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THE ENVIRONMENT***

GEUS

Department of Geochemistry
Ref. VE

Journal: HESS

Att. Prof. dr. F.C. (Frans) van Geer

29th June, 2015

Re.: Manuscript HESS-2014-524

Dear Prof. dr. F.C. (Frans) van Geer,

Please find enclosed the revised version of our manuscript *“Long-term monitoring of nitrate-N transport to drainage from three agricultural clayey till fields”*

We have addressed and carefully considered the comments by Reviewer 1 and 2, and made the suggested revisions and modifications where we find them appropriate. Altogether we believe the manuscript with the modifications has improved with the revisions made, and we hope that you will consider the revised manuscript for publication.

The responses to the comments are enclosed in separate listings.

Sincerely,
Vibeke Ernstsen

Enclosed:

- The revised manuscript *“Long-term monitoring of nitrate transport to drainage from three agricultural clayey till fields”*
- Response to the comments of Reviewer 1 and 2.

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The reviewer comments are marked in italic, and our response is given in plain text.

REVIEWER 1

This paper describes an 11 year field experiment monitoring water and nitrate fluxes in tile drains of three field throughout Denmark. The long monitoring period with detailed nitrate measurements and the combination of discharge, nitrate, fertilizer input, crop growth stages, and agricultural practices make this a very interesting and valuable dataset.

With this dataset the authors aim to provide insight in the important factors that need to be taken into account when legislation of nitrate leaching is scaled-down to the field scale.

In the manuscript the authors meticulously describe their data in clear English, which I appreciate. I thus also have very little comments for this manuscript.

1R1: *However after reading the manuscript I'm left with the feeling: "What to do with all this data?". The authors provide no outlook to how this data can be used to down-scale legislation to the field scale. I would appreciate if the authors could provide/speculate on this outlook more. Is it based on these measurements, in their opinion, possible to downscale legislation to the field-site?*

The manuscript has been revised. It describes now the representativeness of the three fields. Average air temperatures under drainage (Table 5), average number of days per year with drainage for each of the three fields, drainage intensities, and how the outcome of this study may be used for future N-regulation have been included in the manuscript.

1R2: *Or is the variability too large and too complex to come up with sensible field scale target values for N (could we ever make a model that produces sensible/realistic target values?)*

Application of the data from the three fields in the future N regulations is now addressed in the manuscript.

1R3: *And how would these target values look like? One annual value for flux or average concentration, or even seasonal values for flux and concentrations?*

On-field and of-fields regulation is now discussed in the manuscript.

1R4: *What are alternatives?*

Obvious water management tools applied in this study are discussed.

Specific comments:
Abstract:

1R5: *If you put Nitrate leaching data in the abstract I would uses Kg N ha^{-1} Year^{-1}. This unit can more easily be compared to other sites.*

Annual leaching data are now expressed as kg N ha^{-1} yr^{-1}.

1R6: *I don´t understand line 17 Input had short-term and low intensity drainage?*

"and fertiliser input" has been deleted.

1R7: *Page 641 Line 16: outcome of what?*

The sentence has been rewritten – it was unclear!

1R8: *Page 647 You don´t report the days with drainage and days with groundwater lower than 2.5m for Faardrup. It is nicer to keep the same format/data for each site.*

We do agree with the reviewer in preferring the same format/data for measurements of the ground water table for all three fields. Nonetheless we cannot provide daily values for Faardrup as for the two other field (Silstrup, Estrup) and have to settle with monthly measurements.

1R9: *Page 654 line 23 d?*

“d” has been corrected to days.

1R10: *Page 654 line 25: if you report annual values I think it is best to also use units year^{-1}to prevent misunderstanding. This throughout your manuscript, figures and tables. I sometimes struggled to find out if fluxes where per year of for the entire period.*

Annual leaching data are now expressed as kg N ha^{-1} yr^{-1} throughout your manuscript, figures and tables.

Recommended references:

1R11: *Rozemeijer, JC., Y Van der Velde, FC Van Geer, MFP Bierkens, HP Broers 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.*

Van der Velde, Y., JC Rozemeijer, GH de Rooij, FC van Geer, HP Broers, 2010. Fieldscale measurements for separation of catchment discharge into flow route contributions. Vadose Zone Journal 9 (1), 25-35. Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 639, 2015.

The references: Rozemeijers et al. (2010) and Van der Velde et al. (2010) have been included.

REVIEWER 2

This paper reports fluxes and concentrations of nitrate in tile drains from three fields with contrasting hydrological regimes in Denmark over an 11-year period. Hydrological and climatic variables were also measured, as were details on cropping, fertilisers, slurry inputs and other aspects of agricultural practice. The authors took care to ensure that each sampling point drained a single field with a single crop at any one time. This and the long sampling period makes this a very valuable dataset, since drained clay soils like these are an extremely common land use in the wetter areas of Europe and elsewhere, and contribute significantly to the nitrate load of rivers. The paper thus addresses relevant scientific questions and presents new data. The methods used are clearly described, and the English is generally good (see below for a few suggestions for improvement).

I think, however, that the paper needs some more work on the results before it is a suitable quality for HESS. There is a lot of information in these results which could be used better, but the authors give no indication that they are proposing to take the analysis further. At present, the paper contains some measurements of nitrate concentration for 3 sites which differ in various ways, but the main driver of the difference in responses seems to be rainfall and the resulting hydrological relationships.

2R1: *The main difference in response is that the high rainfall site has the greatest mass flux of nitrate, and the greatest flux as a percentage of inputs, but lower concentrations. The low rainfall site has high concentrations but a lower mass flux. There may be differences in nitrate leaching due to cropping regime, but these are not systematically explored, just presented in a single figure. There is no discussion of how or whether the 3 sites could be generalised to tile-drained fields in general, which leaves the wider significance of the paper in doubt. Faced with these results, my instinct would be to try and fit a simple model to get a feel for the extent to which the results could be generalised rather than just being characteristic of these 3 fields.*

The manuscript has been revised. It now describes the representativeness of the three fields. The importance of the cropping regimes on nitrate leaching especially the catch crops and their ability to reduce the nitrate leaching to drainage is now discussed. The potential side effect of using catch crops is addressed. It has been stated that the crop regimes at all three fields in 2001-2011 were without catch crops.

2R2: *It would be helpful if the authors would define some hypotheses which they could use their data to test. For instance, that nitrate loss from the lower rainfall site is dependent on a few large rainfall events whereas that from the high rainfall site occurs over the whole spectrum of rainfall intensities. This appears to be true from Fig. 6, but it needs to be quantified. Other hypotheses might be that that N loss is due to an interaction between rainfall and stage of crop growth, or N application date or rate, or the crop being grown. Are there differences between crops in N retention or release? The information is shown in Fig. 4, but needs to be quantified and preferably tested for differences statistically.*

The aim of the study has been rewritten and expanded. Main conclusions from Gastal and Lemaire (2002) on N uptake have been included.

2R3: *The authors are right is saying that field-scale information is necessary for differentiation of N regulation, but they are missing an opportunity here to show how this information can be quantified and used for regulation. So I agree with Referee 1 that the authors need to show how to use their data for this purpose. The Abstract concludes that ". . .local hydrogeological conditions need to be taken into account in a differentiated N-regulation of agricultural fields. . .".*

A description on how the outcome of this study can be used in future N legislation is added together with an initial guideline for whether it is possible to N regulate on-field or off-field (regional-scale). Table 5 showing daily average air temperatures (5°C for "biological zero", 10 °C, and 15 °C) at days with drainage has been added.

2R4: *Would they say that it would be beneficial to restrict N applications on high (hydrologically-effective) rainfall sites in order to reduce N loads on rivers?*

A recommendation about applications of N fertilisers in regard to weather conditions is included.

2R5: *Or to restrict N application on low rainfall sites to reduce nitrate concentrations?*

Profitable crop production at reduced input of N is now added to the manuscript.

2R6: *Or to restrict applications at certain times of year or under certain weather conditions?*

See 2R4.

2R7: *Should certain crops be avoided in some situations? Merely saying it needs to be done lacks credibility if not supported by data from the paper, and is not helpful to regulators.*

Please see our answer to 2R1. The word "significant" is removed.

2R8: *As well as taking the data analysis further, the authors need to consider how well the data support some of their conclusions. There is some discussion (e.g. p. 655 l.15) of how denitrification would be expected to be more effective at the wettest site (Estrup), yet this is the site with the lowest percentage nitrate retention. Why is this? Is there any evidence that denitrification is occurring at all (e.g. from the seasonal pattern of nitrate concentration, or in relation to temperature)? The authors need to take a more critical look at their data in general.*

Table 5 with discussions of its content has been added to describe drainage in relation to different air temperature intervals. This gives an indication of the potential for denitrification both on-field and out-of-field.

2R9: *The Abstract is rather unclear and does not do the paper justice. In particular it is not obvious that the descriptions (A), (B), (C) in line 16 onwards represent the three fields referred to in line 11. Transport fluxes should have a time dimension (kgN/ha.yr?) here and throughout the paper. The main results need to be stated more clearly, as well as the main differences between the sites (i.e. hydrologically-active rainfall).*

The abstract has been revised.

Technical Comments and Queries:

2R10: *p. 644 l.12 Define Ap for those not familiar with this terminology.*

The definition of a Ap-horizon has been added.

2R11: *p. 646 l.18 on. The nature of temperature variation at the sites is clear from Fig. 2, but this description of temperature ranges gives an impression that the temperature regime is more severe than it actually is. I would recommend using standard metrological statistics e.g. mean temperature, mean seasonal maximum and minimum temperatures etc. to characterise the temperature regime. A meteorologist would advise.*

Average min., average max., and average mean air temperatures for each of the three fields are given in Table 3. Additionally the daily air temperature span (from min to max) for temperatures above zero degree Celsius has been added to Figure 2.

2R12: *p.647 l.10, Fig. 3 etc. Water fluxes in m3/ ha.time would be better expressed in mm/time (1 m^3/ha = 0.1 mm). This will be a more familiar unit for hydrologists, and they can then be compared directly with the precipitation, evaporation and runoff fluxes in Table 1, Fig.3 etc.*

The dimension m^3 ha^{-1} has been changed to mm day^{-1} throughout your manuscript, figures, and tables.

2R13: *p. 645 l.9 and p.648 l.8 Does "commercial N-fertiliser"mean "inorganic N fertiliser"? Organic N fertilisers and even slurry are available commercially, so this distinction needs to be made.*

"commercial N fertiliser" has been changed into "inorganic N fertiliser".

2R14: *p.667 Fig. 4 What is the crop in the white areas of the graph?*

A white box has been included in the legend with the explanation "Bare soil".

Specific Comments and Corrections

2R15: *p. 642 l.11 Awkward phrase – suggest ". . .enhances crop yields on highly productive soils with poor natural drainage."*

The awkward phrase has been revised.

2R16: *p. 646 l.3 “filtered” for “filtrated”*
The word “filtered” has been changed to “filtrated”.

2R17: *p. 648 l.4 and elsewhere. No need for a dash between “N” and “fertiliser”. “N fertiliser” is correct.*

The dash between N and fertiliser has been removed throughout the manuscript.

2R18: *p. 656 l.7 “primary” should be “primarily”*

The word “primary” has been changed into “primarily”.

2R19: *p.657 l.14 This reference (“Commission. . .”) is out of alphabetical order.*

The reference (“Commission. . .”) is now in alphabetical order.

2R20: *p. 659 l.8 “Kladivko” should be “Kladikov” both here and where referred to in the text.*

The spelling “Kladivko” is in accordance with the spelling given in the paper. No change has been made.

2R21: *p. 667 Fig. 4 legend “BBCH” should be defined both here and in the text.*

“BBCH” has been defined both in the legend of Fig. 4 and more precise in the text.

Long-term monitoring of nitrate 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 required to sustain most modern crop production, but it 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 essential for introducing water management actions on-field or off-field and producing an optimal differentiated N-regulation in future. This study strives to provide such knowledge by evaluating on 11 years of nitrate-N concentration measurements in drainage from three subsurface-drained clayey till fields (1.3-2.3 ha) representing approximately 71 % of the surface sediments in Denmark dominated by clay. The fields differ in their inherent hydrogeological field settings (*e.g.* soil-type, geology, climate, drainage and groundwater table) and the agricultural management of the fields (*e.g.* crop type, type of N fertilisers and agricultural practices). The evaluation revealed three types of clayey till fields characterised by: (i) low net precipitation, high concentration of nitrate-N, and short-term low intensity drainage at air temperatures often below 5 °C; (ii) medium net precipitation, medium concentration of nitrate-N, and short-term medium intensity drainage at air temperatures often above 5 °C; and (iii) high net precipitation, low concentration of nitrate-N and long-term high intensity drainage at air temperatures above 5 °C. For each type, on-field water management actions, such as the selection of crop types and introduction of catch crops, appeared relevant, whereas off-field actions only seemed relevant for the latter two field types given the temperature-dependent reduction potential of nitrate off-field. This initial well-documented field-scale knowledge from fields that are representative of large areas in Denmark is a first step towards establishing a differentiated N-regulation for clayey till areas. Additionally, it

provide a unique starting point by identifying important parameters for future mapping of catchment-scale variations in nitrate concentrations and fluxes.

Comment [ve1]: 1R1, 2R3, and 2R9

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 the aim of protecting the aquatic environment and nature in general. Recently, the Danish Commission on Nature and Agriculture issued a report (The_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 agricultural sector, however, 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) and 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 has reduced the mean concentration by 50 % on an annual scale (Beaudoin *et al.*, 2005) and a winter cover of mustard has reduced the nitrate-N concentrations in temperate soils (Premrov *et al.*, 2014).

The installation of tile drains is a common agricultural water management practice for improving moisture and aeration conditions (Tiemeyer *et al.*, 2010; Van Der Ploeg *et al.*, 1999) in areas with shallow groundwater and seasonally perched groundwater tables. The presence of tile drains enhances crop yields on soils, which are highly productive and poorly natural drained, and helps reduce year-on-year variability in yields (Nangia *et al.*, 2010) by promoting earlier sowing and improving traffic ability. The drains remove water from the

Comment [ve2]: 2R15

land more quickly than under natural conditions and 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. 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) whereas denitrification processes may be common at temperatures above approximately 5 ˚C in the root zone with renewable source of bioavailable organic matter and restricted access of oxygen due to high water saturation or high microbial activity (Christensen *et al.*, 1990; Ernstsen *et al.*, 1998). Drainage decreases the possibilities of nitrate being denitrified or adsorbed by plants on-field (Gilliam *et al.*, 1999) and off-field, the temperature-drainage signatures are crucial for denitrification in natural and constructed wetlands. 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).

Comment [ve3]: 2R3

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 Denmark has been systematically tile drained, with horizontal spacing of 8-20 metres (Olesen, 2009) and a total length of around 750,000 km (Breuning-Madsen, 2010).

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 and catch 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, *e.g.* the nitrate uptake of field crops is highly variable in the course of a year and between crops as the N uptake and growth stage are very complex (Gastal and Lemaire, 2002), whereas other factors may be adjusted to minimise the N-loss for the benefit of the environment and farmers’ incomes.

Comment [ve4]: 2R2

To the authors’ knowledge, there has been limited documentation of nitrate-N concentrations and leaching *via* tile drain systems from field-size areas that have been 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; Pedersen, 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. To go from field scale to catchment scale, smaller-scale monitoring is important to provide an understanding of the ways in which field-scale processes influence catchment-scale discharge and water quality (Rozemeijer *et al.*, 2010; van der Velde *et al.*, 2010).

Comment [ve5]: 1R11

To be able to optimise the use of N in agriculture and minimise nitrate leaching to the aquatic environment, it is imperative to be able to identify a field’s natural ability to reduce nitrate. The aim of this study was twofold: (i) to provide detailed field-scale insight with regard to the impact of inherent conditions (air temperature, precipitation, and hydrogeological setting) and management (type of crops, crop development, amount and source of N, and time for application of N fertilisers) on nitrate transport to drainage obtained from long-term monitoring in three agricultural clayey till fields exposed to different climatic conditions; and (ii) to elaborate on the impact of such detailed insight on future N regulation and N management “on-field” and “off-field”

Comment [ve6]: 2R2

2 Material and Methods

2.1 Field descriptions

Three fields (Faardrup, Silstrup and Estrup) were selected to cover different types of clayey geological settings and climates, primarily expressed by the amount of annual precipitation (Fig. 1). The study sites are representative for about 71 % of the clayey surface sediments in Denmark, with Faardrup representing 30 %, Silstrup also 30 % and Estrup 11 % (Barlebo *et al.*, 2007). A summary of the main characteristics of each field is provided in Tables 1 and 2 (Lindhardt *et al.*, 2001; Rosenbom *et al.*, 2015).

Comment [ve7]: 1R1 and 2R2

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, the clayey till plain at Silstrup 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 15000 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 surface layer disturbed by cultivation (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 decreased 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) was 10-27 % and varied to six metres below the surface at between 1-65 % due to the heterogeneity of the clayey till. Postglacial 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 metres at Estrup, due to the much longer ongoing weathering processes. In the calcareous zone below, the $CaCO_3$ content varied between 21 % and 82 % in all three fields.

Comment [ve8]: 2R10

Subsurface tile drains were installed in the fields between the 1940s and 1960s. The drains were established at a depth of approximately 1.1 m 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 conventional practices in 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. No catch crop has been grown in any of the fields. Red fescue for grass seed production was grown in Faardrup and Silstrup, as well as peas in Silstrup and Estrup. Each year, the amount of N fertilisers 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}yr^{-1} at Faardrup, 139 kg N ha^{-1}yr^{-1} at Silstrup, and 142 kg N ha^{-1}yr^{-1} at Estrup (Table 3). There were considerable differences in the average annual N-application, ranging from 0 kg N ha^{-1}yr^{-1} for the pea crop to 223 kg N ha^{-1}yr^{-1} for spring barley undersown with red fescue. At Faardrup only inorganic N fertilisers were used, whereas at Silstrup and Estrup animal slurry was applied from time to time (Table 3).

Comment [aer9]: 2R1

Comment [ve10]: 2R14

2.3 Monitoring setup

The specific growth stages for the different crops were characterized using the BBCH scale (Meier, 2001), e.g., the BBCH growth stages for cereals: germination (00-09), leaf development (10-19), tillering (20-29), steam elongation (30-49), inflorescence emergence (51-59), flowering (61-69), development of fruit (71-77), ripening (83-89), and senescence (92-99) (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 m, 4.5-5.0 m, 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.

Comment [ve11]: 2R21

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).

Comment [ve12]: 2R16

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 average air temperatures between 8.8 °C and 9.0 °C for 2001-2011. During monitoring, the average minimum temperatures were 5.6-5.8 °C and the average maximum temperatures were 11.4-12.2 °C, with summer temperatures up to 30.4-32.1 °C and winter temperatures down to -14.1 °C and -19.5 °C (Fig. 2 and Table 4). 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 mm 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).

Comment [ve13]: 2R11

In 2001-2012, 49 %, 16 %, and 3.3 % of drainage at Faardrup was on days on which air temperatures were above 5 ˚C, 10 ˚C and 15 ˚C respectively (Fig. 2 and Table 5). At Silstrup 56 %, 12 %, and 0.3 % and at Estrup 58 %, 22 %, and 5.4 % of drainage occurred in the respective temperature categories (Fig. 2 and Table 5).

Comment [ve14]: 2R3

3.2 Hydrogeological setting

At Faardrup, monthly registration of the groundwater table at the edge of the field showed the overall pattern over the year, even though its full amplitude was not monitored as the filter had not been installed sufficiently deeply to register deepest water tables (Fig. 3). The water table approached the soil surface by the end of autumn and during winter, and dropped in spring, summer and early autumn to about 3.5 m depth or even deeper. During 2001-2012, the average daily drainage was 0.26 mm d^{-1} and max daily drainage was 14.9 mm d^{-1} during an average 88 days of drainage per year (Table 5). Typically, drainage was below 3 mm d^{-1} and rarely above 10 mm d^{-1} (Fig. 3). For 2001-2012, the average annual drainage was 43 % of total discharge to drainage plus groundwater (Table 1).

Comment [ve15]: 1R1,2R3, 2R12

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). During 2001-2011, the average daily drainage was 0.50 mm d^{-1} and max daily drainage was 27.8 mm d^{-1} during an average 86 days of drainage (Table 5). Often, the drainage events were above 5 mm d^{-1}, a few were up to 10 mm d^{-1}, with a maximum drainage

Comment [ve16]: 1R1 and 2R3

of 28 mm d^{-1} in March 2010 (Fig. 3). For 2001-2012 the average annual drainage was 40 % of total discharge to drainage plus groundwater (Table 1).

In Estrup, the groundwater table was highly dynamic and only located deeply for short periods. The lowest groundwater table (4.35 m) was in July 2008 (Fig. 3). On average for 2001-2012, the average daily drainage was 1.16 mm d^{-1} and max daily drainage was 57.8 mm d^{-1} during an annual average 243 days of drainage (Table 5). Daily drainage was often above 5-6 mm d^{-1}, in some cases up to 10 mm d^{-1}, and the highest amounts registered were 35 mm d^{-1} in March 2005 and 58 mm d^{-1} in February 2010 (Fig. 3). For 2001-2012 the average annual drainage was 68 % of total discharge to drainage plus groundwater (Table 1).

Comment [ve17]: 1R1 and 2R3

3.3 Management - N fertilisers and crop types

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

Comment [ve18]: 2R1

At the Faardrup field only inorganic N fertiliser was used (Table 3). 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 at about BBCH stage 23-32, while 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 the 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 (Table 3 and Fig. 4). At Silstrup inorganic N fertiliser, injected slurry (pig/cattle) or a combination of inorganic 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 inorganic 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, inorganic N fertiliser, injected slurry (cattle/sow/pig) or a combination of the two was applied to all the crops except the pea crop (Table 3 and Fig. 4). Application of fertilisers was performed at BBCH 20-30 for winter wheat and at about BBCH 30 for winter rape. In total, inorganic N fertiliser and slurry were applied 12 times and seven times 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 Nitrate concentrations

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. 2). 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} and rarely exceeded the European limit for drinking water (Fig. 2). 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. 2). 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. 2). 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 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 $ha^{-1}d^{-1}$ were common (Fig. 2). 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. 5) and a good correlation (R^2 = 0.83) between cumulated nitrate flux and drainage intensity in the time between water sampling (Fig. 6). In this field, annual nitrate fluxes varied between 3 and 24 kg N $ha^{-1}yr^{-1}$ 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 $ha^{-1}d^{-1}$. Only a few were within the range of 1-2 kg N $ha^{-1}d^{-1}$ and were rarely above 2 kg N $ha^{-1}d^{-1}$ (Fig. 2). Large and lasting drainage (2002, 2004, 2006/2007, 2008 and 2009/2010) coincided with high N-fluxes out of the field (Fig. 5), and increasing N-fluxes with increasing drainage cumulated for the time interval between sampling (R^2=0.60) (Fig 6). The annual export of nitrate-N from the field with drainage varied between 3-32 kg N $ha^{-1}yr^{-1}$, equivalent to 2-33 % of the annual applied N fertilisers (inorganic N 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 $ha^{-1}d^{-1}$, and only above 1 kg N $ha^{-1}d^{-1}$ during a few events (Fig. 2) and the correlation between the N-fluxes and drainage, cumulated between sampling, was R^2=0.55 (Fig. 6). 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. 5). The annual nitrate-N leaching was 13-32 kg N $ha^{-1}yr^{-1}$, the equivalent of 8-22 % of the total amount of N applied 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

For 2001-2012, the average air temperature at the three fields was approximately the same (8.8–9.0 °C) throughout the years studied. The maximum temperatures (30-32 °C) were measured in June to August and the minimum (-14.1 - -19.5°C) in December to February. Even though the average air temperatures varied only slightly between the three fields, air temperature during drainage was markedly different. At Faardrup, an often late drainage resulted in 51 % run-off at temperatures below 5 °C (below biological “zero”) whereas at Silstrup and Estrup most drainage (56 % and 58 %) was at temperatures above 5°C. At Estrup, with drainage taking place during about two-thirds of the year, 5.4 % of drainage was at temperatures above >15 °C. The field-specific temperature-drainage signature provides valuable input to future water management, including on-field and off-field N regulation.

Comment [ve19]: 1R2 and 1R4

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 nitrate-N in water leaving the root zone from the different crops and from bare soil than at the two other fields in 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 from this 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, with 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 (on average 88 days year^{-1}), commenced late (middle of winter), was at the lowest air temperature (51 % at <5 °C) and was of low intensity (average 0.26 mm d^{-1}). Compared to the other two fields, Silstrup had a medium precipitation and discharge. The groundwater table was located deep for a long period of time, whereas drainage (on average 86 days year^{-1}) often started in autumn at higher temperatures (56 % at >5 °C), and was of a higher intensity (average 0.50 mm d^{-1}). At Estrup, where there is the highest precipitation and recharge as well as a shallow and highly dynamic ground

Comment [ve20]: 1R6

water table, drainage occurred most of the year (on average 243 days year^{-1}), and often at high intensity (1.16 mm d^{-1}). 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 most 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 the drainage depth, due to preferential flow. This flow 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 in 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 for two thirds of the year, together with higher temperatures (58 % at >5 °C), 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.

Comment [ve21]: 2R8

4.3 N fertilisers

Only at Estrup, with its shallow and highly dynamic groundwater table, were the applications of N fertilisers (inorganic N fertilisers 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 inorganic N fertilisers and injected slurry. 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 crops efficiently use up available nitrate-N. Gentry *et al.* (2014) have found that changing from autumn to spring N-application for maize improves water quality in tiled-drained catchments.

It seems that current regulations concerning the timing of N application – often in spring – have helped to reduce the immediate impact of nitrate on drainage quality at fields like

Faardrup and Silstrup. At Estrup, however, leaching of nitrate could be reduced further if the time for N application is aligned with the weather conditions so that high intensity rainfall is avoided just after application.

Comment [ve22]: 2R4 and 2R6

4.4 Crop types

The results from all three fields confirmed that the choice of crops and crop rotation had an effect on the leaching of nitrate-N into drainage, 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 leave 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 leave soil bare (without winter cover crops or catch crops) at high air (and soil) temperatures, this favours mineralisation and the release of nitrate-N that can percolate to the tile drain system or groundwater 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).

Comment [ve23]: 2R7

4.5 Nitrate-N concentrations

The nitrate-N concentrations in drainage exhibited annual and seasonal variability over the 11-year monitoring period. The final nitrate-N concentrations in drainage were governed by multiple factors, of which climate conditions (precipitation and evaporation) and types of crop were the most significant. Thus, the low precipitation and percolation at Faardrup seemed to be the governing factors behind the field 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. Profitable crop production at reduced input of N fertilisers may be very difficult in these low rainfall areas, but the right choice of crops combined with growing of catch crops may be a solution for optimal N-management of such fields. The net outcome of catch crops, however, may lead to lower N-fluxes in drainage but higher nitrate concentrations due to the catch crop water uptake and hence lower ground water infiltration.

Comment [ve24]: 2R5

Comment [ve25]: 2R1 and 2R7

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 clayey till areas (3-22 ha) in 1971-1981 (Hansen and Pedersen, 1975; Pedersen, 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 days 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}yr^{-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 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 N ha^{-1}yr^{-1} and therefore higher than the 15 kg N ha^{-1}yr^{-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 reached 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, USA (Kladivko *et al.*, 1999).

Comment [ve26]: 1R9

Comment [ve27]: 1R5, 1R10

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 around a depth of four metres.

5 Summary and conclusions

To the authors' knowledge this study presents the first long-term monitoring (11 years) of nitrate-N concentrations and fluxes in drainage from well-defined tile-drained fields in Denmark. Data collected simultaneously on nitrate-N, drainage, climate (precipitation and air temperature), ground 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 y^{-1}(Faardrup) at the lowest to 1089 mm y^{-1} at the highest (Estrup). Major differences in drainage nitrate-N concentrations were identified. Most often the highest concentrations were measured in drainage 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 primarily controlled by the site-specific hydrological setting 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 kg N $ha^{-1}yr^{-1}$, 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 water management actions off-field, *e.g.* in natural or 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

Comment [ve28]: 2R18

temperatures, presented the best possibilities for off-field water management actions to reduce the impact of nitrate, whereas the short-term leaching of nitrate at Faardrup at low temperatures presented a limited potential of on-field or off-field water management actions 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 to be addressed when regulating for N fertilisers at field scale, such as in the regulation already proposed. Future N-regulation cannot be based on a single factor, but has to take a combination of field-specific factors into consideration, such as the inherent physical appearance and agricultural management of the fields. The long-term monitoring has revealed that the outcome of on-field or off-field water management actions could differ between fields with different hydrogeological settings and climatic conditions. This initial well-documented field-scale knowledge from three clayey till fields that are representative of large areas in Denmark is a first step towards establishing a differentiated N-regulation for such areas. A future challenge will be to obtain the necessary knowledge to cover all field types represented within a catchment (van der Velde *et al.*, 2010).

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Table 1. Precipitation (P), evaporation (E), drainage (D), and groundwater discharge (G) for the agrohydrological year (June-June) for 2001-2012 for the Faardrup, Silstrup and Estrup fields (partly after Lindhardt *et al.*, 2001).

Field	P	E	D	G	D+G	D/(D+G)	D/P
			mm y^{-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

Comment [ve29]: 2R12

Table 2. Key parameters for the three fields according to Lindhardt *et al.* (2001) and Rosenbom *et al.* (2015).

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. Annual average of minimum, mean, and maximum air temperatures for 2001-2011 at Faardrup, Silstrup and Estrup.

Comment [ve30]: 2R11

	Faardrup	Silstrup	Estrup
Average minimum air temperature (°C)	5.6	6.0	5.8
Minimum air temperature (°C)	-19.5	-14.5	-15.7
Average maximum air temperature (°C)	12.0	11.4	12.2
Maximum air temperature (°C)	31.3	30.4	32.1
Average mean air temperature (°C)	8.8	8.7	9.0

Table 4. Crops and winter cover crops (in bold), crop rotation, types of N-source (F: inorganic 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			1493			1524			1563
Yearly average			136			139			142

Table 5. Minimum (min.), maximum (max.) and average (avg.) daily drainage, average annual number of days with drainage, average air temperatures during drainage, and cumulated drainage, all 2001-2012 at Faardrup, Silstrup and Estrup.

Comment [aer31]: 2R3, 2R8

	Drainage				Average air temperature (˚C)				Drainage
Field	min.	max.	avg.	avg.	<5	≥5	>10	>15	2001-2011
	mm d^{-1}			days yr^{-1}	% of cumulated drainage				mm
Faardrup	0.1	14.9	0.26	88	51	49	16	3.3	961
Silstrup	0.1	27.8	0.50	86	44	56	12	0.3	2304
Estrup	0.1	57.8	1.16	243	42	58	22	5.4	4921

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

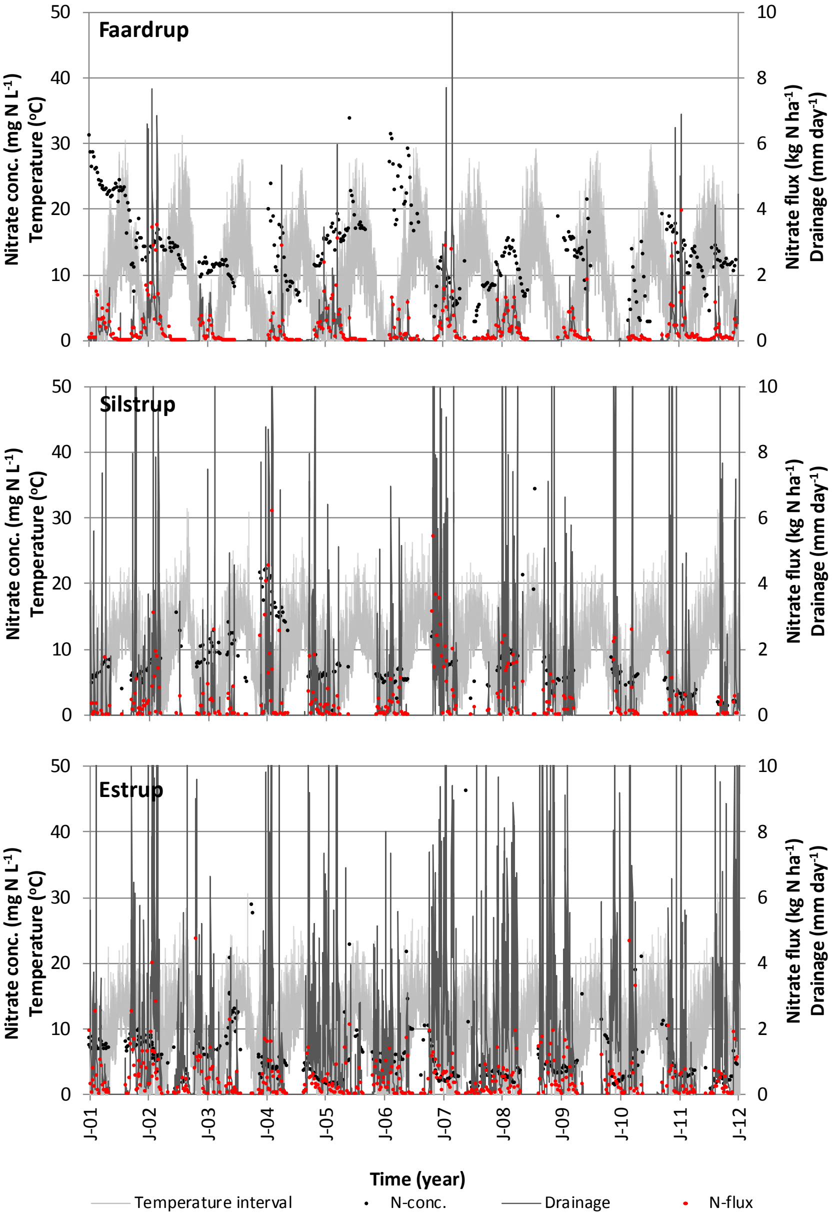

Figure 2. Concentration of nitrate-N, nitrate-N fluxes, drainage and the daily minimum-maximum temperature span for temperatures above zero degrees Celsius for 2001-2012 at Faardrup, Silstrup and Estrup.

Comment [ve32]: 2R11

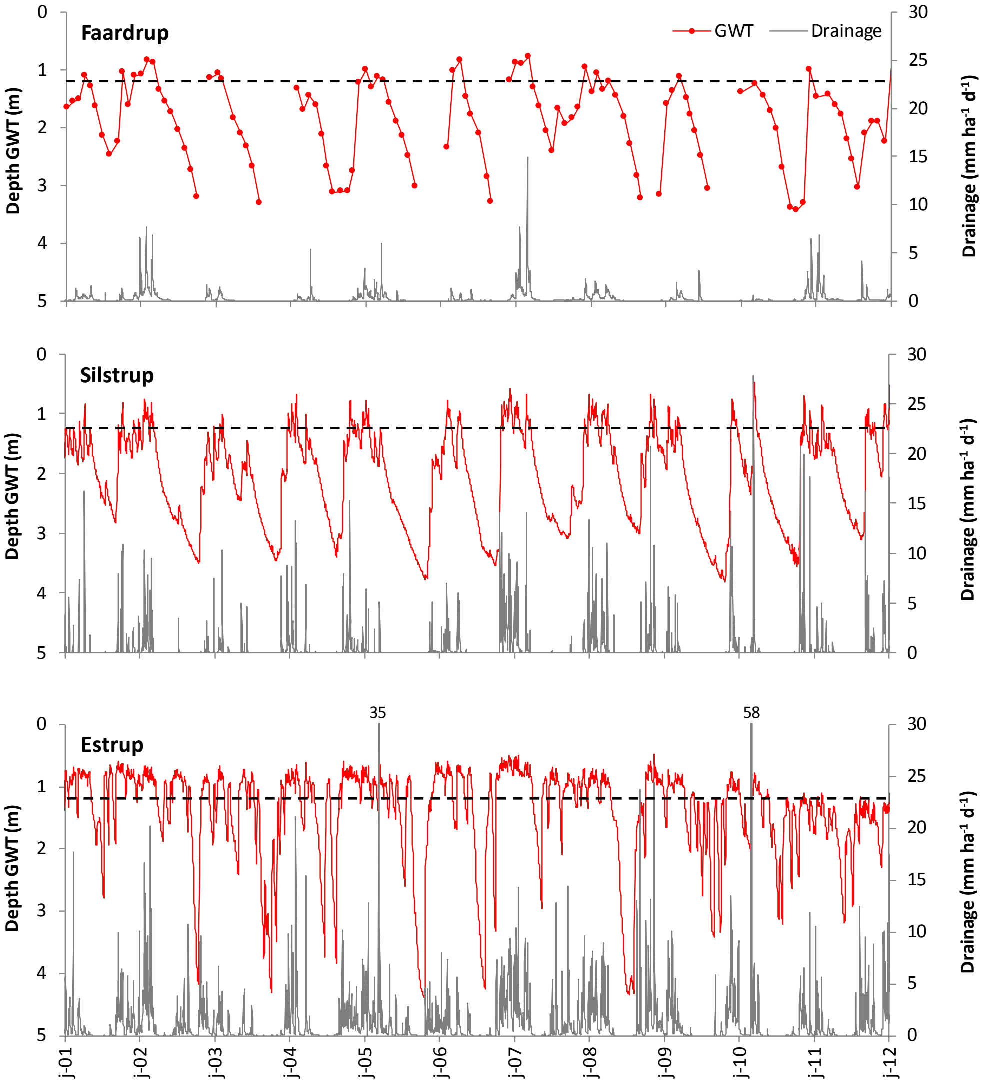

Figure 3. Drainage and depth to groundwater table (GWT) in 2001-2012 at Faardrup, Silstrup and Estrup. The black dashed lines indicate tile drain depth.

Comment [ve33]: 2R12

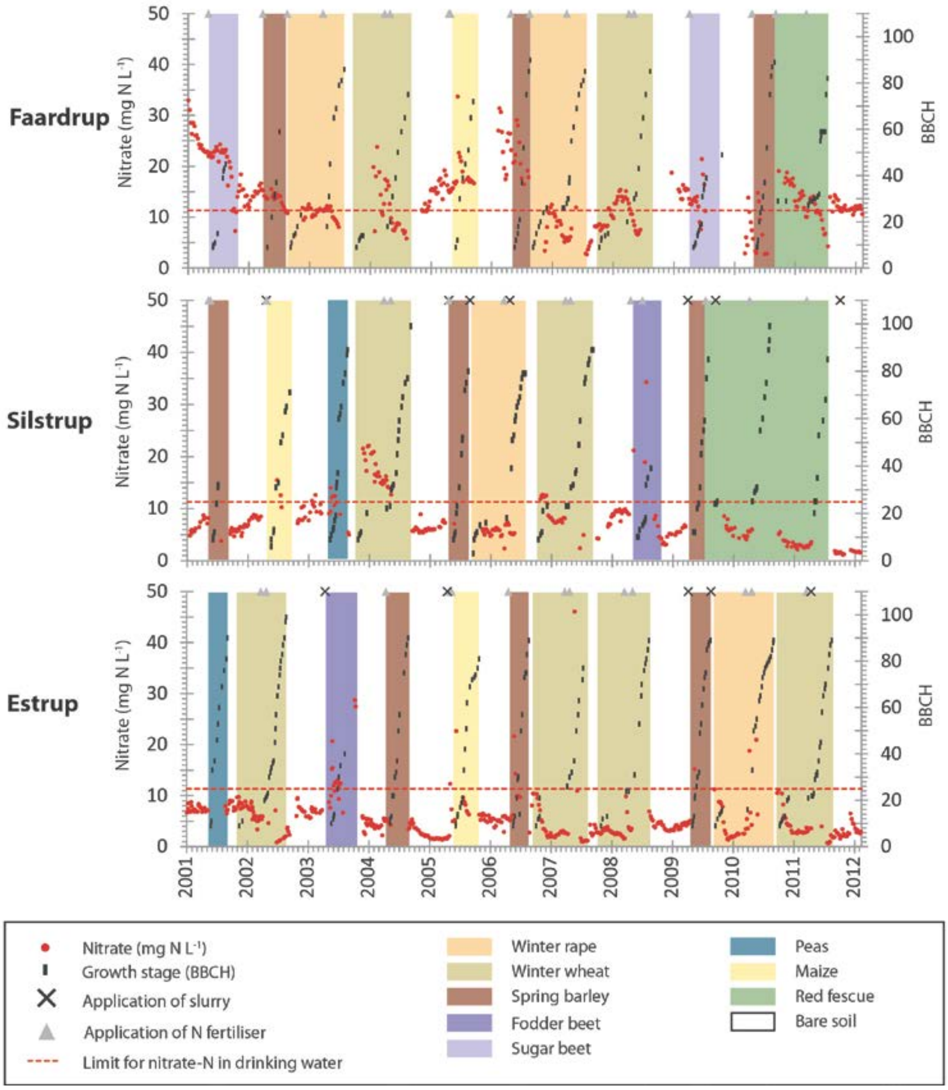

Figure 4. Crop type, specific growth stage of crops according to the BBCH scale, application of inorganic N fertiliser and injection of slurry and concentration of nitrate-N (mg N L^{-1}) in drainage at Faardrup, Silstrup and Estrup.

Comment [ve34]: 2R14

Comment [ve35]: 2R21

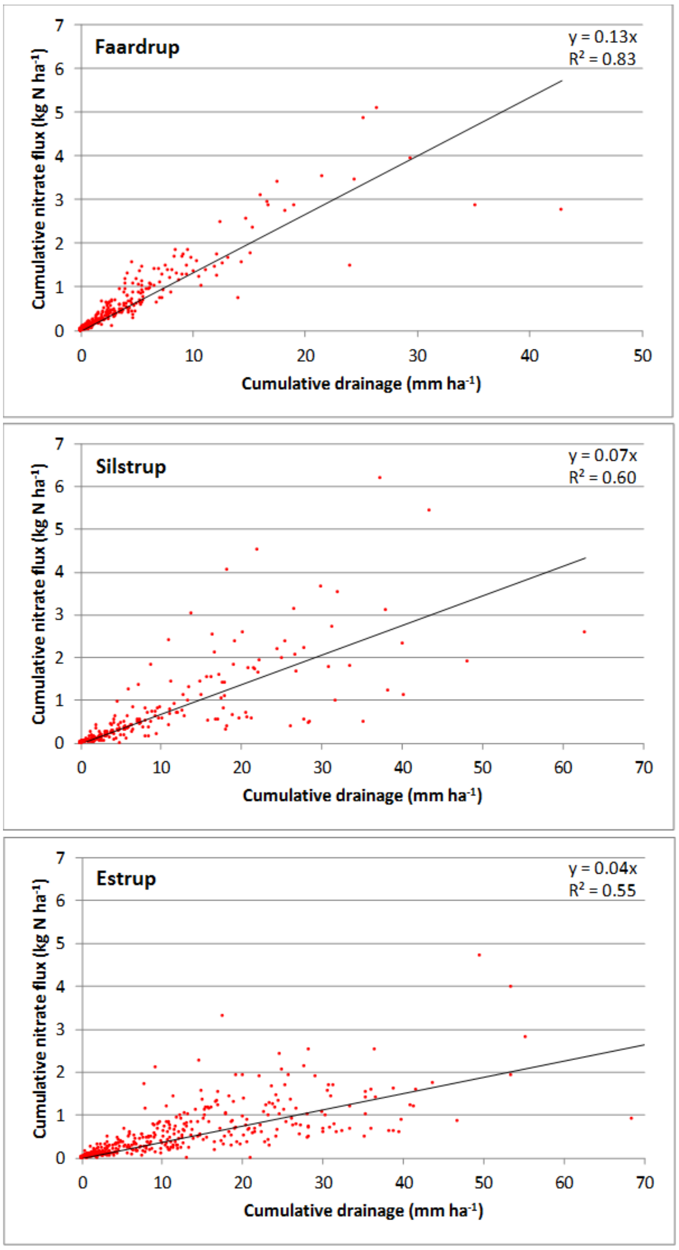

Figure 5. Nitrate-N flux per cumulated drainage for each sampling period at Faardrup, Silstrup and Estrup.

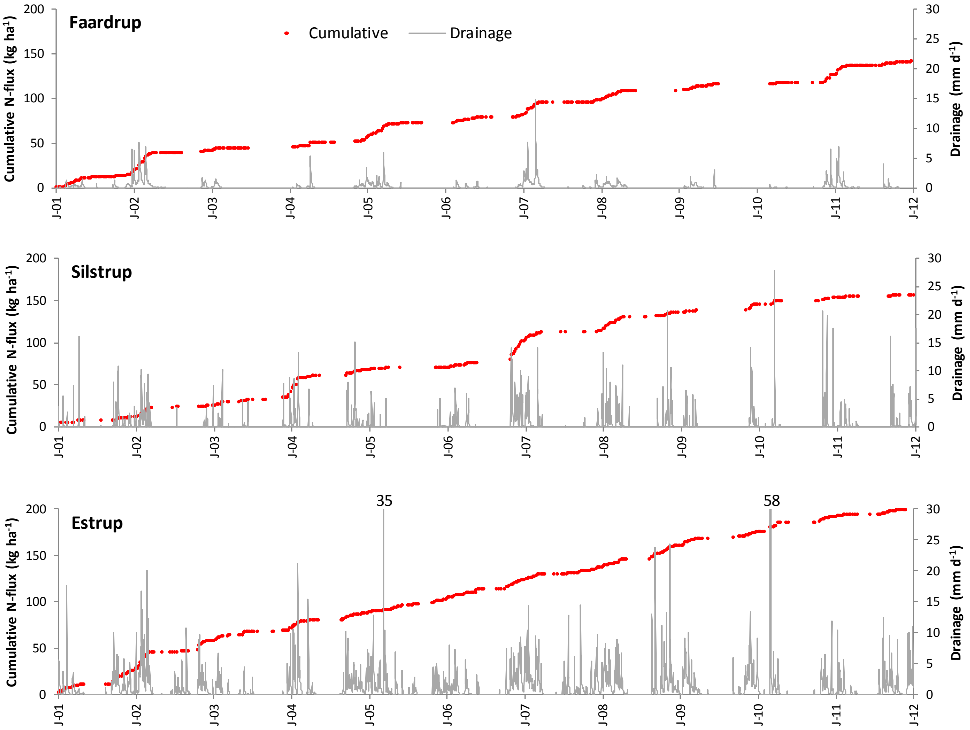

Figure 6. Cumulative nitrate-N flux and drainage for 2001-2012 at Faardrup, Silstrup and Estrup.

Comment [ve36]: 2R12

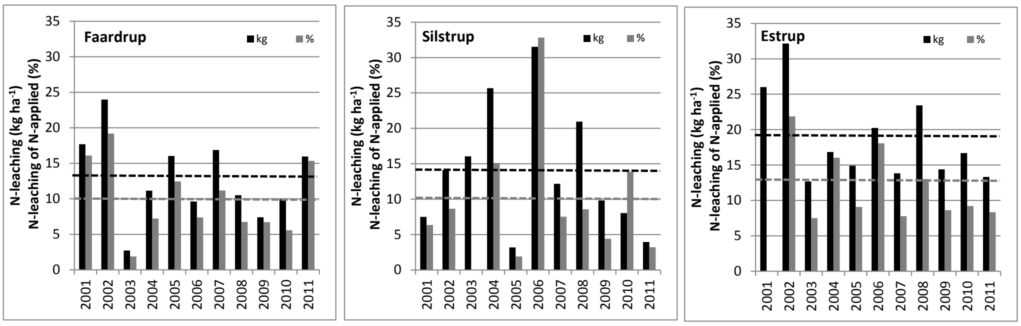

Figure 7. Nitrate-N in drainage in mass (kg N ha^{-1}) and of applied N (%) (inorganic N fertilisers plus slurry) for the years 2001 to 2011 at Faardrup, Silstrup and Estrup. The black dashed line indicates the average annual N-leaching in 2001-2012 and the grey dashed line is the average nitrate-N leaching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