Received: 2 March 2023 | Revised: 7 March 2024 | Accepted: 15 March 2024

DOI: 10.1002/ird.2965

RESEARCH ARTICLE

WILEY

The effects of improved subsurface drainage on runoff and nitrogen leaching from a clayey field section

Vilma Jokinen[1] | **Heidi Salo**[1] | **Minna Mäkelä**[2] | **Jyrki Nurminen**[3] | **Helena Äijö**[2] | **Hanne Laine-Kaulio**[5] | **Merja Myllys**[4] | **Harri Koivusalo**[1]

[1]Department of Built Environment, Aalto University, School of Engineering, Espoo, Finland

[2]Finnish Field Drainage Association, Helsinki, Finland

[3]Drainage Research Association, Helsinki, Finland

[4]Natural Resources Institute Finland, Jokioinen, Finland

[5]Sven Hallin Research Foundation Sr, Helsinki, Finland

Correspondence
Minna Mäkelä, Finnish Field Drainage Association, Simonkatu 12 A 11, 00100, Helsinki, Finland.
Email: minna.makela@salaojayhdistys.fi

Funding information
Drainage research association; Drainafe foundation sr; Aalto-Yliopisto

Abstract

The aim of this study was to investigate the effects of improved subsurface drainage installation on nitrogen (N) loss in drain discharge (DD) and topsoil layer runoff (TLR). Data on DD and TLR, as well as on concentrations of total, nitrate and ammonium N in the runoff components, were collected from four sections of an experimental field in southern Finland (June 2007–December 2018). Supplementary drains were installed in one of the field sections in June 2014, and the data from that section were compared with those from three reference sections. Differences between the sections were statistically analysed based on annual and monthly values of runoff components and concentrations, as well as the loads of N fractions. The results revealed that improved drainage increased the N load in the DD, reducing the load in the TLR. Changes in N loads were more clearly driven by changes in the runoff volumes rather than by changes in the N concentrations in the runoff waters. Before the drainage improvement, most of the total N load was nitrate (53%), while the share of rest N (fraction of the total N after the mineral N fractions were subtracted) was 45%. After improved drainage, the percentages of nitrate and rest N were 73 and 26%, respectively. The results demonstrate the importance of agricultural water management as the key driver for controlling nutrient loads.

KEYWORDS

cumulative sums, long-term field experiment, N fractions, time series analysis

Résumé

L'objectif était d'étudier les effets d'une installation de drainage souterrain amélioré sur la perte d'azote (N) dans le débit de drainage (DD) et le ruissellement de la couche arable (RCA). Des données relatives au débit de drainage (DD) et au ruissellement de la couche arable (RCA), ainsi que sur les concentrations en N total, nitrate et ammonium dans les composants du ruissellement

Article title in French: Effets d'un drainage souterrain amélioré sur le ruissellement et le lessivage de l'azote d'une section de terrain argileux.

ont été collectées à partir de quatre sections d'un terrain expérimental du sud de la Finlande (06/2007–12/2018). Des drainages supplémentaires ont été installés sur l'une des sections en juin 2014, et les données de cette section ont été comparées avec les données de trois sections de référence. Les différences entre les sections ont été analysées statistiquement en se basant sur les valeurs annuelles et mensuelles des composants de ruissellement et des concentrations et charges des fractions en azote. Les résultats ont révélé qu'un drainage amélioré augmentait la charge en N dans le DD, et la réduisait dans le RCA. Les changements dans les charges en N ont été plus clairement provoqués par des changements dans les volumes de ruissellement plutôt que dans les concentrations en N dans les eaux de ruissellement. Avant l'amélioration du drainage, la forme majoritaire du N total était la forme nitrate (53%), alors que la part de N résiduel (fraction du N total après soustraction des fractions de N minéral) était de 45%. Après l'amélioration du drainage, les parts de nitrate et de N résiduel étaient de 73 et 26%, respectivement. Les résultats démontrent l'importance de la gestion de l'eau agricole comme facteur clé pour contrôler les charges en nutriments.

MOTS CLÉS

fractions en azote, sommes cumulatives, analyse de séries temporelles, expérience de terrain à long terme

1 | INTRODUCTION

A short growing period, rapid snowmelt in spring and high precipitation combined with low evapotranspiration in autumn create challenging conditions for cultivation in northern areas. Agricultural drainage is especially important in the clayey fields of Finland since they have a high risk of harmful soil compaction when heavy machinery is operated under excessively wet field conditions (Alakukku et al., 2003; Mueller et al., 2003). Thus, efficient field drainage is necessary to avoid soil degradation, facilitate field operations and maximize crop production and profitable cultivation in these areas.

In Finland, artificial drainage is carried out as open or subsurface drainage, with approximately 70% of the fields being subsurface drained (Official Statistics of Finland (OSF), 2022; Natural Resources Institute Finland LUKE, 2015). However, most subsurface drainage was installed between the 1960s and 1980s and is now in need of improvement in terms of reparation, renewal or installing supplementary drains (Häggblom et al., 2019). According to a survey among farmers, functioning of the drainage and/or soil dewatering needs to be improved on approximately 204,000 ha of farmland (Ovaska et al., 2021). A large number of current drainage installations are improvements to existing drainage systems.

Agriculture accounts for approximately 50% of the total anthropogenic nitrogen (N) loading to surface water bodies at the national scale in Finland (Suomen ympäristökeskus, 2022). Previous experimental studies in northern areas have shown that introducing subsurface drainage increases N losses because of increased soil oxygen content and enhanced drain discharge (DD) (e.g. Gilliam et al., 1999; Seuna & Kauppi, 1981; Turtola & Paajanen, 1995). Seuna and Kauppi (1981) examined both total nitrogen (tot-N) and nitrate nitrogen (NO_3-N), noting that the N losses were mainly NO_3-N, and after drainage installation, the share of NO_3-N increased further. Reducing drain spacing has been found to increase NO_3-N leaching in both experimental (Kladivko et al., 2004; Kladivko & Bowling, 2021) and modelling studies (Davis et al., 2000). Gramlich et al. (2018) conducted an extensive review on the impacts of agricultural drainage on nutrient leaching and concluded that intensifying drainage increases tot-N, especially NO_3-N losses, due to increasing drain discharge and to higher mineralization rates caused by a deeper water table.

Subsurface drainage and improved drainage have been found to increase drain discharge volume, reduce the response time of discharge after a rainfall event (e.g. Tao et al., 2017) and reduce the amount of topsoil layer runoff (TLR) (e.g. Äijö et al., 2016: Häggblom et al., 2019; Singh et al., 2007; Tao et al., 2017). Field studies have shown that the N concentrations in TLR can be high (Paasonen-Kivekäs et al., 1999), resulting in high loads even with limited discharge volumes. Norberg et al. (2022) reported that total N concentrations were highest during the summer months, but losses were the lowest due to a lack of discharge water. Preferential flow paths, which are common but not exclusive to clay soils, provide a fast route for water and solutes from the field surface via subsurface soil layers to subsurface drains (e.g. Bronswijk et al., 1995; Frey et al., 2016; Salo et al., 2015; Turunen et al., 2013; Salo et al., 2017; Villholth et al., 1998). The fraction of larger soil pores and macropores and the resulting presence of preferential flow pathways depend on the soil drainage conditions, as more macropores are present in well-drained soils with wide pore size distributions and well-developed soil structures (e.g. Alakukku et al., 2010). Surface and subsurface flow processes impact N losses, but studies investigating both DD and TLR water quality before and after improved drainage are lacking. Although NO_3-N is typically the main component of the total N load from agricultural fields (Seuna & Kauppi, 1981), there is a need to examine the different fractions of N in soil and drainage water to better understand the effects of water management practices on soil N processes and loads.

Comprehensive long-term field-scale studies on the impacts of drainage improvement on N loads, considering both the water balance components (precipitation, evapotranspiration, TLR, drainage discharge, groundwater outflow and soil water storage) and the different fractions of N (NO_3-N, ammonium nitrogen [NH_4-N] and others), are rare. Given the large annual variation in field hydrology and nutrient processes, the monitoring period of an experimental drainage improvement study should cover several years before and after treatment. Subsurface drainage increases N losses via drain discharge (e.g. Gilliam et al., 1999), but how drainage affects N fractions in discharge waters is less obvious. Continuous long-term monitoring to inspect seasonal changes in N loads and their controlling factors is a prerequisite for planning measures to prevent or minimize N losses. Studying the effects of drainage practices on N fraction loads can provide insights into how these practices affect field-scale N processes, such as mineralization, nitrification and denitrification.

In this study, N leaching in the DD and TLR before and after improved drainage was investigated in an agricultural, clayey field in southern Finland. Here, improved drainage refers to the installation of supplementary drains between existing drains. Focusing on NO_3^- and tot-N, previous studies have indicated that improving drainage has a similar impact on N leaching as the first installation of subsurface drainage (Gramlich et al., 2018; Seuna & Kauppi, 1981; Turtola & Paajanen, 1995). Here, measured data on the concentrations and loads of tot-N, NO_3-N, NH_4-N and residual nitrogen (rest-N) in DD, TLR and total runoff from a field section that underwent drainage improvement were compared to those from three other sections of the same field. The objective of this study was to determine the magnitude of drainage improvement on runoff, N concentrations and N loads under varying seasonal and yearly hydrological conditions. The study period covered 7 years before and 4 years after the improved drainage installation. Differences between the field sections were investigated using statistical analysis.

2 | MATERIALS AND METHODS

2.1 | Site description

The Nummela experimental field is in Jokioinen, southern Finland (Figure 1). The area is 9.3 ha, and it has a mean slope of 1% towards Raiskionoja Creek at the northern border of the field (Figure 1). The soil type is heavy clay. The organic matter content at 0–35 cm depth varies between 4 and 8%, with a small decrease observed between 2006 and 2018 (Äijö et al., 2021). According to the FAO-UNESCO classification (1988), the soil class of the field is Vertic Cambisol (Vakkilainen et al., 2010).

The experimental field is administered by the Natural Resources Institute Finland (Luke), and it is divided into four monitored field sections with their own subsurface drainage networks (sections A, B, C and D in Figure 1). The entire field was originally drained in 1952 when section D was drained with a drain spacing of 32 m and the remaining sections (A, B and C) had a drain spacing of 16 m (Vakkilainen et al., 2010). The original tile drains were installed at a depth of 1 m. At the end of May 2008, the drainage network in section A was renewed with 6 m spacing, and the drainage of section C was improved, reducing its drain spacing to 8 m (Vakkilainen et al., 2010). At the end of May 2014, drainage was improved by installing supplementary drains to section D, reducing the drain spacing from 32 to 10.7 m (Äijö et al., 2014). The improved drainage installations in sections C and D were made with a trenching machine, using plastic pipes and gravel as the envelope material and with additional gravel inlets in the trenches. Figure 1 presents the current drainage networks in the field. In autumn 2011, three drains were added between sections A and B as the area had been suffering from flooding during snowmelt, causing unsuccessful TLR measurements in section B.

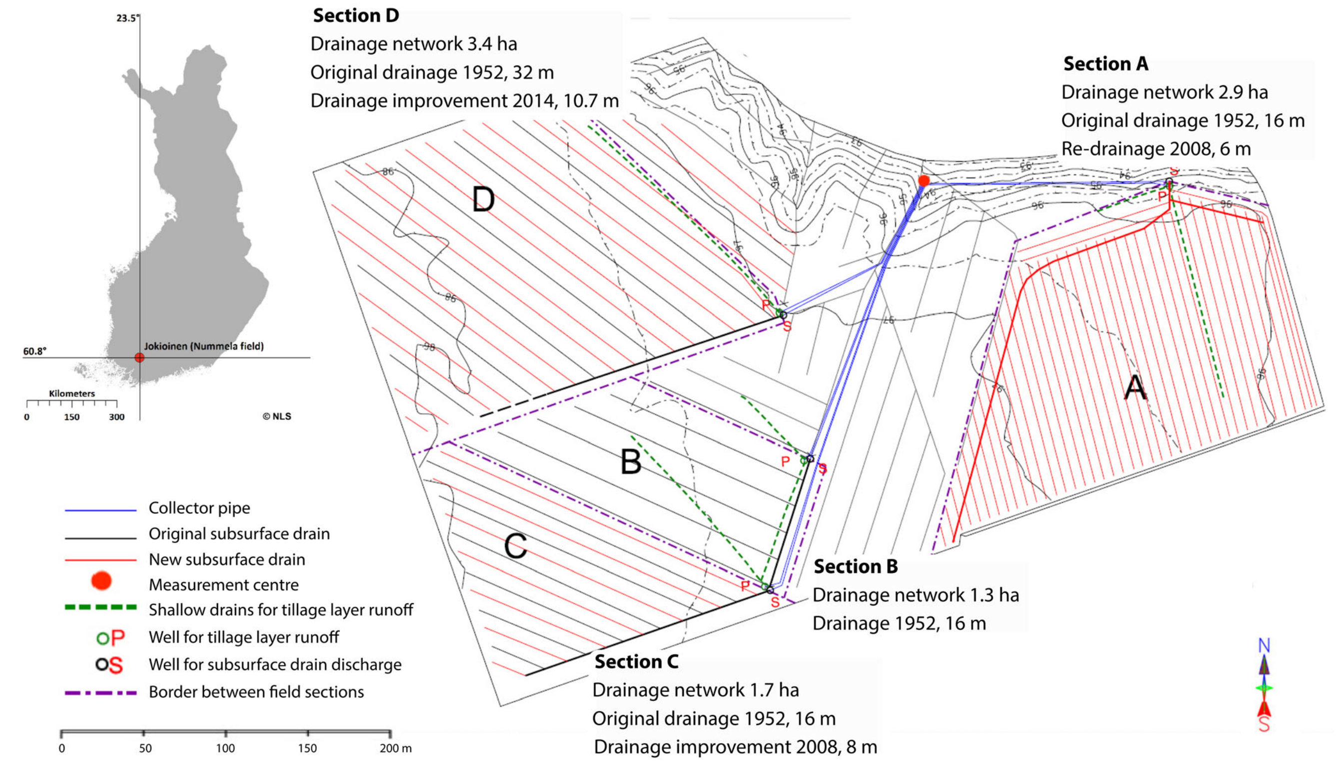

FIGURE 1 Location of the study site in Finland and current drainage networks and measurement set-up of the study site.

Agricultural practices were constant and simultaneous throughout the field during the observation period of 2007–2019 (Äijö et al., 2021). Oat and barley were grown, and mineral fertilizer was applied every spring. In addition, manure was spread in the spring of 2007, 2008, 2017 and 2018, as well as in the autumn of 2007. In autumn 2012, the entire Jokioinen area suffered from exceptionally wet conditions, and the oat harvest partly failed (Äijö et al., 2014).

2.2 | Data acquisition

The data consisted of runoff measurements and runoff N concentration analyses (tot-N, NO_3-N and NH_4-N) for each field section from June 2007 to December 2018. DD and TLR were measured continuously with a Datawater WS vertical helix water meter (Maddalena, Povoletto, Italy) with a measurement range of 0.2–50 m^3 h^{-1} and were observed at 15-min intervals. The TLR was collected with perforated pipes installed to a depth of approximately 0.4 m, and both the TLR and DD were routed to a measurement centre (Figure 1) where the flow rate gauging took place.

Flow-weighted samples for N concentration analyses were automatically aggregated at the measurement centre for DD and TLR. Approximately 0.15 L of sample was collected at

100-L intervals, from which the tot-N, NH_4-N and NO_3-N concentrations were determined in the laboratory (Korpelainen, 2021). The concentration of the aggregated sample was assumed to represent the average concentration of the sampling interval. The laboratory analyses were performed on average 22 (7–36) times per year. The methods for water quality analyses are described in more detail by Äijö et al. (2021) and Vakkilainen et al. (2010).

Precipitation data were obtained from the Jokioinen Observatory weather station, 7 km south-east of the site and operated by the Finnish Meteorological Institute (FMI).

2.3 | Data processing and statistical analysis

The data from section D were compared to those from sections A, B and C to determine the effects of improved drainage on N concentrations and loads. Section B was the reference section, as no drainage alterations had been made there after the original subsurface drainage in 1952. Sections A and C were also used as reference sections in the analysis because section B had been influenced by flooding during snowmelt periods (Äijö et al., 2014), and the TLR was more comparable among sections A, C and D. DD, TLR and total runoff, as well as tot-N, NO_3-N, NH_4-N and rest-N concentration and load in DD, TLR and total runoff, were determined. Rest-N represents the N concentration and loads obtained by subtracting the mineral N (NO_3-N and NH_4-N) values from the total N values. Rest-N may contain N compounds in sediments (ammonium N or organic N) and soluble organic N.

Monthly or annual values were aggregated from the collected data, which had a higher measurement resolution. The monthly and annual data series were input to the statistical analyses that were performed for the quantity and quality of DD, TLR and total runoff (sum of DD and TLR). For the runoff, hourly data were summed into monthly and annual data series. For the N loads, daily loads of the different fractions of N were calculated by multiplying the runoff component (DD or TLR) by the corresponding concentration, and the data were aggregated into monthly and annual values. For the concentrations, the monthly N concentrations were calculated by dividing the monthly load by the monthly runoff, while the annual concentrations were calculated as the mean of the monthly concentrations.

Differences between monthly time series from section D and from a reference field section (D–A, D–B and D–C) were studied to detect the impacts of improved drainage on N leaching. Differences between field sections were used rather than absolute values (runoff, concentration or load series) to minimize the impact of annually varying weather conditions and cultivation methods. Previous studies have shown that both weather conditions and cultivation methods affect absolute values (e.g. Salo & Turtola, 2006), but using reference field sections to analyse the differences between the experimental section and a reference section can better detect the effects of the experimental practice (e.g. Äijö et al., 2014). Monthly differences were accumulated over time to visualize and analyse the temporal development of the cumulative difference series. The cumulative sum is a statistic that does not require the data to follow a normal distribution or to be parametric; thus, it allows time dependency of the observations and seems suitable for hydrological time series (e.g. Salo et al., 2019).

Statistical analysis was performed with Pettitt's test (Pettitt, 1979) to determine the difference in the monthly time series between section D and the other field sections. Pettitt's test is a non-parametric change-point detection test that is widely used in hydrological and climate studies with long, continuous data series (Conte et al., 2019; Pohlert, 2016). The null hypothesis (H0), that the tested variables follow the same distribution, is tested against the alternative that there is a change in the distribution of the data (Conte et al., 2019; Pettitt, 1979; Pohlert, 2016). Such a change point can be defined as a point in time when any parameter of the data distribution, such as the mean, median, variance and/or autocorrelation, does not maintain a continuous average over long time periods but undergoes an abrupt change (Conte et al., 2019). In this study, a significance level of $p \leq 0.05$ was used to reject H0, and the timing of the change point was determined based on the change in the mean of the data distribution. The analysis was performed using the pyHomogeneity package for python (Shourov, 2020).

To analyse the seasonal variation in the impact of improved drainage, mean monthly values were calculated for the periods before (January 2008–May 2014) and after (June 2014–December 2018) the improvement. The difference in the mean monthly values between section D and the other field sections was calculated and plotted to compare how the difference changed from the period before to the period after drainage improvement.

3 | RESULTS

3.1 | Runoff and weather conditions

The total runoff in all field sections (A–D) clearly corresponded to the annual precipitation, whereas the shares of DD and TLR relative to the total runoff were mostly affected by drain spacing (Figure 2). During the study period, the annual precipitation ranged from 442 to 743 mm (the mean annual precipitation was 591 mm). The mean annual precipitation before drainage improvement (2008–2013) was 624 mm, and after improvement (2014–2018), it was 552 mm.

The mean annual temperature varied between 2.7°C (in 2010) and 6.3°C (in 2015), with no apparent trend during the period investigated (Figure 2). The annual runoff or the proportions of its components showed no clear dependency on the mean annual temperature. The mean monthly temperatures in Table 1 show that the first year of observation (2008) had an unusually warm winter, and greater than average rainfall (Figure 2) contributed to the large amount of observed runoff.

The mean annual DD in section D was 67.3 mm (39.3–93.2 mm) before drainage improvement and 132.0 mm (68.7–203.7 mm) after improvement. Correspondingly, the mean annual TLR from section D was 75.9 mm (24.5–110.0 mm) before the improvement and 30.1 mm (12.5–51.5 mm) afterwards. As a result of the drainage improvement, the share of TLR in the total runoff decreased from 51 to 18% (section D in Figure 2).

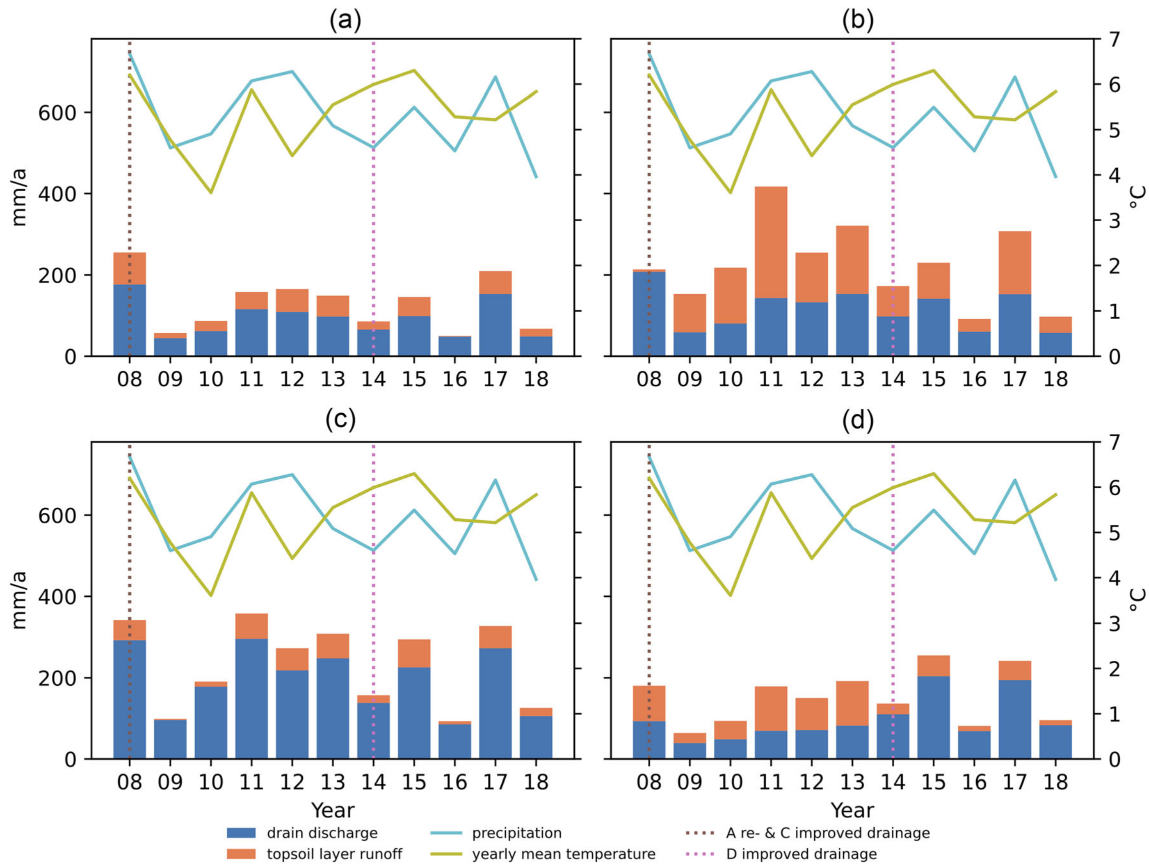

FIGURE 2 Annual precipitation, mean annual temperature, DD and TLR of each field section. The years of re-drainage in section A and improved drainage on section C are marked with a dashed line. Only full calendar years were considered.

TABLE 1 Mean monthly temperature throughout the study period. The cells highlighted in orange are the values one standard deviation above the monthly average, and the cells highlighted in blue are those with values one standard deviation below the monthly average.

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2008–2018
Jan	−1.0	−5.2	−12.5	−5.9	−6.3	−6.4	−8.8	−2.6	−10.7	−3.3	−3.2	−6.0
Feb	−0.4	−5.3	−9.3	−11.9	−8.3	−3.1	−0.4	−0.7	−1.2	−4.2	−9.3	−4.9
Mar	−1.3	−2.6	−2.8	−2.1	−0.4	−7.6	1.1	1.2	−0.3	0.4	−5.8	−1.8
Apr	5.7	4.3	4.2	5.4	3.5	2.0	4.8	4.5	4.2	1.8	4.3	4.1
May	10.1	11	11.4	10.0	10.5	12.9	10.2	8.9	12.8	8.9	14.6	11.0
Jun	13.8	13.4	–	16.7	12.6	16.6	12.7	12.4	14.7	12.8	14.6	14.0
Jul	16.3	16.2	20.8	19.0	16.7	16.4	19.1	15.1	16.8	14.9	20.3	17.4
Aug	14.0	15.3	16.3	15.6	14.5	15.8	16.3	15.8	15.0	14.6	16.8	15.5
Sep	8.8	11.9	10.6	12.1	10.7	10.8	11.2	11.5	11.5	10.4	12.1	11.1
Oct	7.2	2.6	4.0	6.8	4.9	5.8	5.5	4.2	3.6	4.2	5.8	5.0
Nov	1.4	1.9	−3.0	3.7	2.7	2.7	1.9	3.6	−1.4	2.2	2.3	1.6
Dec	−0.2	−6.2	−10.5	1.1	−8.0	0.7	−1.7	1.7	−1.6	−0.1	−2.5	−2.5

High TLR peaks (1.7–2.0 mm h^{-1}) were observed in section B in April during the years 2009–2013, while the maximum peaks in the other sections were 0.3–0.6 mm h^{-1}. These values are further reflected in the high annual TLR values of section B (Figure 2).

The cumulative sums of the differences between the runoff components of the field sections show that improving drainage in section D increased DD (Figure 3). Before the drainage improvement in June 2014, all the other field sections (A, B and C) had greater DDs than

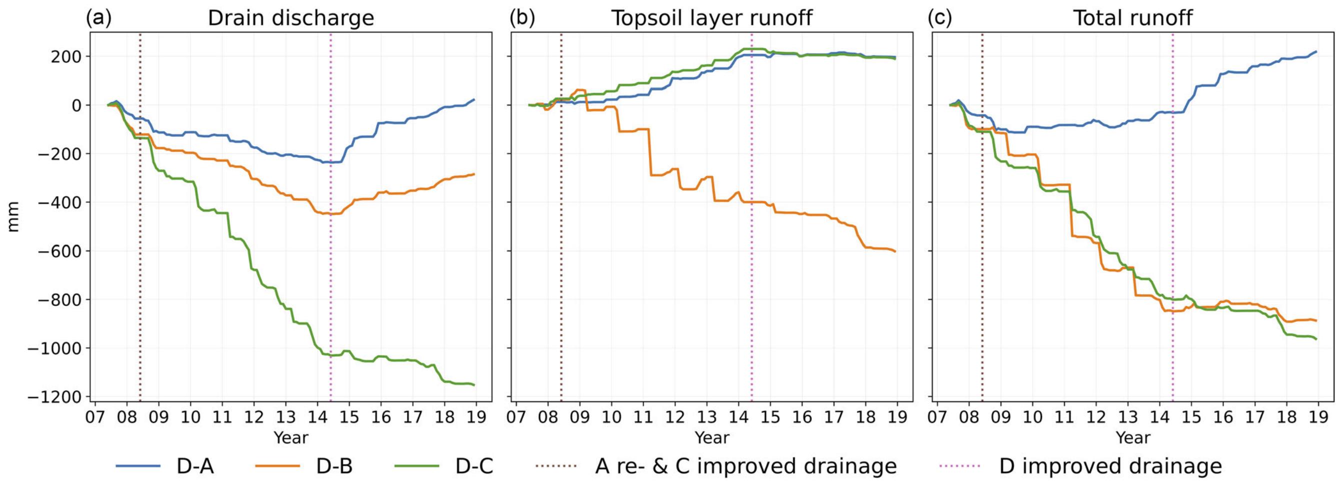

FIGURE 3 Cumulative sums of differences between the field sections in DD, TLR and total runoff (June 2007–December 2018). Positive *y*-axis values indicate that section D had more runoff than did the other sections, whereas negative values indicate that the reference sections (A, B or C) had greater runoff than did the experimental section (D). The years of re-drainage in section A and improved drainage on section C are marked with a dashed line.

did section D (Figure 3a). After the improvement, section D had a greater DD than sections A and B (positive slopes of the blue and orange lines in Figure 3a). The DD from section C was still greater than that from section D, but the difference was smaller (green line in Figure 3a). According to Pettitt's test, the change in DD in section D was significant. Changes were detected within a few months after drainage improvement in section D, with a *p*-value less than 0.05 (Table S1).

Improved drainage had the opposite effect on TLR and not on DD (Figure 3b): before 2014, the TLR in section D was greater than that in sections A and C, but after drainage improvement, the TLR in section D was similar to or smaller than that in sections A and C. The impact of improved drainage on TLR was statistically significant (Table S1).

The total runoff (sum of DD and TLR) from section D increased in relation to that from the other sections after the improved drainage (Figure 3c). The change in the difference in total runoff between sections D and B was statistically significant. However, a significant change point in the difference between sections D and A was found almost 2 years before the improvement, and no significant change point was found between sections D and C (Table S1).

3.2 | Nitrogen concentrations

The annual mean concentrations of tot-N, NO_3-N, NH_4-N and rest-N in DD and TLR showed that NO_3-N formed a major part of the tot-N concentration (approximately 74% of tot-N) (Figure 4). The rest-N fraction was considerably smaller (approximately 25% of tot-N) but still relevant, while the fraction of NH_4-N was in this case negligible (approximately 1% of tot-N) in terms of the annual total N concentrations.

The annual mean tot-N concentration in DD increased in section D after the improvement (Figure 4). This was a result of a rising NO_3-N concentration (on average from 4.0 to 7.3 mg L^{-1}), as no increase was observed in rest-N. The share of NO_3-N in tot-N increased from 64 to 84%. The tot-N concentration in the TLR decreased after drainage improved (on average, the tot-N decreased from 9.9 to 7.8 mg L^{-1}). The distributions of NO_3-N and rest-N were the same in the TLR before and after the improvement (NO_3-N approximately 72% of the total N).

No statistically significant effect of improved drainage was detected for most of the studied concentration differences between the field sections (Table S1). Pettitt's test revealed significant changes close to the drainage improvement only for the concentration differences between D–A tot-N in DD and D–B NO_3-N in total runoff. However, significant change points were found in 2012 for the rest of the studied concentration differences of tot-N and NO_3-N in DD and total runoff.

The cumulative changes in concentration differences between section D and other field sections are presented in Figure S1. There appears to be a moderate increase in the concentrations from section D compared to those from other sections around the time of drainage improvement in terms of tot-N and NO_3-N in DD and total runoff (Figure S1a, c, d, f). Before 2014, these concentrations were mostly lower in section D than in the other sections, whereas after the improvement, the difference between

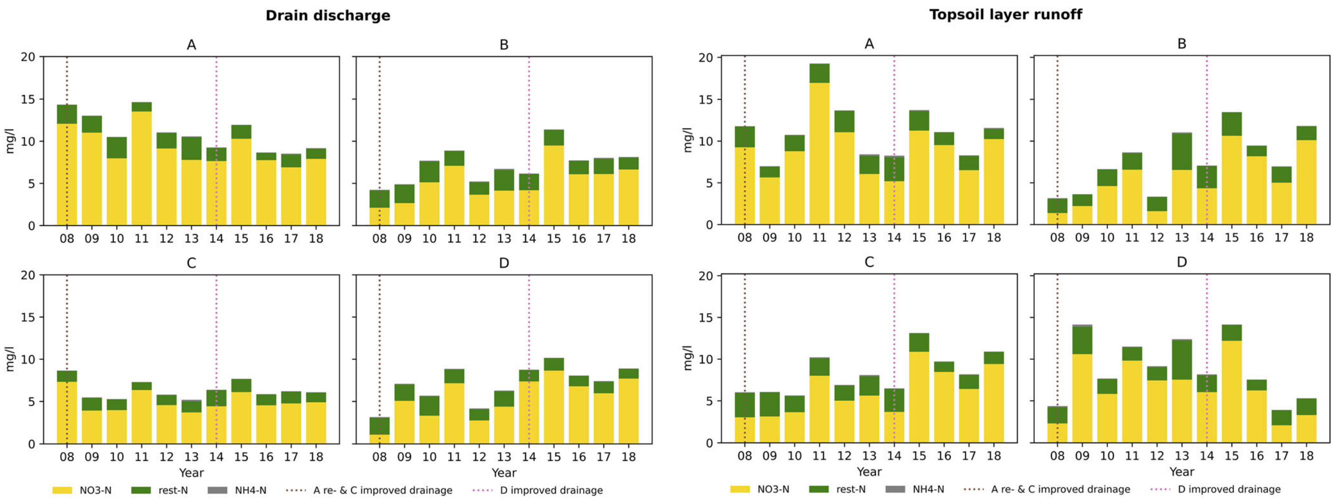

FIGURE 4 Annual mean N concentration in the DD and TLR of each field section, calculated from the data of full calendar years. The years of re-drainage in section A and improved drainage on section C are marked with a dashed line.

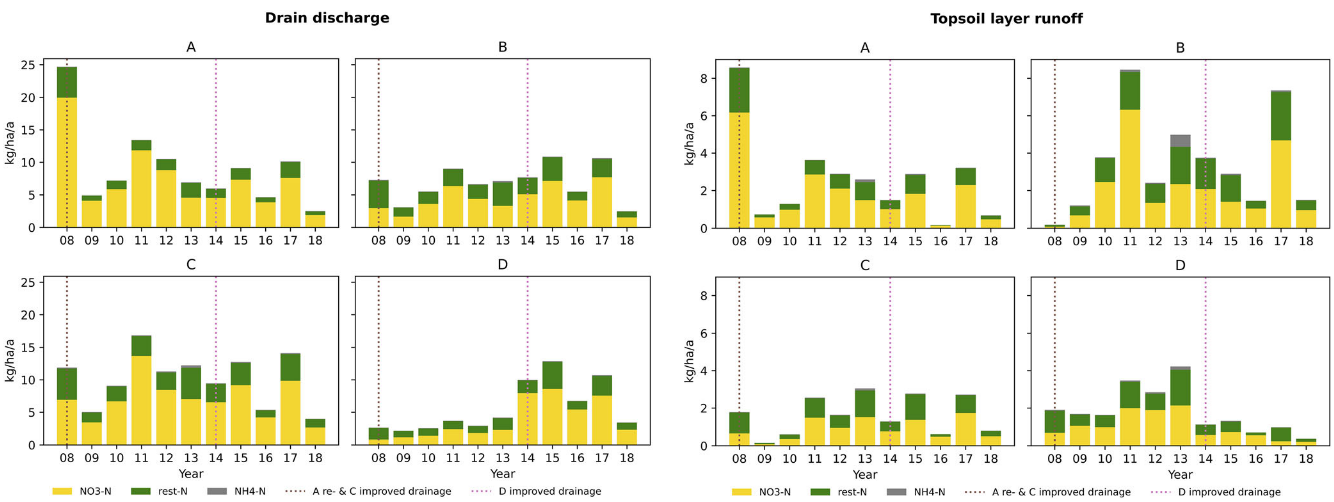

FIGURE 5 Annual N loads in the DD and TLR in each field section, calculated from the data of full calendar years. Note the different *y*-axes. The years of re-drainage in section A and improved drainage on section C are marked with a dashed line.

regions was reduced, or D even had higher concentrations (D–C, green line in Figure S1a, c, d, f).

No change in the concentration of TLR was detected around the improvement point (Table S1). However, after 2015, the tot-N and NO_3-N concentrations in the TLR of section D were consistently lower than those in the other sections (Figure S1b, e). No change was observed in the rest-N concentration differences in any of the runoff components (Figure S1g, h, i; Table S1).

3.3 | Nitrogen loads

NO_3-N formed a major part of the annual tot-N loads, while the shares of rest-N were considerably smaller, and the NH_4-N loads were negligible (Figure 5). Most of the N loads occurred through DD (Figure 5).

In section D, the DD tot-N loads increased after the drainage improved. Before 2014, the mean annual DD tot-N load from section D was 3.0 kg ha^{-1} (2.2–4.2 kg ha^{-1}), and after the improvement, it was 8.7 kg ha^{-1} (3.4–12.8 kg ha^{-1}). The relative fraction of rest-N in tot-N decreased from 45 to 26%, while the relative fraction of NO_3-N increased from 53 to 73%.

The TLR tot-N loads in section D decreased after the drainage improved from 2.6 kg ha^{-1} (1.6–4.2 kg ha^{-1}) to 0.9 kg ha^{-1} (0.4–1.3 kg ha^{-1}). The fraction of NO_3-N in tot-N decreased from 56 to 53%, and the fraction of rest-N increased from 42 to 45%.

The cumulative sums of the load differences between section D and the other field sections changed their slope direction after the improved drainage, indicating that the loads from section D increased (Figure 6). The change point was statistically significant (Table S1). The TLR

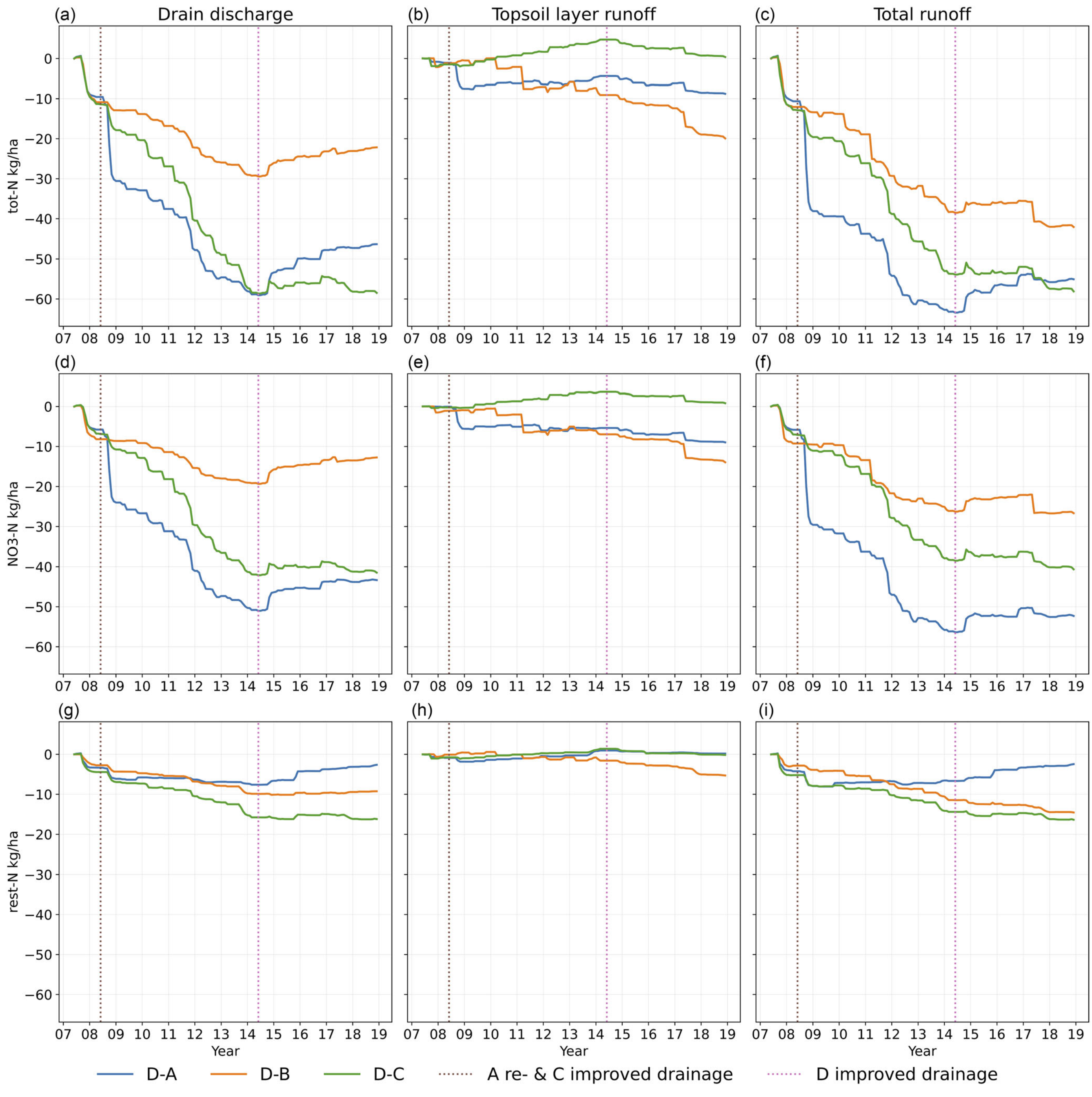

FIGURE 6 Cumulative sums of load differences for tot-N, NO_3-N and rest-N (rows) in DD, TLR and total runoff (columns), June 2007–December 2018. Positive *y*-axis values indicate that section D had greater loads than did the other sections, whereas negative values indicate that the reference sections (A, B or C) had greater runoff than did the experimental section (D). The years of re-drainage in section A and improved drainage on section C are marked with a dashed line.

tot-N loads from section D were greater than those from sections A and C before the improved drainage but lower after the improvement (Figure 6b). However, the impact of improved drainage on the TLR was not as clear as that on the DD (Table S1).

From June 2014 onwards, the tot-N loads of total runoff were approximately the same among all the field sections, including section D (Figure 6c). A significant increase was observed in 2014 in the tot-N loads of total runoff from section D in comparison to all the other sections (Table S1).

The impact of improved drainage on NO_3-N loads resembled that on tot-N loads (Figure 6d–f). The DD rest-N loads increased (significant change point detected in D–A and D–B), while the TLR rest-N decreased (significant change point detected in D–B and D–C). However, the differences between the rest-N loads of the field sections were approximately two to three times smaller than the differences in the tot-N loads. The improved drainage did not have a significant effect on the total runoff rest-N loads (Figure 6i and Table S1). The increase in the DD rest-N load was almost equal to the decrease in the TLR rest-N load.

3.4 | Seasonal variation in tot-N leaching

Prior to drainage improvement, most of the tot-N load (79% of the average annual load) formed during April and between October and December (Figure 7). After the improvement, the monthly tot-N load was otherwise similar, but instead of October, June became one of the months with the highest tot-N loads (22% of the average annual load) across all field sections.

Most of the changes in the differences in the monthly average tot-N loads between section D and the other field sections occurred in spring (April) and in winter (October–December) (Figure 8). Compared with those in the reference sections (A, B and C), the loads in section D increased. The TLR tot-N values remained similar, and therefore, the changes in the tot-N loads in total runoff were similar to the changes in the loads in DD.

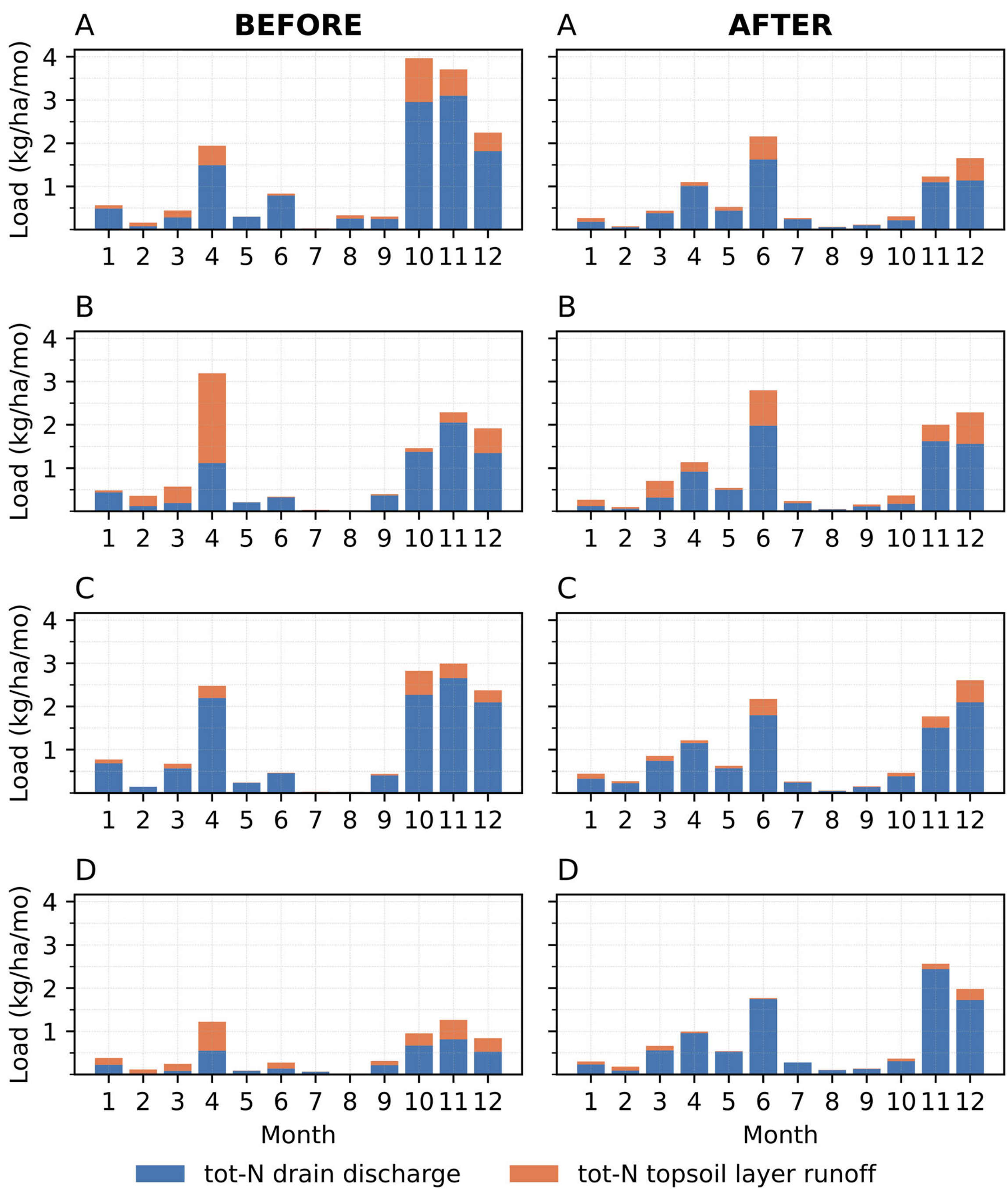

FIGURE 7 Monthly mean total N loads from each field section before and after drainage improvement in section D.

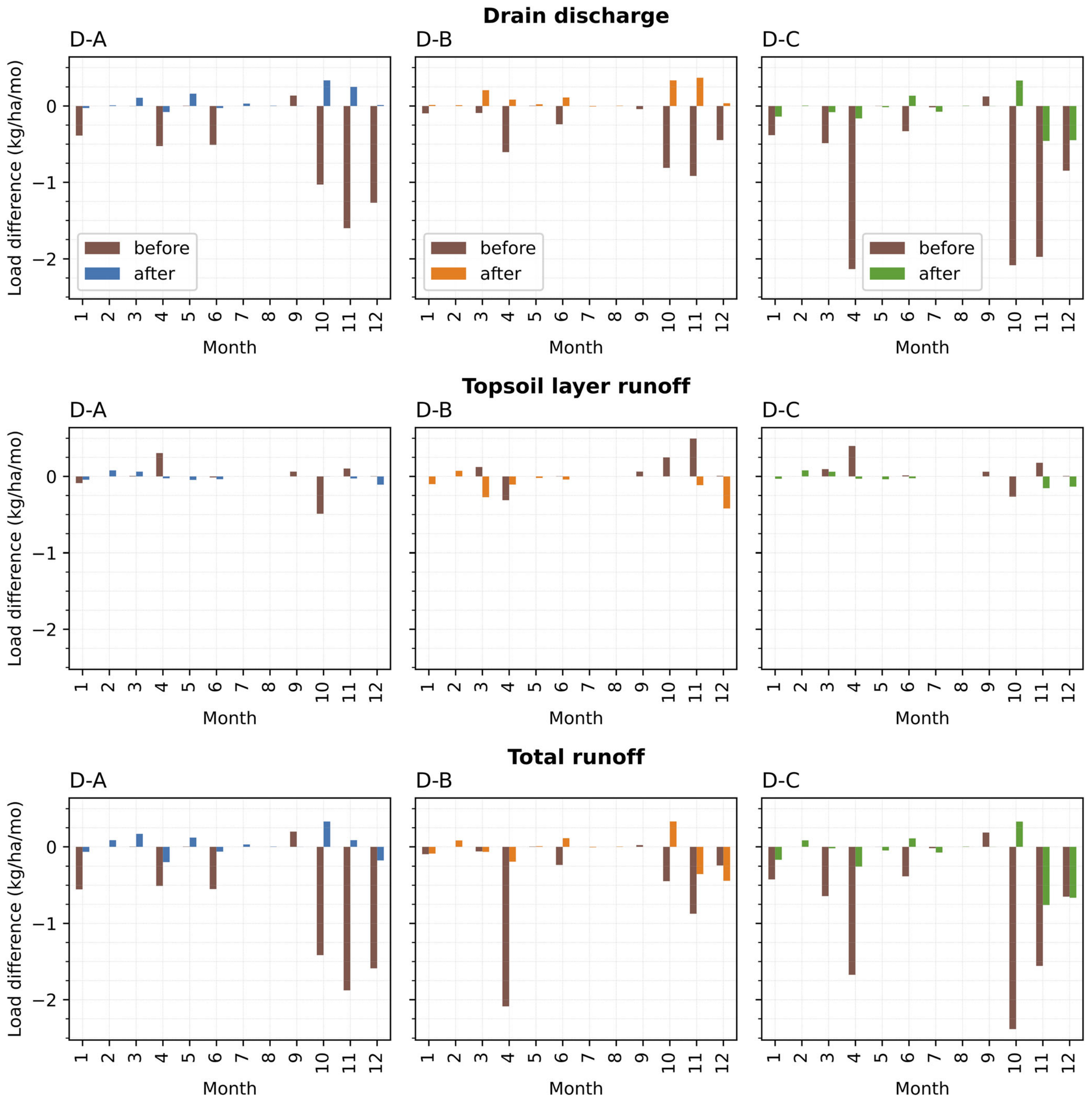

FIGURE 8 Differences in the monthly total N loads between section D and sections A, B and C before and after drainage improvement. The first row represents the total N loads from DD, the second row from TLR and the third row from total runoff.

4 | DISCUSSION

4.1 | Runoff and weather conditions

The meteorological conditions varied greatly throughout the study period, affecting the runoff components. Typically, in a boreal climate, winter months (Dec–Feb/Mar) are characterized by temperatures below 0°C, and all precipitation falls as snow. During that time, the surface soil is mostly frozen, and there is little drainage discharge or nutrient loading. The temperatures in April 2008 and 2011 were warmer than average, which may explain the greater total N load observed in April for the period before the improved drainage, as the warm spring contributed to early snowmelt runoff.

By studying the differences between the field sections, it was possible to minimize the effects of changing conditions that were equal for all the field sections (e.g. weather). This method has also been applied in other studies on the effects of water management practices on runoff and nutrient loads (Äijö et al., 2017; Salo et al., 2019).

Äijö et al. (2016) and Häggblom et al. (2019) summarized results regarding improved drainage in the Nummela field, but here a longer data series was utilized, and a systematic comparison in terms of statistical methods was made between section D and the other field sections (A, B and C). The data analysis revealed increasing DD and decreasing TLR after improved drainage, which has been reported in similar field sites (Kladivko et al., 1999; Seuna & Kauppi, 1981; Turtola & Paajanen, 1995). Even though the impacts on DD and TLR were statistically significant, the impact on total runoff was not significant when comparing section D to sections A and C. The opposite changes in DD and TLR compensated for each other and reduced the impact on total runoff. While the current study included DD and TLR in total runoff, modelling studies have demonstrated that additional subsurface components of total runoff may exist (e.g. Häggblom et al., 2019; Turunen et al., 2013). The current study did not focus on evapotranspiration, but according to the simulations by Häggblom et al. (2019), evapotranspiration remained at similar levels before and after drainage improvement.

Section B was the main reference section because it had the original drainage system, while the other reference sections underwent drainage improvement or renewal. In section B, flooding occurs during the spring snowmelt season (mainly in April), which has caused uncertainty in the TLR measurements (Äijö et al., 2016). Melting waters are suspected to have flowed into the section from surrounding areas, leading to unusually high runoff values compared to those in the other field sections. The difference between the TLR values of sections B and D in April decreased towards the end of the investigation period. The reasons for this could be variations in hydrological conditions, especially snow accumulation and melt, or the three supplementary drains installed between sections B and A in the autumn of 2011. Before the improved drainage, section D suffered from poor drainage capacity, and it is possible that snowmelt water did not infiltrate completely into the soil in this section but flowed into section B instead. The drainage improvement decreased the soil moisture in spring in section D, creating more efficient infiltration of the snowmelt water to the soil rather than overflowing to the neighbouring section B.

In addition to DD and TLR, Häggblom et al. (2019) noted that groundwater outflow also formed a considerable part of the water balance in the field. They defined groundwater outflow as lateral subsurface outflow to the main ditch at the border of the field. Even though drainage improvement reduced it, it still comprised 22% of the water balance of the improved drainage scenario (Häggblom et al., 2019). Groundwater outflow was not included in this study, but considering the results of Häggblom et al. (2019), it should be taken into consideration in future studies to analyse N losses through groundwater outflow. The importance of groundwater outflow for the water balance of cultivated fields and its possible impact on nutrient leaching have been reported previously by Turunen et al. (2013) and Rozemeijer et al. (2010).

4.2 | Nitrogen concentrations

After the drainage improvement of section D, moderately higher NO_3-N concentrations appeared in DD (4.0 vs 7.3 mg L^{-1}), but there was not much change in the rest-N concentrations. NO_3-N formed most of the tot-N concentration, and NH_4-N concentrations were negligible, which has been noted in previous studies from clayey fields in Finland (e.g. Paasonen-Kivekäs et al., 1999; Seuna & Kauppi, 1981; Turtola & Paajanen, 1995). Due to higher NO_3-N concentrations, there was a moderate increase in DD tot-N concentrations. These changes were generally not statistically significant according to Pettitt's test, and in some cases, the change point was found in 2012 (i.e. 2 years before the improved drainage installation). This could be due to the exceptionally wet conditions in the autumn of 2012, most likely through diminished N uptake with the poor harvest in that year. Pettitt's test is only able to detect one change point per time series (Pettitt, 1979), so a change occurring earlier than drainage improvement would make its effect undetectable by the test. Bechmann and Bøe (2021) reported that conditions similar to those in 2012 in Nummela (poor harvest combined with rainy autumn) resulted in high N losses. The load impacts of field drainage and drain spacing in previous studies are ambiguous: some have reported increased N loads (e.g. Seuna & Kauppi, 1981; Turtola & Paajanen, 1995), while others have shown that NO_3-N concentrations are unaffected by changes in the drainage system (e.g. Davis et al., 2000; Kladivko et al., 2004; Kladivko & Bowling, 2021). The main reason for the higher NO_3-N concentrations (and thus tot-N) is enhanced nitrification due to a higher oxygen content in the soil (Davis et al., 2000; Gramlich et al., 2018; Randall & Goss, 2008; Turtola & Paajanen, 1995). Section D had previously suffered from high soil moisture, and improving the drainage aimed at reducing the moisture content in the soil. A field suffering from excessive moisture (water-filled pore space greater than 70%) is prone to gaseous N loss through denitrification, reducing N leaching through drainage (Gramlich et al., 2018). Increased nitrification and decreased denitrification result in increased production of NO_3-N. As NO_3-N is highly soluble and poorly retained by the soil (Jury & Nielsen, 1989), it is easily leached into runoff pathways.

The study results from Nummela showed no distinct effect of improved drainage on TLR N concentrations, although a few years after the improvement (in 2017–2018), the tot-N and NO_3-N concentrations seemed to decrease, while the rest-N concentrations started to slightly increase (Figure S1e, h). One reason may be that improved drainage enhances soil microbiological activity and increases the immobilization of NO_3-N (e.g. Castellano et al., 2019).

4.3 | Nitrogen loads

The annual loads from the Nummela field were on average lower than the estimates by Tattari et al. (2017) from agricultural fields in Finland (15.5 kg ha^{-1}). The annual tot-N load from section D before drainage improvement was on average only 5.6 kg ha^{-1} (from both the DD and TLR). Drainage improvement increased the average total N load from section D to 9.6 kg ha^{-1} yr^{-1}, that is, to a similar level as that in other field sections and the results of Paasonen-Kivekäs et al. (2008).

Drainage improvement increased the DD tot-N load and decreased the TLR tot-N load. The total N loss in total runoff from section D increased, indicating that the increase in DD was greater than the decrease in TLR. Similar results have been reported by previous studies focusing on the nutrient load effects of subsurface drainage (Gramlich et al., 2018; Seuna & Kauppi, 1981), drain spacing (Davis et al., 2000; Kladivko et al., 2004; Kladivko & Bowling, 2021), improved subsurface drainage (Äijö et al., 2016; Turtola & Paajanen, 1995) and mole drainage (Valbuena-Parralejo et al., 2019). Although some of the previous studies reported no effect on concentrations (Davis et al., 2000; Kladivko et al., 2004; Kladivko & Bowling, 2021), all of them reported increased N loads due to increased DD. Blann et al. (2009) reported that the drain flow volume and NO_3-N loss are correlated when the drain flow volume varies due to the use of crops with different water types. The analyses of the Nummela field time series showed that improved drainage had an impact on the N loads through increased runoff volumes and that the increase in the tot-N load was due to increased NO_3-N load, while the rest of the N load remained similar before and after drainage improvement. The impact on both the runoff and N loads was statistically significant, while the effect on concentrations was not. Therefore, runoff and its drivers, including snowmelt and rainfall, have a strong influence on N loads.

The increase in tot-N loads from section D was caused by increased NO_3-N loads, as improved drainage had only small impacts on the rest-N loads in total runoff. DD rest-N loads increased slightly, which was compensated for by decreased TLR rest-N loads. However, due to the higher NO_3-N loads after the improvement, the share of rest-N in the total N load was halved compared to that in the years before the improvement. After improvement, rest-N still accounted for, on average, 16% of the total N loss. Many studies only consider NO_3-N and tot-N (e.g. Turtola & Paajanen, 1995) or only consider NO_3-N (e.g. Davis et al., 2000; Kladivko et al., 2004; Kladivko & Bowling, 2021) and thus might ignore N losses in the form of rest-N. Even though improved drainage was not found to change the rest-N loads in our study, it is an important proportion to consider when, for example, modelling N leaching.

In addition to the long-term change, a peak in N loads was observed after the drainage operations. The impact was most distinct in section A after the renewed drainage in 2008, but a smaller peak was also found after the improved drainage in sections C and D (2008 and 2014, respectively). The peak may be due to increased DD, enhanced mineralization after reduced soil moisture, or merely the installation of drains. Soil disturbance, such as soil tillage, has been reported to increase the leaching of NO_3-N via DD (e.g. Grönroos et al., 2007).

Changes in the monthly tot-N loads caused by drainage improvement were greatest during the months when most of the nutrient loads occurred at the times of the highest runoffs (Äijö et al., 2017), as the volume of runoff primarily controlled the changes in N loads. Runoff was most abundant in spring because of snowmelt and in autumn and winter because of moderately high rainfall and low evapotranspiration. There was an increase in the monthly tot-N loads in June after 2014 in all field sections, which was caused by the rainiest months of the study period (June 2015 and 2017; data not shown). Additionally, manure was spread to the field in May 2015 and 2017.

5 | CONCLUSIONS

Improved drainage increased N loads, especially NO_3-N loads, in the DD. Improved drainage increased the DD volume and decreased the TLR volume. The increase in N loads mostly reflected the changes in runoff, which indicates that N leaching could be controlled by controlling runoff generation and volume. Although the nutrient load was mostly determined by runoff volume, changes in N concentrations were observed as the concentration of NO_3-N in drainage discharge increased due to the improvement. This is attributed to an increase in nitrification as a result of improved soil aeration.

Most of the N load increase occurred in spring and autumn, after snowmelt and during heavy rainfall events, respectively, creating potential for controlling field water management during those periods. After the drainage improvement, the DD increased more than the TLR decreased, highlighting the need to consider other water outflow pathways, such as groundwater outflow.

The results showed that rest-N is an important fraction of the tot-N load (26% of the average annual tot-N load). For example, when modelling the leaching of nutrients, fractions other than mineral N should be considered.

ACKNOWLEDGEMENTS

The study was funded by the Drainage Research Association and Drainage Foundation Sr and Aalto University. We wish to acknowledge Ilkka Mellin for his guidance related to the statistical analysis. We also acknowledge Maija Paasonen-Kivekäs for her insights on the topic of field hydrology and nitrogen processes in agricultural fields. PhD Timo Larsson is acknowledged for helping with the abstract translation from English to French.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Heidi Salo https://orcid.org/0000-0002-4267-0569
Minna Mäkelä https://orcid.org/0000-0001-8238-7007

REFERENCES

Äijö, H., Myllys, M., Nurminen, J., Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Korpelainen, E., Salo, H., Sikkilä, M., Alakukku, L., Koivusalo, H. & Puustinen, M. 2014. Salaojitustekniikat ja pellon vesitalouden optimointi. Loppuraportti 2014. *Salaojituksen tutkimusyhdistys ry:n tiedote 31*. Drainage Research Association, Helsinki, Finland. 126 p.

Äijö, H., Myllys, M., Sikkilä, M., Salo, H., Nurminen, J., Häggblom, O., Turunen, M., Paasonen-Kivekäs, M., Warsta, L., Koivusalo, H., Alakukku, L., Puustinen, M. 2017. Toimivat salaojitusmenetelmät kasvintuotannossa (TOSKA). Loppuraportti 2017. Salaojituksen tutkimusyhdistys ry:n tiedote 32. Drainage Research Association, Helsinki, Finland. 109 p.

Äijö, H., Myllys, M., Sikkilä, M., Salo, H., Salla, A., Nurminen, J., Paasonen-Kivekäs, M. & Koivusalo, H. (2021). Vesitalouden hallinta vesiensuojelussa (VesiHave): Loppuraportti 2021. Salaojituksen tutkimusyhdistys ry:n tiedote 35. Drainage Research Association, Helsinki, Finland. 82 p.

Äijö, H., Paasonen-Kivekäs, M., Myllys, M., Nurminen, J., Turunen, M., Salo, H. et al. (2016) The effect of additional subsurface drainage on water discharge and nutrient load on clay soil. In: *2016 10th international drainage symposium conference, 6–9 September 2016*. Minneapolis, Minnesota: American Society of Agricultural and Biological Engineers, pp. 1–6.

Alakukku, L., Nuutinen, V., Ketoja, E., Koivusalo, H. & Paasonen-Kivekäs, M. (2010) Soil macroporosity in relation to subsurface drain location on a sloping clay field in humid climatic conditions. *Soil and Tillage Research.*, 106(2), 275–284. Available from: https://doi.org/10.1016/j.still.2009.11.002

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., Van Der Linden, J.P., Pires, S. et al. (2003) Prevention strategies for field traffic-induced subsoil compaction: a review: part 1. Machine/soil interactions. *Soil and Tillage Research*, 73(1–2), 145–160. Available from: https://doi.org/10.1016/S0167-1987(03)00107-7

Bechmann, M.E. & Bøe, F. (2021) Soil tillage and crop growth effects on surface and subsurface runoff, loss of soil, phosphorus and nitrogen in a cold climate. *Land*, 10(1), 77. Available from: https://doi.org/10.3390/land10010077

Blann, K.L., Anderson, J.L., Sands, G.R. & Vondracek, B. (2009) Effects of agricultural drainage on aquatic ecosystems: a review. *Critical Reviews in Environmental Science and Technology*, 39(11), 909–1001. Available from: https://doi.org/10.1080/10643380801977966

Bronswijk, J.J.B., Hamminga, W. & Oostindie, K. (1995) Rapid nutrient leaching to groundwater and surface water in clay soil areas. *European Journal of Agronomy*, 4(4), 431–439. Available from: https://doi.org/10.1016/S1161-0301(14)80095-6

Castellano, M.J., Archontoulis, S.V., Helmers, M.J., Poffenbarger, H.J. & Six, J. (2019) Sustainable intensification of agricultural drainage. *Nature Sustainability*, 2(10), 914–921. Available from: https://doi.org/10.1038/s41893-019-0393-0

Conte, L.C., Bayer, D.M. & Bayer, F.M. (2019) Bootstrap Pettitt test for detecting change points in hydroclimatological data: case study of Itaipu hydroelectric plant, Brazil. *Hydrological Sciences Journal*, 64(11), 1312–1326. Available from: https://doi.org/10.1080/02626667.2019.1632461

Davis, D.M., Gowda, P.H., Mulla, D.J. & Randall, G.W. (2000) Modeling nitrate nitrogen leaching in response to nitrogen fertilizer rate and tile drain depth or spacing for southern Minnesota, USA. *American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America*, 29(5), 1568–1581. Available from: https://doi.org/10.2134/jeq2000.00472425002900050026x

FAO. (1988). FAO/Unesco Soil Map of the World. Revised Legend, with corrections. World Soil Resources Rep. 60. FAO, Rome, Italy. Reprinted Technical Paper 20, ISRIC, Wageningen, The Netherlands, 1994.

Frey, S.K., Hwang, H.T., Park, Y.J., Hussain, S.I., Gottschall, N., Edwards, M. et al. (2016) Dual permeability modeling of tile drain management influences on hydrologic and nutrient transport characteristics in macroporous soil. *Journal of Hydrology*, 535, 392–406. Available from: https://doi.org/10.1016/j.jhydrol.2016.01.073

Gilliam, J.W., Baker, J.L. & Reddy, K.R. (1999) Water quality effects of drainage in humid regions. *Agricultural Drainage*, 38, 801–830. Available from: https://doi.org/10.2134/agronmonogr38.c24

Gramlich, A., Stoll, S., Stamm, C., Walter, T. & Prasuhn, V. (2018) Effects of artificial land drainage on hydrology, nutrient and pesticide fluxes from agricultural fields—a review. *Agriculture, Ecosystems & Environment*, 266, 84–99. Available from: https://doi.org/10.1016/j.agee.2018.04.005

Grönroos, J., Hietala-Koivu, R., Kuussaari, M., Laitinen, P., Lankoski, J., Lemola, R. et al. (2007) *Analyysi maatalouden ympäristötukijärjestelmästä 2000–2006*. Helsinki: Suomen ympäristökeskus SYKE.

Häggblom, O., Salo, H., Turunen, M., Nurminen, J., Alakukku, L., Myllys, M. et al. (2019) Impacts of supplementary drainage on the water balance of a poorly drained agricultural field. *Agricultural Water Management*, 223, 105568. Available from: https://doi.org/10.1016/j.agwat.2019.03.039

Jury, W.A. & Nielsen, D.R. (1989) Nitrate transport and leaching mechanisms. In: *Developments in agricultural and managed forest ecology*, Vol. 21. Amsterdam, The Netherlands: Elsevier Science Publishers B.V., pp. 139–157 https://doi.org/10.1016/B978-0-444-87393-4.50011-3

Kladivko, E.J. & Bowling, L.C. (2021) Long-term impacts of drain spacing, crop management, and weather on nitrate leaching to subsurface drains. *Journal of Environmental Quality*, 50(3), 627–638. Available from: https://doi.org/10.1002/jeq2.20215

Kladivko, E.J., Frankenberger, J.R., Jaynes, D.B., Meek, D.W., Jenkinson, B.J. & Fausey, N.R. (2004) Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. *Journal of Environmental Quality*, 33(5), 1803–1813. Available from: https://doi.org/10.2134/jeq2004.1803

Kladivko, E.J., Grochulska, J., Turco, R.F., Van Scoyoc, G.E. & Eigel, J.D. (1999) Pesticide and nitrate transport into subsurface tile drains of different spacings. *American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America*, 28(3), 997–1004. Available from: https://doi.org/10.2134/jeq1999.00472425002800030033x

Korpelainen, E. (2021) Typpitase ja -huuhtouma salaojitetussa savimaassa. Master's thesis. Aalto University, School of Chemical Engineering, Environmental Management. Espoo. 79 p.

Mueller, L., Schindler, U., Fausey, N.R. & Lal, R. (2003) Comparison of methods for estimating maximum soil water content for optimum workability. *Soil and Tillage Research*, 72(1), 9–20. Available from: https://doi.org/10.1016/S0167-1987(03)00046-1

Natural Resources Institute Finland LUKE. (2015). Farmland management and irrigation 2013. Helsinki [referred: 27.6.2022]. Available from: https://www.luke.fi/en/statistics/farmland-management-and-irrigation/farmland-management-and-irrigation-2013

Norberg, L., Linefur, H., Andersson, S., Blomberg, M. & Kyllmar, K. (2022) Nutrient losses over time via surface runoff and subsurface drainage from an agricultural field in northern Sweden. *Journal of Environmental Quality*, 51(6), 1235–1245. Available from: https://doi.org/10.1002/jeq2.20413

Official Statistics of Finland (OSF). (2022). Utilised Agricultural Area [e-publication]. Helsinki: Natural Resources Institute Finland [referred: 27.6.2022]. Access method: http://www.stat.fi/til/kaoma/index_en.html

Ovaska, S., Liski, R., Äijö, H., Häggblom, O. & Paasonen-Kivekäs, M. 2021. Perusparannukset ja ravinnetase suomalaisessa peltoviljelyssä: Loppuraportti. Salaojituksen tutkimusyhdistys ry:n tiedote 36. Helsinki, Finland: Finnish Field Drainage Association. 94 p. ISBN 978–952-5345-47-6

Paasonen-Kivekäs, M., Koivusalo, H., Karvonen T., Vakkilainen P., Virtanen J. 1999. Nitrogen transport via surface and subsurface flow in an agricultural field. Impact of land-use change on nutrient loads from diffuse sources. Heathwaite, L. (ed.). IAHS. Publ. No. 257. P. 163–169.

Paasonen-Kivekäs, M., Vakkilainen, P. & Karvonen, T. (2008) Salaojitus ja savimaiden ravinnekuormitus. *Vesitalous*, (4), 20–24.

Pettitt, A.N. (1979) A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 28(2), 126–135.

Pohlert, T. (2016). Non-parametric trend tests and change-point detection. CC BY-ND.

Randall, G.W. & Goss, M.J. (2008) Chapter 6—nitrate losses to surface water through subsurface, tile drainage. In: Hatfield, J.L. & Follett, R.F. (Eds.) *Nitrogen in the environment*, Second edition, Vol. 2008. Amsterdam, The Netherlands: Elsevier Science Publishers B.V., pp. 145–175. ISBN:9780123743473.

Rozemeijer, J.C., van der Velde, Y., van Geer, F.C., Bierkens, M.F.P. & Broers, H.P. (2010) Direct measurements of the tile drain and groundwater flow route contributions to surface water contamination: From field-scale concentration patterns in groundwater to catchment-scale surface water quality. *Environmental Pollution*, 158(12), 3571–3579.

Salo, H., Mellin, I., Sikkilä, M., Nurminen, J., Äijö, H., Paasonen-Kivekäs, M. et al. (2019) Performance of subsurface drainage implemented with trencher and trenchless machineries. *Agricultural Water Management*, 213, 957–967. Available from: https://doi.org/10.1016/j.agwat.2018.12.010

Salo, H., Warsta, L., Turunen, M., Nurminen, J., Myllys, M., Paasonen-Kivekäs, M. et al. (2017) Simulating 3-D water flow in subsurface drain trenches and surrounding soils in a clayey field. *Soil and Tillage Research*, 168, 20–32.

Salo, H., Warsta, L., Turunen, M., Paasonen-Kivekäs, M., Nurminen, J. & Koivusalo, H. (2015) Development and application of a solute transport model to describe field-scale nitrogen processes during autumn rains. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, 65(sup1), 30–43. Available from: https://doi.org/10.1080/09064710.2014.971861

Salo, T. & Turtola, E. (2006) Nitrogen balance as an indicator of nitrogen leaching in Finland. *Agriculture, Ecosystems & Environment*, 113(1–4), 98–107. Available from: https://doi.org/10.1016/j.agee.2005.09.002

Seuna, P. & Kauppi, L. (1981). Influence of subdrainage on water quantity and quality in a cultivated area in Finland. Publications of the Water Research Institute, 43, 32–47.

Shourov M. H. (2020) pyHomogeneity [downloaded: 26.5.2022]. Access method: https://github.com/mmhs013/pyhomogeneity

Singh, R., Helmers, M.J., Crumpton, W.G. & Lemke, D.W. (2007) Predicting effects of drainage water management in Iowa's subsurface drained landscapes. *Agricultural Water Management*, 92(3), 162–170. Available from: https://doi.org/10.1016/j.agwat.2007.05.012

Suomen ympäristökeskus. (2022) Rehevöittävä kuormitus, Vesi.fi. [referred 10.6.2022]. Available from: https://www.vesi.fi/vesitieto/rehevoittava-kuormitus/

Tao, Y., Wang, S., Xu, D., Yuan, H. & Chen, H. (2017) Field and numerical experiment of an improved subsurface drainage system in Huaibei plain. *Agricultural Water Management*, 194, 24–32.

Tattari, S., Koskiaho, J., Kosunen, M., Lepisto, A., Linjama, J. & Puustinen, M. (2017) Nutrient loads from agricultural and forested areas in Finland from 1981 up to 2010 - can the efficiency of undertaken water protection measures seen? *Environmental Monitoring and Assessment*, 189(3), 95. Available from: https://doi.org/10.1007/s10661-017-5791-z

Turtola, E. & Paajanen, A. (1995) Influence of improved subsurface drainage on phosphorus losses and nitrogen leaching from a heavy clay soil. *Agricultural Water Management*, 28(4), 295–310. Available from: https://doi.org/10.1016/0378-3774(95)01180-3

Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Nurminen, J., Myllys, M., Alakukku, L. et al. (2013) Modeling water balance and effects of different subsurface drainage methods on water outflow components in a clayey agricultural field in boreal conditions. *Agricultural Water Management*, 121, 135–148. Available from: https://doi.org/10.1016/j.agwat.2013.01.012

Vakkilainen, P., Alakukku, L., Koskiaho, J., Myllys, M., Nurminen, J., Paasonen-Kivekäs, M., Peltomaa, R., Puustinen, M., Äijö, H., 2010. Pellon vesitalouden optimointi—Loppuraportti 2010. Salaojituksen tutkimusyhdistys ry:n tiedote 30. Drainage Research Association, Helsinki, Finland 114 p.

Valbuena-Parralejo, N., Fenton, O., Tuohy, P., Williams, M., Lanigan, G.J. & Humphreys, J. (2019) Phosphorus and nitrogen losses from temperate permanent grassland on clay-loam soil after the installation of artificial mole and gravel mole drainage. *Science of the Total Environment*, 659, 1428–1436. Available from: https://doi.org/10.1016/j.scitotenv.2018.12.173

Villholth, K.G., Jensen, K.H. & Fredericia, J. (1998) Flow and transport processes in a macroporous subsurface-drained glacial till soil I: field investigations. *Journal of Hydrology*, 207(1–2), 98–120. Available from: https://doi.org/10.1016/S0022-1694(98)00129-2

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Jokinen, V., Salo, H., Mäkelä, M., Nurminen, J., Äijö, H., Laine-Kaulio, H. et al. (2024) The effects of improved subsurface drainage on runoff and nitrogen leaching from a clayey field section. *Irrigation and Drainage*, 1–16. Available from: https://doi.org/10.1002/ird.2965