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Long-term monitoring of nitrate-N transport to drainage from three agricultural clayey till fields

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Abstract

The application of nitrogen (N) fertilisers to crops grown on tile-drained fields is necessary to sustain most modern crop production, but poses a risk to the aquatic environment since tile drains facilitate rapid transport pathways with no significant reduction in nitrate. To maintain the water quality of the aquatic environment and the provision of food from highly efficient agriculture in line with the EU's Water Framework Directive and Nitrates Directive, field-scale knowledge is imperative if there is to be differentiated N-regulation in future. This study describes nitrate-N leaching to drainage based on coherent monitoring of nitrate-N concentrations, the climate, the groundwater table and crop-specific parameters obtained over eleven years (2001–2011) at three subsurface-drained clayey till fields (1.3–2.3 ha). The monitoring results showed significant field differences in nitrate-N transport to drainage. Not only were these caused by periods of bare soil after short-season crops and N-fixing crops (pea), which have been shown to generate high nitrate-N concentrations in drainage, but by the hydrogeological field conditions that were shown to be the controlling factor of nitrate-N transport to drainage. The fields had the following characteristics: (A) the lowest mass transport (13 kg N ha^{-1}) and fertiliser input had short-term and low-intensity drainage with the highest nitrate-N concentrations detected, representing 40 % of net precipitation (226 mm) combined with low air temperatures, (B) the medium mass transport (14 kg N ha^{-1}) had medium-term and medium-intensity drainage, representing 42 % of net precipitation (471 mm) combined with periods of both low and higher air temperatures, (C) the highest mass transport (19 kg N ha^{-1}) had long-term drainage, representing 68 % of net precipitation (617 mm), but had the highest potential for in-situ soil denitrification and post-treatment (e.g. constructed wetlands) due to long periods with both high water saturation in the soil and high air temperatures. These results show that local hydrogeological conditions need to be taken into account in a differentiated N-regulation of agricultural fields in future.

1 Introduction

Future regulations covering aquatic environments under the Nitrates Directive (EEC, 1991), the EU Water Framework Directive (EC, 2000), the EU Groundwater Directive (EC, 2006) and additional national laws and regulations (Danish-EPA, 2012) call for long-term monitoring data to describe the complex interaction between soil, geology, geochemistry and hydrology at a local level as well on larger scales. Since Denmark presented its first national hydrological action plan in 1985, several political agreements have been adopted that aim to protect the aquatic environment and nature in general. Recently, the Danish Commission on Nature and Agriculture issued a report (Commission on Nature and Agriculture, 2013) that recommended that nitrogen (N) regulations should be adapted locally in future and, if possible, at field scale. As an integrated part of such a policy, there is a need to develop tools to identify fields that are vulnerable or non-vulnerable to nitrate-N leaching.

N is an essential plant nutrient, which is why N-application to agricultural land is essential for sustaining food and fibre production for a rapidly growing population. The outcome is that the agricultural sector has been identified as the largest nonpoint source contributor of nitrate to surface and groundwater bodies (Bakhsh et al., 2004; Beaudoin et al., 2005; Billy et al., 2011). The effects of agriculture may extend beyond the boundaries of fields or farms since the drainage systems will inevitably affect the flow pathways of water away from agricultural land and into the receiving water bodies (Robinson and Rycroft, 1999). However, the nonpoint loss of N from agricultural fields is controlled by an array of factors such as soil properties (physical, chemical and biological), climatic factors (precipitation and temperature patterns), farming practices (cropping system, fertilisation and tillage), as well as hydrology (Billy et al., 2011; Dinnes et al., 2002). Thus, high doses of N-fertilisers may increase the N-transport to drainage, especially when there is no further crop response (Delin and Stenberg, 2014). Crop response by catch crops in intensive agriculture in northern France reduced the mean concentration by 50 % on an annual scale (Beaudoin et al., 2005) and a winter cover of mustard reduced the nitrate-N concentrations in temperate soils (Premrov et al., 2014).

The installation of tile drains is a common agricultural water management practice to improve moisture and aeration conditions (Tiemeyer et al., 2010; Van Der Ploeg et al., 1999) in areas with shallow groundwater and seasonally perched groundwater tables, and they remove water from the land more quickly than under natural conditions. These drains increase infiltration and deliver shallow groundwater more quickly to surface water, preventing its recharge to groundwater. This artificial drainage modifies N-dynamics by facilitating the rapid transport of nitrate-N and greatly reducing or even suppressing the water residence time within natural retention zones. The presence of tile drains enhances crop yields on poorly naturally drained but highly productive soils, and helps reduce year-on-year variability in yields (Nangia et al., 2010) by promoting earlier sowing and improving trafficability. However, tile drain systems not only remove excess water from the root zone, but also facilitate N-transport, primarily as soluble nitrate-N, from the bottom of the root zone to the edge of the field (Billy et al., 2011; Mulla and Strock, 2008) and to surface water (Cordeiro et al., 2014; Eidem et al., 1999; Gilliam et al., 1979; Lapen et al., 2008). They also contribute to hypoxia (Billy et al., 2011). Drainage increases N-losses from agricultural areas as compared to former undrained fields. In addition, no biogeochemical processes such as denitrification are known to occur in buried pipes, which are considered inert pathways (Billy et al., 2013; Gilliam et al., 1999). This decreases the possibilities for nitrate-N to be denitrified or adsorbed by plants (Gilliam et al., 1999). Therefore the loss of nitrate-N leaching from the root zone is not solely an environmental concern, but also an economic loss to farmers (Schjonning et al., 2013).

The greatest intensity of drainage in Europe is concentrated in the northern areas around the Baltic and North Seas. This is largely due to climatic conditions and the presence of glacially derived clayey tills that can cause prolonged water-logging (Robinson and Rycroft, 1999). Since around 1850, 50 % of agricultural land in Den-

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mark has been systematically tile drained with a horizontal spacing of 8–20 m (Olesen, 2009) and a total length of around 1 000 000 km (Breuning-Madsen, 2012).

A number of factors may affect the loss of nitrate-N from fields via drainage. The local climate (temperature and precipitation), soil type, crop type, length of growing season, options of (winter) cover crops, tillage and soil management are also important factors in the concentration and leaching of nitrate-N from the root zone. Some of these factors are field specific and cannot be changed, whereas other factors may be adjusted to minimise the N-loss for the benefit of the environment and farmers' incomes.

To the authors' knowledge, there has been limited documentation of nitrate-N concentrations and leaching via tile drain systems from field-size areas monitored over a long period. In Denmark, data exist on nitrate-N concentrations and leaching from a few short-term local-scale studies (Bennetzen, 1978; Hansen and Pedersen, 1975, 1983; Simmelsgaard, 1998; Simmelsgaard and Djurhuus, 1998). Common among these studies is that there is no knowledge of the specific field contribution of nitrate-N to drainage because the extent of the field's tile drain system is unknown or because there are different fields with different crops contributing to the drainage.

For the implementation of field-specific N-regulation aimed at minimising N-leaching, more knowledge is needed on this scale. In the present study, field-scale insight was provided with regard to the impact of climate, crop, N-fertilisers and hydrogeological setting on nitrate-N concentration and transport to drainage obtained from long-term monitoring at three geologically different clayey till settings situated on agricultural land.

2 Material and methods

2.1 Field descriptions

The geographical location of the three fields (Faardrup, Silstrup, and Estrup) is shown in Fig. 1. A summary of the main characteristics of each field, based on Lindhardt et al. (2001), is provided in Tables 1 and 2.

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The three fields (1.3–2.3 ha) are located on clay till plains with a small slope (0–3 %). The clayey till plain at Faardrup is homogenous, at Silstrup the clayey till plain comprises dislocated Oligocene clay, and at Estrup there is a complex structure with deposits of different ages and compositions. At Faardrup and Silstrup, located on sediments from the Late Weichselian age (about 12 000 years BP), moderately well-drained argiudoll was mapped with hapludoll (Silstrup) and both hapludoll and vermudoll (Faardrup). Estrup is located on older sediments deposited under the Saalian glaciation (about 100 000 years BP) with argiudoll and glossudalf (Table 2). The content of organic matter in the Ap-horizon was lowest (1.4–1.5 % C) in Faardrup, medium in Silstrup (1.6–2.0 % C), and highest (1.6–3.2 % C) in Estrup. In all fields, the C-contents decrease markedly at depths just below the Ap-horizon to contents of 0.06 to 0.8 % C. The clay content in the upper 0.2 m (Ap horizon) is 10–27 % and varies to six metres below the surface at between 1–65 % due to the heterogeneity of the clayey till. Post-glacial leaching processes have formed an upper calcium-free zone about one metre thick in the youngest sediments of Faardrup and Silstrup and down to 1 to 4 m at Estrup, due to the much longer ongoing weathering processes. In the calcareous zone below, the $CaCO_3$ content varies between 21 and 82 % in all three fields.

Subsurface tile drains were installed in the fields between the 1940s and the 1960s. The drains were established at a depth of approximately 1.1 m and with a horizontal spacing of 10–20 m. Before monitoring began, the fields' tile drain system was isolated from the surrounding tile drain systems to ensure that drainage only came from the fields. Any modifications were made outside the monitoring fields (Lindhardt et al., 2001).

2.2 Farming practices

The farming practices for the fields were in line with the conventional practice within the different regions and with the application of nitrogen as recommended as good management practice in Denmark. In 2001–2011, crops of spring barley and winter wheat were the most common types in rotation with spring or winter rape, fodder or sugar beets and maize in all the fields. Red fescue for grass seed production was also grown in Faardrup and Silstrup, as well as peas in Silstrup and Estrup (Table 3). In each year, the amount of N-fertilizers applied was adjusted to suit the selected crop type and the previous year's climatic conditions. As an average for 2001–2011, the annual N-application was 136 $kg\,N\,ha^{-1}$ at Faardrup, 139 $kg\,N\,ha^{-1}$ at Silstrup, and 142 $kg\,N\,ha^{-1}$ at Estrup (Table 3). There were considerable differences in the average annual N-application, ranging from 0 $kg\,N\,ha^{-1}$ for the pea crop to 223 $kg\,N\,ha^{-1}$ for spring barley undersown with red fescue. At Faardrup only commercial N-fertilisers were used, whereas at Silstrup and Estrup animal slurry was applied from time to time (Table 3).

2.3 Monitoring setup

The crop development and growth stage (BBCH stage) was mapped according to Meier (2001). Precipitation was measured on site and air temperature was recorded at nearby meteorological stations. The water table was registered in piezometers constructed of 6.3 cm diameter polyvinyl chloride with 0.5 m screens placed at depths of 3.0–3.5, 4.5–5.0, and 6.1–6.6 m at the edge of the Faardrup, Estrup, and Silstrup fields. Daily monitoring of the water table at Silstrup and Estrup was performed using a D-Diver (Van Essen Instruments, Delft, the Netherlands) and monthly monitoring of the water table at Faardrup was performed with a hand-held Water Level Meter, type 010 (HT Hydrotechnik, Obergünzburg, Germany). ISCO samplers (Teledyne ISCO, Lincoln, NE, USA) were used to collect samples of drainage water. Drainage water was sampled time proportionally until July 2004 and then flow proportionally, with sub-samples collected for every 3000 L of drainage during the winter season (September–May) and for every 1500 L during the summer season (June–August). Each week, all the collected subsamples were pooled and a sample analysed in the laboratory.

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2.4 Nitrate-N analysis

Samples of drainage were refrigerated at all times until analysis. The water samples were 0.45 µm filtrated (Millex HV syringe filter, Millipore, Ireland) and nitrate-N (NO_3-N) was measured using a Metrohm Anion system equipped with a Metrosep A Supp 15–250 IC column and a suppressor module (MSM) and with conductivity detection (Mehrohm, Herisau, Switzerland). The eluent was a mixture of 1 mM $NaHCO_3$ and 3.2 mM Na_2CO_3. The system was connected to an 838 Advanced IC Sample processer (Mehrohm, Herisau, Switzerland).

2.5 Calculation of N-flux in drainage

The total mass of nitrate-N transported out of the field by drainage was calculated by multiplying the concentration of nitrate-N for the pooled water sampled by the drainage volume between the time of sampling and the previous time of sampling. The nitrate-N losses were all calculated as $kg\,N\,ha^{-1}$, taking into account the different sizes of the three fields.

3 Results

3.1 Climate

All three fields are located in a temperate climate with typical summer temperatures up to 20–25 °C and winter temperatures between −5 and −10 °C (Fig. 2). The geographical location of the fields led to differences in annual precipitation. Average annual precipitation between 2001 and 2012 was 685 mm at Faardrup and 943 mm at Silstrup, with the highest being Estrup at 1089 mm (Table 1). As the fields' average annual evaporation only varied slightly (between 459 and 476 mm), the annual leaching to drainage and groundwater was 226 mm at Faardrup, 471 mm at Silstrup, and 617 mm at Estrup (Table 1).

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3.2 Hydrogeological setting

Monthly registration of the groundwater table at the edge of the field in Faardrup showed the overall pattern over the year, even though its full amplitude was not monitored as the filter has not been installed sufficiently deeply for the deepest water tables to be registered (Fig. 3). The water table approaches the soil surface by the end of autumn and during winter, and drops in spring, summer and early autumn to about 3.5 m depth or even deeper. During 2001–2012, the groundwater table rose to or above the depth of the tile drain system only for a short period and delivered drainage flow, often at a time when the average air temperature was low, down to −11 °C (Fig. 2). Typically, drainage was below 10 $m^3 ha^{-1} d^{-1}$ and rarely above 50 $m^3 ha^{-1} d^{-1}$. On one occasion up to 149 $m^3 ha^{-1} d^{-1}$ was measured (Fig. 2). For 2001–2012, the average annual drainage was 42 % of total discharge to drainage plus groundwater (Table S1).

At Silstrup, the groundwater table was above drainage depth from late autumn to late winter and dropped during spring and summer to a depth of 3.82 m at its lowest (October 2009) (Fig. 3). On average, the groundwater table was above drainage depth on 18 $d yr^{-1}$ (3–46 d) and was deeper than 2.5 m on 123 $d yr^{-1}$ (36–191 d) (Fig. S1). Most often, the drainage events in late autumn and winter were above 50–60 $m^3 ha^{-1} d^{-1}$, a few were up to 100 $m^3 ha^{-1} d^{-1}$, with a maximum drainage of 278 $m^3 ha^{-1} d^{-1}$ in March 2010 (Fig. 2). For 2001–2012 the average annual drainage was 40 % of total discharge to drainage plus groundwater (Table S1).

In Estrup, the groundwater table was highly dynamic and only located deep for short periods. On average for 2001–2012, the water table was above drainage depth on 150 d (0–239 d) and deeper than 2.5 m on 42 d (5–70 d) (Fig. S1), with the lowest groundwater table (4.35 m) in July 2008 (Fig. 3). Daily drainage was often above 50–60 $m^3 ha^{-1} d^{-1}$, in some cases up to 100 $m^3 ha^{-1} d^{-1}$, and the highest amounts registered were 348 $m^3 ha^{-1} d^{-1}$ in March 2005 and 479 $m^3 ha^{-1} d^{-1}$ in February 2010 (Fig. 3). Annual drainage accounted for 56–92 % of the total discharge leaving the field

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(Table S1). For 2001–2012 the average annual drainage was 68 % of total discharge to drainage plus groundwater (Table S1).

3.3 N-fertilisers

The time of application and amount of N-fertilisers applied to the crops were in line with present legislation (slurry) and the type of crop (slurry and commercial fertiliser) (Ministry of Food, Agriculture and Fisheries, The Danish AgriFish Agency, http://agrifish.dk/).

At the Faardrup field only commercial N-fertiliser was used. The time of application for the different crops is indicated in Fig. 4. For sugar beet, spring barley and maize, N-fertiliser was applied immediately before or after sowing. N-fertiliser was applied twice during the growing season for winter cover crops: for winter wheat the first occasion was at about growth stage BBCH 12–26 and the second occasion was about BBCH stage 23–32 and for winter rape it was at around sowing time and at growth stage 14–37. The red fescue received small amounts of fertiliser just after spring barley was harvested and at the beginning of the growing season. The application of N-fertilisers was not reflected in simultaneous/subsequent increases in nitrate-N concentrations in the drainage. A total of 16 applications of N were performed.

The time of N-application at Silstrup was as described for Faardrup. A crop of pea in 2001 received no N-fertilisation (Fig. 4). At Silstrup commercial N-fertiliser, injected slurry (pig/cattle) or a combination of N-fertiliser and slurry were applied to the crops. Application took place at BBCH stage 20–30 for both winter wheat (2004 and 2007) and red fescue (2010 and 2011). In 2001–2012, the application of commercial N-fertiliser (in total 13 times) and slurry (in total seven times) was not reflected in immediate increased N-concentrations in the drainage, except for fodder beet in 2008.

At Estrup, commercial N-fertiliser, injected slurry (cattle/sow/pig) or a combination of the two were applied to the crops, except the pea crop (Fig. 4). Application of fertilisers was performed at BBCH 20–30 for winter wheat and at about BBCH 30 for winter rape. In total, commercial N-fertiliser and slurry were applied 12 times and seven times

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respectively. In seven of the 11 years (2003, 2005, 2006, 2007, 2008, 2009, and 2010) the application of N-fertilisers was reflected in short-term increases (maximum concentration of 47 mg N L^{-1} in 2007) in drainage from the field.

3.4 Crop types

In Faardrup, the nitrate-N concentrations in drainage were often well above the European limit for drinking water supply (11.3 mg N L^{-1}) (Fig. 4). The drainage signature was characterised by a large range of nitrate-N concentrations (3–34 mg N L^{-1}). Prolonged high nitrate-N concentrations were measured below bare soil after harvesting winter wheat in 2000/2001, 2004/2005, and 2009, and after harvesting maize in 2006. Increasing nitrate-N concentrations were measured up to a BBCH growth stage of about 30 for winter rape (2002/2003, 2006/2007) and winter wheat (2007/2008). At later BBCH stages and up to harvest, nitrate-N concentrations decreased. Decreasing nitrate-N concentrations were also observed during the growing seasons of sugar beet (2001), spring barley (2002, 2006), maize (2005), and red fescue (2010/2011).

In 2001–2012, the nitrate-N concentrations in drainage at Silstrup varied between 1–34 mg N L^{-1}, but mostly stayed below the European limit for drinking water (Fig. 4). Prolonged, elevated nitrate-N concentrations were measured below bare soil after fodder beet (2000/2001, 2008/2009), spring barley (2001/2002), maize (2002/2003), and winter wheat (2004/2005, 2007/2008), whereas the nitrate-N concentrations in drainage after red fescue remained at a constant low level (1–2 mg N L^{-1}) (Fig. 4). Remarkably high (maximum 22 mg N L^{-1}) nitrate-N concentrations, well above the EU limit for drinking water, were recorded only following the winter wheat crop (2003/2004).

Except for some short-term peak concentrations, the N-concentration in drainage at Estrup was below the EU limit for drinking water (Fig. 4). This also applied to the periods with bare soil, where the nitrate-N concentrations remained almost constant, except following spring barley (2004/2005) when concentrations decreased and after winter wheat (2011/2012), when they increased. Concentrations of nitrate-N decreased

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during the growing seasons of fodder beet (2003), winter wheat (2007), and winter rape (2009).

3.5 Nitrate-N fluxes

At Faardrup, short-term N-leaching events, often in winter (or the start of the year), with daily fluxes of nitrate-N below 1 kg N ha^{-1} were common (Fig. 5). Some leaching events were in the range of 0.5–1 kg N ha^{-1} d^{-1} and very few events were in the range of 1–4 kg N ha^{-1} d^{-1}. The nitrate-flux signature was highly related to the drainage events, as indicated by the step-like shape in 2002/2003, 2005 and 2011 (Fig. 6). At this site, annual nitrate fluxes varied between 3 and 24 kg N ha^{-1} and made up the equivalent of 2–19 % of the annual applied N-fertilisers (Fig. 7). The total nitrate flux for 2001–2012 in drainage was 142 kg N ha^{-1} and in this period 1493 kg N ha^{-1} was applied as N-fertilisers (Table 3).

Most nitrate-N leaching events in 2001–2012 at Silstrup took place during the autumn and winter, and often the daily fluxes were below 1 kg N ha^{-1}. Only a few were in the range of 1–2 kg N ha^{-1} and were rarely above 2 kg N ha^{-1} (Fig. 5). Large and lasting drainage (2002, 2004, 2006/2007, 2008, and 2009/2010) coincided with high N-fluxes out of the field (Fig. 6). The annual export of nitrate-N from the field with drainage varied between 3–32 kg N ha^{-1}, equivalent to 2–33 % of the annual applied N-fertilisers (commercial fertilisers and slurry) (Fig. 7). For the period 2001–2012 the total nitrate-N leaching from the field was 153 kg N ha^{-1}, as compared to the total application of 1524 kg N ha^{-1} (Table 3).

Leaching from Estrup was present throughout the year, often with daily nitrate-N fluxes of below 1 kg N ha^{-1}, and only above 1 kg N ha^{-1} during a few events (Fig. 5). The drainage signature at Estrup, with a long drainage period and renewable pool of crop-generated available organic matter with low nitrate fluxes, made the cumulated N-leaching curve very smooth, with only a few small steps (Fig. 6). The annual nitrate-N leaching was 13–32 kg N ha^{-1}, the equivalent of 8–22 % of the total amount of N applied

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to the field (Fig. 7). In 2001–2012 the total loss with drainage was 205 kg N ha^{-1} and the total N-application was 1563 kg N ha^{-1} (Table 3).

4 Discussion

4.1 Climate

The average air temperature at the three locations was approximately the same throughout the years studied. The maximum temperatures were measured in June to August and the minimum in December to February. The almost identical temperature regimes made evaporation vary only slightly between the three fields and hence groundwater recharge was lowest in Faardrup where there was the least precipitation. The low groundwater recharge at Faardrup generated a higher concentration of nitrates in the water leaving the root zone from the different crops and from bare soil than at the two rainier locations of Silstrup and Estrup. Due to the low recharge and despite Faardrup receiving the lowest total amount of N as well as in a form readily available to plants, concentrations of nitrate-N in drainage out of the field remained highest. At Silstrup and Estrup much higher precipitation managed to keep the average concentration of nitrate-N below the EU limit for drinking water.

4.2 Hydrological setting

The drainage signatures were significantly different at the three fields, each representative of its own type, due to the local climatic and hydrological conditions. At Faardrup, where there is low precipitation and recharge and a long-lasting deeply located groundwater table, drainage runoff was short-lived, commenced late (middle of winter) and was of low intensity. Compared to the other two locations, Silstrup had a medium precipitation and discharge. The groundwater table was located deep for a long period of time, whereas drainage lasted longer (often starting in autumn) and was of a higher intensity. At Estrup, where there is the highest precipitation and recharge as well as a shallow and highly dynamic water table, drainage occurred most of the year, often at a low intensity. The different drainage signatures also led to differences in the total nitrate-N leaching for 2001–2012, with the least drainage leaching at Faardrup with 142 kg N ha^{-1}, medium leaching at Silstrup with 153 kg N ha^{-1}, and largest leaching at Estrup with 205 kg N ha^{-1}. Drainage mainly occurred when a water table was close to the surface. Drainage was only observed a few times at Silstrup (e.g. July 2001 and 2002, May 2003, and October 2007), when the groundwater table was far below drainage depth, due to preferential flow. This transport may rapidly take chemicals from the surface to the tile drain system (Kladivko et al., 1999). The combination of site-specific climatic and hydrological conditions resulted in far greater drainage at Estrup (average 68 % in 2001–2012) than at Faardrup (40 %) and Silstrup (43 %), providing the greatest input to groundwater at the latter two fields.

Besides the transport of nitrate-N in drainage out of the fields, the prevailing hydrological conditions also strongly influenced the potential for denitrification of nitrate-N released from decaying material such as plant parts and bacteria and other soil fauna and flora. The shallow water table at Estrup made the potential for in-situ denitrification much greater here than at Faardrup and Silstrup, where a deep water table and vadose conditions impaired the presence of the oxygen-free conditions essential for the denitrification process to occur. Under these conditions, in-situ denitrification would be limited to oxygen-free micro-environments.

4.3 N-fertilisers

Only at Estrup with its shallow and highly dynamic groundwater table were the applications of N-fertilisers (commercial as well as slurry) reflected in the concentration of nitrate-N, but only as a short-term increase in the nitrate-N concentration after application. Even though the applications of N-fertilisers at Faardrup and Silstrup were performed at similar plant growth stages, no immediate effects on nitrate-N concentrations were observed. This applied to both commercial N-fertilisers and injected slurry.

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This may be because most of the N-applications were performed just around the time of sowing or at the beginning of the growing season when the crops efficiently use up available nitrate-N. It therefore seems that current regulations concerning the timing of N-application – often in spring – help to reduce the immediate impact on drainage quality. Therefore changing from autumn to spring N-application for maize improves water quality in tiled-drained catchments (Gentry et al., 2014).

4.4 Crop types

The results from all three fields confirmed that the choice of crops and crop rotation had a significant effect on the leaching of nitrate-N through the drains, primarily due to their different growth periods. Thus, it is clear that crops with a long growing season (sugar beet, red fescue, winter rape and winter wheat) help to reduce the concentration of nitrate-N compared to crops with a short growing season (maize, spring barley, and pea) and thereby leaving the land without vegetation for a longer period of time. Red fescue used the applied N-fertilisers most efficiently, and thereby lowered the concentration of nitrate-N to about 1 $mg\,N\,L^{-1}$. Since crops with a short growing period lead to bare soil at times of high air (and soil) temperatures, this favours mineralisation and the release of nitrate-N that can percolate to the tile drain system or groundwater when there is no green cover in winter months (Premrov et al., 2014). Pea in rotation with wheat at Estrup seemed not to increase the concentration of nitrate-N at Estrup (2001/2002), whereas at Silstrup the concentrations increased markedly (2003/2004), which was similar to observations by Beaudoin et al. (2005). It was not possible to demonstrate a first flush of nitrate-N in the first water entering the tile drain systems.

4.5 Nitrate-N concentrations

The nitrate-N concentrations in drainage exhibited annual and seasonal variability over the 11 years of monitoring. The final nitrate-N concentrations in drainage were governed by multiple factors, of which climate conditions (precipitation and evaporation)

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and types of crop were the most significant. Thus, the low precipitation and percolation at Faardrup seemed to be the governing factors behind the location often having the highest nitrate-N concentration in the drainage even though it had the lowest application of N-fertilisers. Nitrate-N concentrations at Faardrup for most crop types exceeded the EU limit for drinking water. The monitoring highlighted that crop rotation with crops that have long growing seasons, e.g. red fescue, winter rape and winter wheat, efficiently reduced the pool-leachable nitrate-N. Reduced nitrate-N loss in drainage with cover crops has also been recorded by Drury et al. (2014) when planting a winter wheat cover crop in a cool, humid agricultural soil. The concentrations of nitrate-N at Silstrup and Estrup were below the average concentration of 18 mg N L^{-1} measured in drainage from 15 systematic tile-drained Danish agricultural clay till areas (3–22 ha) in 1971–1981 (Hansen and Pedersen, 1975, 1983).

Unlike at Faardrup, the nitrate-N concentrations at Silstrup and Estrup were often below the EU drinking water limit. Even though the lowest overall nitrate-N concentrations were recorded at Estrup (highest precipitation), the lowest nitrate-N concentrations were measured at Silstrup under a crop of red fescue that efficiently took up all nitrate-N available.

4.6 Nitrate-N fluxes

The results from 2001–2012 showed that the nitrate-N losses were the product of nitrate-N concentrations in the flowing water, and that the amount of water (drainage) was essential for the total impact on the aquatic environment. Leaching of nitrate-N from Faardrup and Silstrup with a deeply located groundwater table during the summer was concurrent with d of high drainage. At Estrup, where the groundwater table is closer to the surface, transport of nitrate-N to the aquatic environment was almost continuous. The annual nitrate-N losses to drainage ranged from 3 to 32 kg N ha^{-1}, with the lowest after winter rape at Faardrup and the highest after winter wheat and rape at Silstrup and Estrup respectively. However, despite major differences in climate, hydrological pattern and amounts of N-fertilisers applied, the average nitrate-N losses for

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2001–2011 were between 13 and 19 kg N ha^{-1}, equivalent to 10–13 % of the amount applied, with the highest losses at Estrup. This was below the 25 % found in a long-term study by Lucey and Goolsby (1993). The losses in kg N ha^{-1} were within the range of 10 and 29 kg N ha^{-1} reported for 15 Danish clayey till agricultural areas monitored between 1971 and 1980 (Pedersen, 1983). The average nitrate-N loss for the 15 areas was 22 kg N ha^{-1} and therefore higher than the 15 kg N ha^{-1} on average for the three fields in the present study. The annual nitrate-N leaching at the three fields fell within the typical range for most European and North American research studies, even though nitrate-N leaching in some studies has been up to 100 kg N ha^{-1} (Randall et al., 2008) and up to 105 kg N ha^{-1} for poorly drained loess soils (loam soils) in Indiana, US (Kladivko et al., 1999).

Due to longer periods of high water saturation of the layers close to the surface, including at times of high air (and soil) temperatures and renewable inputs of surface-derived bioavailable organic carbon in the top two metres (Pabich et al., 2001) e.g. from injected slurry, crop material and roots, it was expected that the in situ denitrification process would be more efficient for nitrate-N attenuation at Estrup than at Faardrup or Silstrup, where most of the year the groundwater table is down to about a depth of 4 m.

5 Summary and conclusions

To the authors' knowledge this study presents the first long-term monitoring (11 yr) of nitrate-N concentrations and fluxes in drainage from well-defined tile-drained fields in Denmark. Data collected simultaneously on climate (precipitation and air temperature), water table, crops (types and growth stage) and N-fertilisers (type and time of application) were collected in 2001–2012 at three fields across Denmark. The annual average air temperature and evaporation were around the same in all fields, but the average annual precipitation varied between 685 mm yr^{-1} (Faardrup) at the lowest to 1089 mm yr^{-1} at the highest (Estrup). Major differences in drainage nitrate-N concentrations were identified. Most often the highest concentrations were measured in drainage

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from the low precipitation field, where concentrations were often above the European limit for drinking water irrespective of whether the field was with or without crop cover. At the two other fields the nitrate-concentrations in drainage often remained below the EU limit. However, different types of crops strongly influenced N-concentrations, with the lowest nitrate-N concentrations during and after red fescue and the highest concentrations after a pea crop or crops with a short growing season followed by bare soil. Nitrate-N fluxes out of the fields were primary controlled by the site-specific hydrological setting (drainage) and only to a minor extent by the nitrate-N content in the drainage. The nitrate-N flux signature of the two fields with deeply located groundwater tables at times and only short and medium-length drainage periods showed major nitrate-N leaching events that were concurrent with intense drainage, whereas more even nitrate-N fluxes were obtained from the field with longer drainage periods. The total impact on the aquatic environment in 2001–2012 due to drainage losses varied between 142 and 205 $\mathrm{kg\,N\,ha^{-1}}$, equivalent to 10–13 % of the amount of N-fertilisers applied. In fields with a shallow vadose zone as well as lengthy periods of water saturation, a renewable source of organic matter from crop residues may make the denitrification processes much more efficient, and thereby contribute to lower nitrate-N concentrations and nitrate-N fluxes in drainage. The time at which drainage out of the field occurs may also influence the potential efficiency of post-treatment of drainage by agricultural engineering, e.g. in small constructed wetlands where the effectiveness due to microbial processes and plant growth is highly temperature dependent. Here, as at Estrup, long-term leaching of nitrate-N, including at higher temperatures, presented the best possibilities for post-treatment of drainage to reduce the impact of nitrate-N, whereas the short-term leaching of nitrate-N at Faardrup at low temperatures presented limited potential of post-treatment or in-situ treatment due to the very short period of water saturation at low temperatures. The documented differences in nitrate-N fluxes and concentrations at a local scale reveal some of the future challenges that need addressing when regulating for N-fertilisers by field size, such as in the regulation already proposed. N-regulation cannot be based on a single factor, but has to take a combination of field-specific factors into consideration, including climate (temperature and precipitation pattern), crop selection, crop-related organic matter supply, drainage and hydrogeology in nitrate-N loss to surface water as well as groundwater.

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Table 1. Precipitation (P), evaporation (E), drainage discharge (D) and groundwater discharge (G) for the agrohydrological year (June–June) for 2001–2012 for the Faardrup, Silstrup, and Estrup fields.

Field	P	E	D	G	$D+G$	$D/(D+G)$	D/P
	$mm\,yr^{-1}$					%	
Faardrup	685	459	95	131	226	43	13
Silstrup	943	472	188	283	471	40	20
Estrup	1089	476	421	196	617	68	39

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Table 2. Key parameters for the three fields according to Lindhardt et al. (2001).

Field	Faardrup	Silstrup	Estrup
Size of field (ha)	2.3	1.7	1.3
Slope (%)	1–3	1–2	0–1
Soil type (USDA)	Argiudoll Hapludoll Vermudoll	Argiudoll Hapludoll	Argiudoll Glossudalf
Drainage status	Moderately well drained	Moderately well drained	Moderately well drained
Depth of tile drains (m)	1.1	1.1	1.1
C in Ap (0–0.2 m) (%)	1.4–1.5	1.6–2.0	1.6–3.2
C below Ap (0.2–6 m) (%)	0.06–0.23	0.06–2.1	0.1–50
Clay in Ap (0–0.2 m) (%)	15–16	18–27	10–20
Clay below Ap (0.2–6 m) (%)	16–37	18–58	1–65
Depth to calcareous zone (m)	1.5	1.1	1–4
$CaCO_3$ (%) (0–6 m)	0–21	0–46	0–82
Age of sediments	Late Weichselian glaciation	Late Weichselian glaciation	Saalian glaciation
Landscape	Till plain	Till plain	Till plain
Geology	Homogenous	Dislocated structure	Complex structure

Table 3. Crops and winter-cover crops (in bold), crop rotation, types of N-source (F: fertilisers; C: cattle manure, S: sow manure and P: pig manure), and the amount of N-fertilisers ($kg N ha^{-1} yr^{-1}$) applied in 2001–2012 at Faardrup, Silstrup, and Estrup.

Year	Faardrup			Silstrup			Estrup		
	Crop	Source	Dose $kg N ha^{-1} yr^{-1}$	Crop	Source	Dose $kg N ha^{-1} yr^{-1}$	Crop	Source	Dose $kg N ha^{-1} yr^{-1}$
2001	Sugar beet	F	110	Spring barley	F	118	Peas **Winter wheat**	–	0
2002	Spring barley **Winter rape**	F	125	Maize	F, C	163	Winter wheat	F	147
2003	Winter rape **Winter wheat**	F	145	Peas **Winter wheat**	–	0	Fodder beet	C	169
2004	Winter wheat	F	154	Winter wheat	F	170	Spring barley	F	105
2005	Maize	F	129	Spring barley **Winter rape**	F, P	167	Maize	F, S	164
2006	Spring barley **Winter rape**	F	130	Winter rape **Winter wheat**	F, P	96	Spring barley **Winter wheat**	F	112
2007	Winter rape **Winter wheat**	F	151	Winter wheat	F	162	Winter wheat **Winter wheat**	F	178
2008	Winter wheat	F	156	Fodder beet	F	244	Winter wheat	F	180
2009	Sugar beet	F	110	Spring barley **Red fescue**	F, P	223	Spring barley **Winter wheat**	P, S	167
2010	Spring barley **Red fescue**	F	179	Red fescue	F	58	Winter rape **Winter wheat**	F	181
2011	Red fescue	F	104	Red fescue	F, P	123	Winter wheat	F, S	160
Total Yearly average			1493 136			1524 139			1563 142

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Figure 1. Map of Denmark showing the locations of the three clay till fields: Faardrup, Silstrup, and Estrup (Lindhardt et al., 2001).

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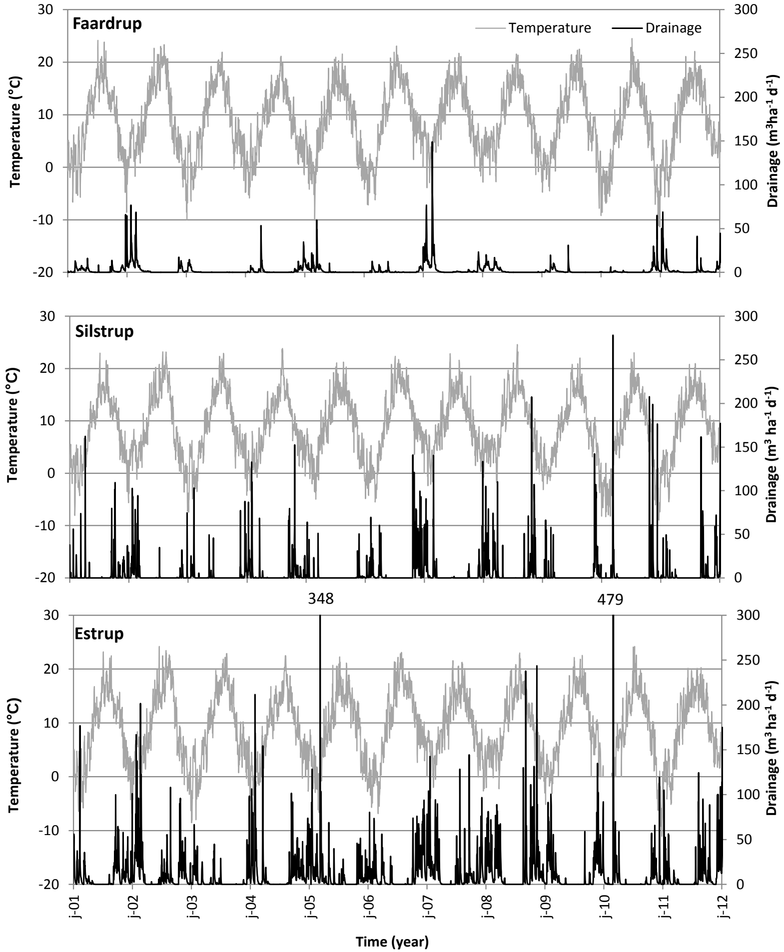

Figure 2. Average air temperature (average of min. plus max.) and drainage in 2001–2012 at Faardrup, Silstrup, and Estrup.

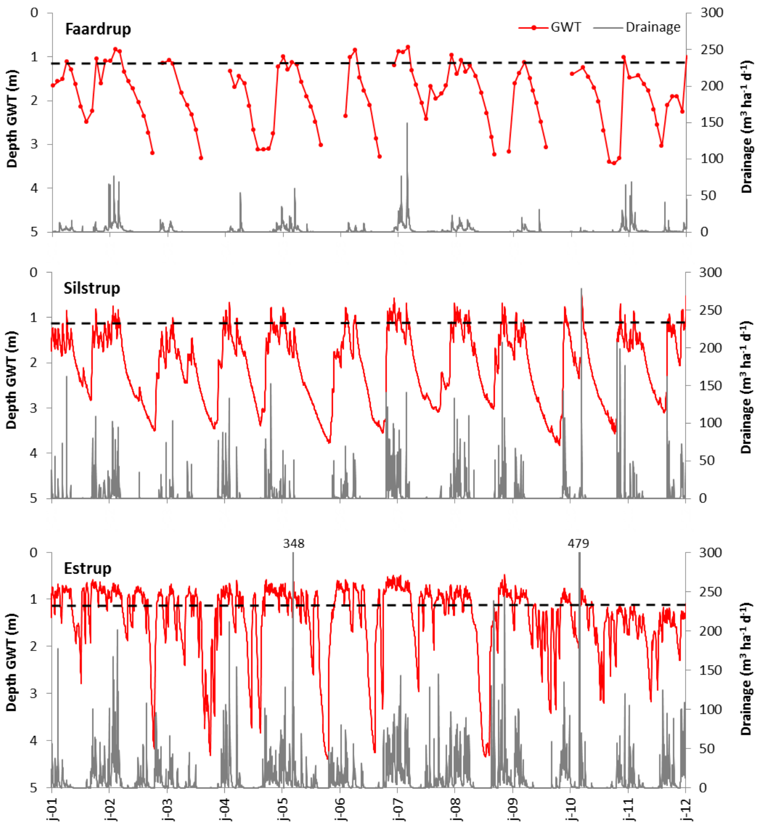

Figure 3. Drainage and depth to groundwater table (GWT) in 2001–2012 at Faardrup, Silstrup and Estrup. The black dashed lines indicate depth of tile drains.

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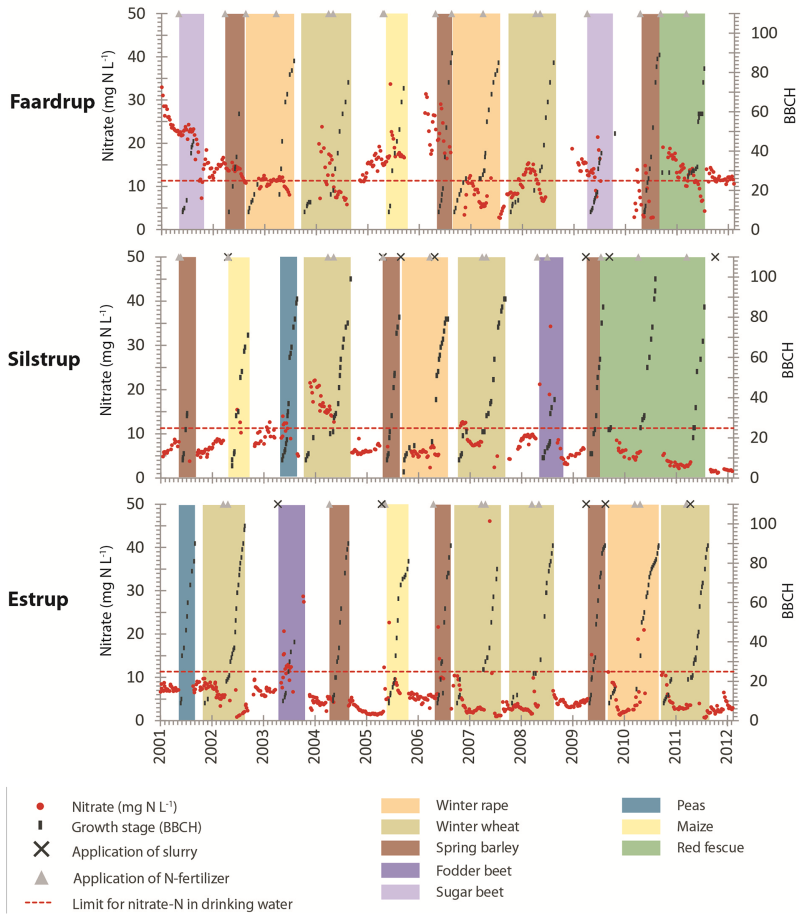

Figure 4. Crop type, plant growth stage (BBCH), application of commercial fertiliser and injection of slurry, and concentration of nitrate-N ($mg\,N\,L^{-1}$) in drainage at Faardrup, Silstrup, and Estrup.

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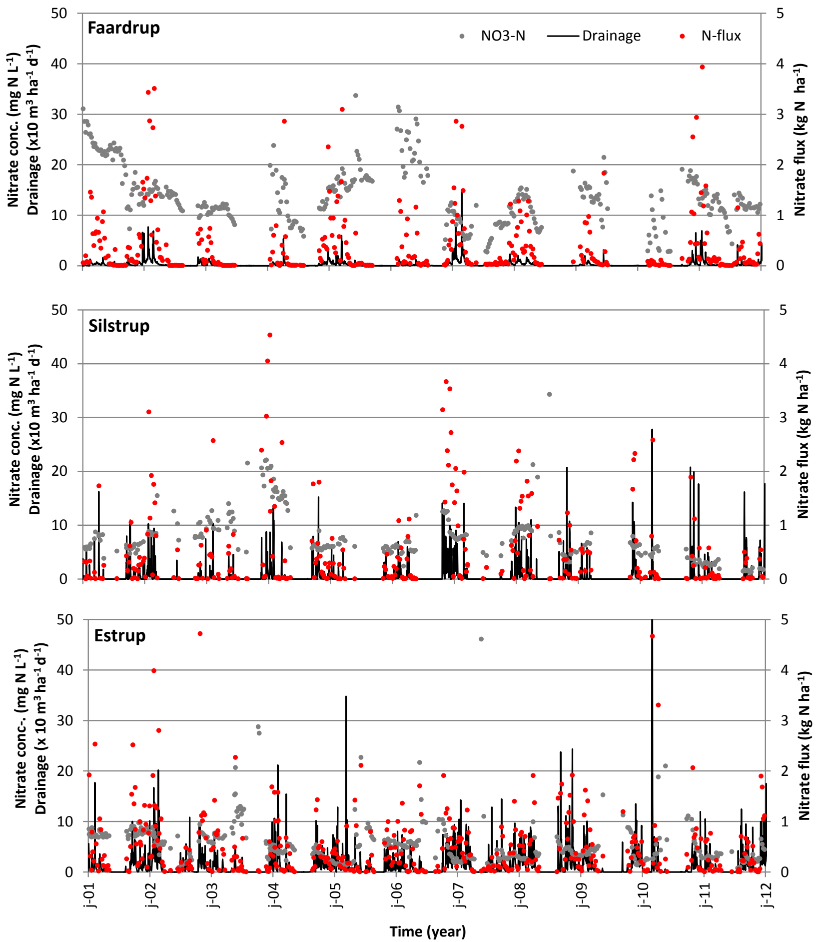

Figure 5. Concentration of nitrate-N and nitrate-N leaching in drainage 2001–2012 at Faardrup, Silstrup, and Estrup.

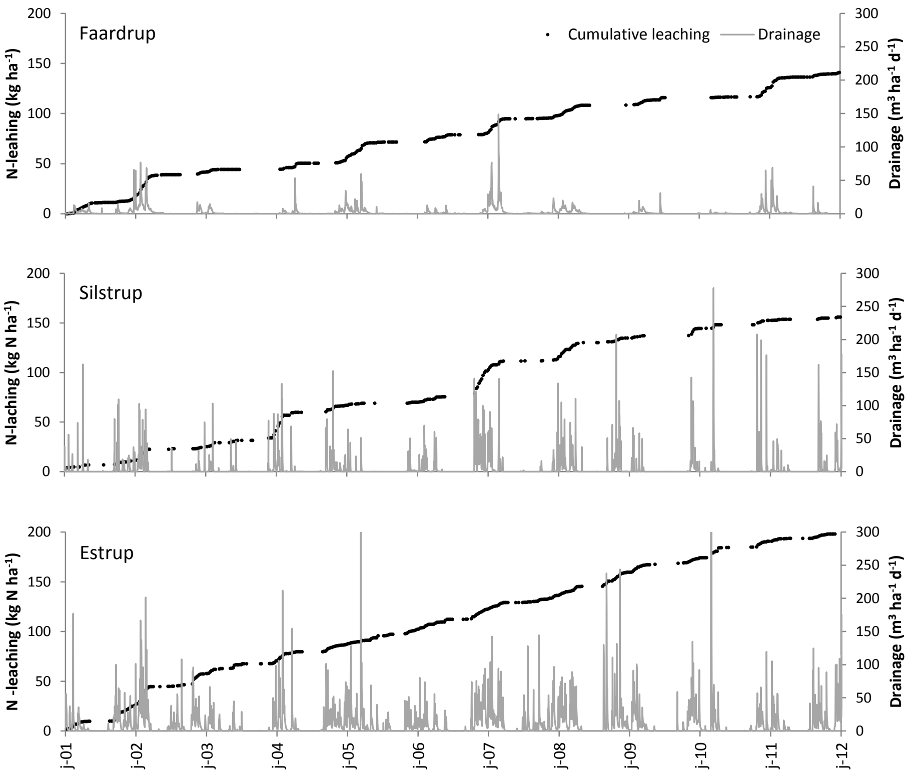

Figure 6. Cumulative nitrate-N leaching ($kg\,N\,ha^{-1}$) and drainage in 2001–2012 at Faardrup, Silstrup, and Estrup.

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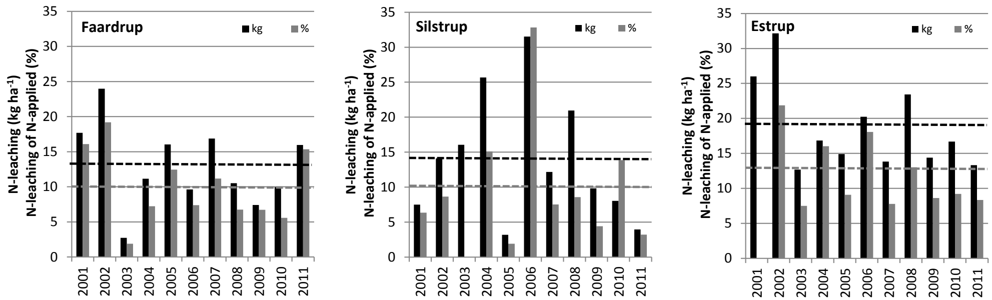

Figure 7. Nitrate-N in drainage in mass ($kg\,N\,ha^{-1}$) and of applied N (%) (commercial N-fertilisers plus slurry) for the years 2001 to 2011 at Faardrup, Silstrup, and Estrup. The black dashed line indicates the average annual N-leaching in 2001–2012 and the grey dashed line is the average nitrate-N leaching of applied N in 2001–2012.