N loss was 5.1 kg ha^{-1}, TSS loss 149 kg ha^{-1}, and total P loss 0.12 kg ha^{-1} over the three drain flow events.

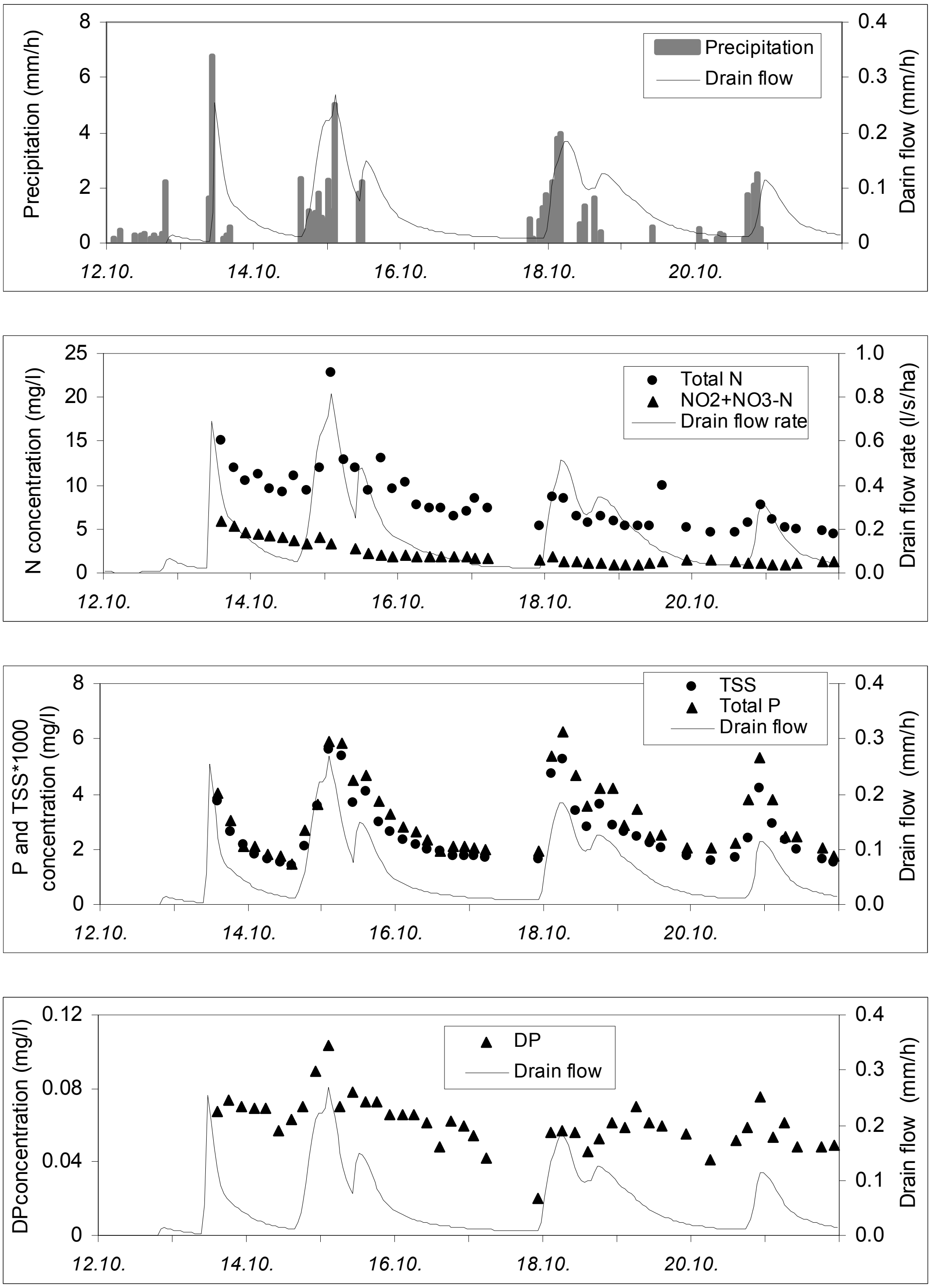

Fig. 2. Hourly rainfall and tile drain flow (a), total N and NO_2+NO_3-N concentration (b), total P total suspended solids (TSS) concentration (c), and dissolved P concentration (DP; d) in subsurface drainage outflow outflow on 12–22 October 1998. Harvest was carried out on 24-25 September, and the field was partly ploughed and partly cultivated on 6 October. Rainfall was 68 mm, subsurface drainage outflow 12.6 mm and surface runoff 33 mm during the period. Total N load was 1.27 kg ha^{-1}, TSS load 441 kg ha^{-1} and total P load 0.52 kg kg ha^{-1} over the four flow events.

The experimental setup of this study did not enable us to reliably evaluate the proportion of subsurface drainage and surface runoff of the total nutrient and sediment loading from the field to the main ditch. The main source of uncertainty was the water sampling schedule. The different schedules also caused some uncertainty in the calculated seasonal loads via drain lines and hampered comparison of the concentrations. Most uncertainty is involved in loading via surface runoff. However, we believe that the presented loads from the drainage outlet in autumn and summer are close to actual values because of the intensive water sampling.

Discussion: Pathways of water flow and nutrient transport to the tile drains

It was expected that preferential flow is an important factor in drain flow generation in the studied clayey field. Following features of the event-scale data revealed preferential flow from the surface layer to drain lines: 1) the rapid response of drain flow to rainfall, 2) the peak N concentrations after fertilizer application, 3) the increase of DP concentrations after fertilization and 4) the high concentrations of TSS and PP in drain discharge after tillage. The NO_3-N concentrations in soil water also reflected that part of the fertilizer nitrogen leached into the tile drains bypassing the soil matrix (Paasonen-Kivekäs et al. 1999). According to the ^{137}Cs measurements conducted by Uusitalo et al. (2001), the soil particles in the drainage water mainly originated from the topsoil.

Besides the experimental results, different model applications (e.g. Al Soufi 1999, Hintikka et al. 2008, Karvonen and Paasonen-Kivekäs 2005, Warsta 2007, Warsta et al. 2008) to the Sjökulla field indicated the central role of preferential flow in drain flow generation.

Preferential pathways in the Sjökulla field can originate from shrinkage cracks and fissured due to soil drying and freezing, biological activity (root channels, earthworm burrows) and the backfill trench lines. Because the drainage system is relatively old and a hard tillage pan existed below the surface layer we assume that the natural macropores has the key role in preferential flow. In clayey fields in south-western Finland, compaction below the plough layer has been observed within 5 years and even earlier after installation of the tile drainage system (Vakkilainen 1980, Aura 1990).

The measured macroporosity and hydraulic conductivity until the depth of 50 cm did not show systematic difference among the sampling points from the tile lines, 2 m from the lines and midpoint of the lines (Alakukku et al. 2003, 2008). The clearest difference was discovered between different soil layers and different parts of the hillslope. The median number and biomass of earthworms were highest above the drains but the variation in the measurements was very large (Alakukku et al. 2003). Deep burrowing earthworms (*Lumbricus terrestris* L.) were almost entirely discovered along the drain lines. However, their number was relatively small compared to other studied fields in Finland (Alakukku et al. 2003).

The Sjökulla soil has a typical vertical distribution of Finnish clayey soils: macroporosity and saturated hydraulic conductivity decreased sharply below the tillage layer (Alakukku et al. 2003, 2008). In a sloping field, such as Sjökulla, this induces flow along the border of the tillage layer and the tillage pan. Part of this flowing water is likely infiltrating to macropores along the slope.

Deeper in the soil (> 50 cm) the backfill might have remained uncompacted promoting bypass flow. It has also been presented that the walls between trench and the bulk soil serve routes for preferential flow (Uusitalo et al. 2001). A Swedish investigation showed a higher drainage efficiency of the trench backfill compared to the undisturbed soil for several decades after the installation of the drain pipes (Messing and Wesström 2006).

There was a visible difference between the seasons and shorter time spans with respect to the surface soil conditions. The soil was strongly cracking during drying increasing infiltration capacity. On the other hand, the short time lags between rainfall and drain flow in late autumn indicated stable water conducting macropores even in the swelling soil. The model application mentioned above could describe the total runoff (surface runoff + drain flow) reasonabily well but failed to calculate correctly the separate runoff components, especially in autumn, which can attributed to changing hydraulic properties. The impact of the spatial variation of soil properties on runoff generation was studied by applying the MACRO model to a down and upper hillslope section in the field (Hintikka et al. 2008). In the Nordic conditions, soil freezing and thawing change soil structure and hydraulic characteristics which further complicates the experimental and modelling research.

Conclusions

This paper dealt with water flow and concentrations and export of nutrients and eroded soil via tile drains from a sloping clayey field. The results from the Sjökulla site indicate that contribution of different runoff components to loading of surface waters can vary a lot even on an individual field under quite stable cultivation practice. The information on transport routes improves evaluation of the effectiveness of the agri-environmental measures, e.g. buffer strips and zones. A correct description of water flow on field scale is also basis of modelling of erosion and nutrient transport in cultivated areas.

The discovered relatively high losses of nutrients and eroded soil via subsurface drains at the Sjökulla site, as in other experimental sites in clayey soils, give cause to pay more attention on nutrient export from subsurface drains. For example, investigation of different type of clayey soils and drainage systems (age and installation) in Finland is needed to get a more precise picture of the role of subsurface drainage in controlling erosion and phosphorus loading.

The results of this study confirm earlier results that preferential flow via biopores and cracks and fissures and/or backfilled drain trenches can be an essential carrier of nutrients and eroded soil to tile drains in clayey soil, especially after fertilization and tillage. However, a good permeability of the backfill material and the undisturbed soil is a prerequisite for an effective drainage and gas exchange in these soils. A challenge is to find trade-off between these opposite points.

The losses via drain lines can likely be diminished with environmentally sound cultivation methods, such as an adjusted rate and timing of fertilization and tillage. Besides this, development of subsurface drainage design, materials and installation technique for clayey soils is needed to meet requirements of sustainable crop production.

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