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Nitrogen and phosphorus losses in Nordic and Baltic agricultural monitoring catchments – Spatial and temporal variations in relation to natural conditions and mitigation programmes

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ABSTRACT

Nitrogen (N) and phosphorus (P) losses via agricultural drainage water have negative impacts on receiving water bodies and large-scale programmes to reduce nutrient losses have been established in the Nordic and Baltic countries, together with agricultural catchment monitoring programmes. This study evaluated time series (9–40 years) of data from 34 selected Nordic-Baltic catchments for spatial and temporal variations in area-specific water discharge (mm) and in concentrations and transport of total nitrogen (TN) and total phosphorus (TP).

Water discharge from the catchments varied from 125 mm (Denmark) to > 1000 mm (Norway). Catchments with low TN concentrations ($\leq$3 mg L^{-1}) were dominated by clay or grass leys or were undrained with reduction of nitrate (NO_3) in shallow groundwater. Catchments with high TN concentrations ($\geq$10 mg L^{-1}) had loams and cereal crops. TP concentrations were highest ($\geq$0.45 mg L^{-1}) in catchments with erosive soils, relatively high water discharge and cereal crops, and lowest ($\leq$0.07 mg L^{-1}) in catchments with permeable soils.

Generalised additive mixed model (GAMM) analysis of time series of transport and flow-weighted concentrations of TN and TP for temporal patterns revealed decreases in TN concentrations in seven catchments and increases in eight, while four had periods with opposing trends. TN concentrations decreased in Denmark and Sweden in 1990–2010, following introduction of mitigation programmes. TP concentrations decreased in eight catchments and increased in six, while one showed opposing trends. Decreases in TP coincided with improved P balance in catchments with sand and loam. To further reduce N and P losses, a tailored set of mitigation measures is needed for each combination of soil, climate, geohydrology and agricultural production. Intensive monitoring of small catchments can reveal how N and P losses relate to natural conditions and to changes in agricultural production.

1. Introduction

Nitrogen (N) and phosphorus (P) in drainage water from agricultural land have negative impacts on water quality in receiving water bodies (Deelstra et al., 2014; King et al., 2015). In inland surface waters and coastal waters, P is generally the limiting nutrient for biological growth and hence eutrophication risk (Smith and Schindler, 2009; Dodds et al., 2016). In the open sea, excess N is associated with eutrophication and e. g. algae blooms (Withers et al., 2014). According to the Helsinki Commission (HELCOM, 2018), agricultural activity during the 20th century

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greatly increased nutrient loads to the Baltic Sea, with a four-fold increase in N load and eight-fold increase in P load.

Agricultural land can have two main types of use: open crop rotations on arable land (with cereals, vegetables, ley in rotation etc.) and unploughed permanent grassland used for fodder crops and grazing. Arable land use is concentrated to regions and local areas where soils and drainage conditions are favourable for crop production. Arable soils in northern Europe are young in a global perspective, having developed from residual parent material from the last Ice Age (Weichsel), which ended 10,000 years ago. This means that the weathering process has not yet depleted the soils of natural nutrients, especially fine-textured soils. Many of these nutrient-rich soils are former lake beds and wetlands that have been drained and converted to agricultural land. Land uplift has also exposed previous sea bed for use in agriculture. Agricultural land use has changed greatly over history with the development of new technology, e.g. the introduction of combustion engines in agricultural machinery made it possible to cultivate soils with high clay content. This enabled more arable land to be taken into production during the 19th and 20th Century to secure food production for the people of northern Europe.

Although there are general similarities in geological history within the Nordic-Baltic region, soil types vary. Denmark is almost entirely a lowland area, with coarser soils on Jutland in the west and loam soils on Zealand in the east, and nitrogen (N) is the main cause of water quality deterioration in near-coastal waters and groundwater (Riemann et al., 2016). In Norway, the landscape is characterised by mountains and fjords and agriculture is often concentrated to undulating areas with silty and clay loams, so soil erosion and associated losses of particle-bound P are the main cause of eutrophication of inland waters (Bechmann et al., 2008). In Sweden, agriculture is typically carried out on sandy loam soils in the southwest and southeast and on clay soils in plain areas adjacent to the large lakes. N is the main cause of eutrophication in the areas with sandy loam and P is the main cause in the areas with clay soil (Sandström et al., 2020, Ezzati et al., 2023). Finland has a lowland landscape with clay soils (associated with P losses) and peatlands (associated with N losses). Soils in Estonia, Latvia and Lithuania formed from sediment transported from the Scandinavian mountains by melt water during the post-glacial period, resulting in relatively flat and slightly undulating landscape, and agriculture is conducted mainly in areas characterised by loam or sand soils. In combination with relatively low precipitation in these three countries (700–900 mm year^{-1}) this means that concentrations of N in agricultural streams are the main cause of eutrophication, especially in areas with intensive crop production. Moreover, karst geology is typical in northern Estonia and up to 80% of annual river runoff consists of groundwater that is vulnerable to leaching of nutrients from cultivated land, due to the thin layer of Quaternary sediment on the limestone plateau. A large proportion of the agricultural land in all three Baltic countries is artificially drained, e.g. around 74% of agricultural land in Lithuania is tile-drained and acts as a direct pathway of nutrient transport from agricultural land to streams (Povilaitis et al., 2020).

Dairy, beef, egg, cereal and vegetable farming in the Nordic-Baltic countries tend to be concentrated in the most geographically favourable regions for these enterprises, e.g. high precipitation is favourable for ley production and thus dairy and beef farming. Manure applied to the soil for long time increases the risk for leaching of nitrate N and phosphate P, especially on coarser soils (Liu et al., 2012) and to crops with a short nutrient uptake period, especially cereals and other annual crops (Vogeler et al., 2022). Vegetables are often grown under similar conditions as ley, but pose a much higher risk of nutrient losses, even with similar levels of nutrients applied in both cases. Continuous soil cover with ley results in nutrient uptake for a longer period, while the growing season for vegetables is often short and there is a risk of increased N losses, even when a catch crop is grown (Nett et al., 2011). Annual crops also increase the risk for soil erosion due to soil disturbance during tillage and to N leaching after harvest when plant residues are mineralised, especially after crops with high biomass production or crops fertilised late in the growing season, e.g. winter wheat for the baking industry (Delin et al., 2005).

Action programmes to improve the quality of water bodies in the agricultural landscape have been established in the Nordic and Baltic countries (e.g. Andersen et al., 2014; Bechmann et al., 2016) (Table 1). Point sources, such as manure storage areas and sewage systems, were the first target (e.g Grant and Blicher-Mathiesen, 2004), followed by diffuse leaching from arable land (Kronvang et al., 1993). To control the latter, regulations governing manure management were introduced, e.g. limits on annual application rates and closed seasons for manure spreading and for ploughing erosive soils. Subsidies were introduced for growing catch crops to reduce N leaching and for establishment of buffer zones along streams to prevent surface soil erosion to waters (Andersen et al., 2014; Hellsten et al., 2019). In Finland, strict limits on P fertilisation in order to decrease soil P status has been implemented, but an effect on water quality has been slow to emerge (Ekholm et al., 2005). In the Baltic countries, large areas of agricultural land were abandoned after comprehensive economic and social changes in the late 1980s-early 1990s and use of fertilisers decreased sharply, but there has been a steady upward trend since the mid-1990s. Agricultural production in all three countries has intensified and rationalised, with increasing farm size over recent decades. The agri-environmental measures implemented in the Baltic countries are rather similar to those adopted in the Nordic countries and involve regulations on the use and storage of fertilisers and manure, and requirements for buffer zones, winter green cover, etc. Voluntary measures for sustainable agriculture are included in the code of good agricultural practice. In Lithuania, despite this drastic decrease, there has been very little evidence of changes in riverine concentrations of nutrients (Povilaitis, 2006).

Besides mitigation measures in crop management, also wetlands and ponds have been established, although for various purposes, e.g. nutrient retention, biodiversity or bird game promotion (Arheimer and Pers, 2017; Djodjic et al., 2020; Hellsten et al., 2019).

All Nordic and Baltic countries comply with the European Union (EU) Water Framework Directive (WFD), including Norway, which is not a member of the EU. The WFD requires planned measures to achieve good status in water bodies and monitoring of progress (EC, 2000; Heiskanen et al., 2004). The EU Common Agricultural Policy program (CAP) is an important funding source for implementation of mitigation measures in all Nordic-Baltic countries except Norway. The CAP mainly relies on farmers' own initiative to apply for subsidies and advisory services, which means that implementation of adequate site-specific measures is taking longer than predicted by water authorities (Pe'Er et al., 2019). In Denmark the national approach has been more active, with strict limits on N application rates to 10% below the economic optimum in a defined period (1999–2015) and step-wise increases in specific requirements to improve utilisation of N in manure (Windolf et al., 2012; Petersen et al., 2021). Targets for area of constructed wetlands and stream wetlands have also been set, with local 'catchment officers' as facilitators (Andersen et al., 2014; Hellsten et al., 2019). Catchment officers have recently been introduced in Sweden to promote local initiatives for implementation of mitigation measures (Swedish Agency Marine and Water Management, 2019).

Agricultural catchment monitoring programmes have been established in the Nordic and Baltic countries to assess how farmers respond to policy programmes, and hence the impact on water quality in receiving water bodies (Vagstad et al., 2004). These programmes, which monitor stream water quality, water discharge and, in most catchments, crop management, were initiated in the Nordic countries in the 1990 s (or earlier) and in the Baltic countries between 1995 and 2000. Harmonised monitoring methods (Kyllmar et al., 2014a), to allow comparison of results between countries, has been a key strategy since the 1990s (Øygarden and Botterweg, 1998; Vagstad et al., 2001). Evaluations of catchment N balances for trends have shown changes in N balances related to differences in agricultural development between and

Table 1

Major mitigation measures to control nutrient leaching in the Nordic-Baltic countries around the year 2010 and their policy mechanism (legislation (L) and/or subsidies (S)) (source: after Andersen et al., 2014).

Type of mitigation measure	Denmark	Norway	Sweden	Finland	Estonia	Latvia	Lithuania
Crops, vegetation and soil cultivation							
Wintergreen cover	L	–	L	S	L	L, S	S
Catch crop	L, S	S	S	S	–	–	–
Buffer zones	L, S	S	S	S	L	L, S	S
Soil tillage in spring instead of autumn	L	S	S	–	–	–	–
Manure and fertilisation							
Livestock density	L	L	L	L	L	L, S	L
Manure storage capacity	L	L	L	L	L, S	L, S	L, S
Nutrient balance at farm level	L	–	–	–	–	–	–
Nutrient balance at field level		–	–	S	–	–	–
Periods allowed for spreading of manure	L	L	L	L, S	L	L, S	L
Incorporation of manure in soil after spreading	L	L	L	L, S	L	L, S	L, S
Spreading of manure and fertilisers in vulnerable areas	S	–	L	L, S	L	L	L
Infrastructure investments on arable land							
Restored/constructed wetlands	S	S	S	S	S	–	S
Liming with gypsum or lime	–	–	S	–	S	–	–
Controlled drainage	–	–	S	S	S	–	S
Renovation of drainage systems	–	S	–	–	S	–	S
Other							
Advisory service on nutrient management	–	–	S	–	S	–	–

within the countries, e.g. due to restrictions on N application levels in Denmark, changes in animal production within Norway and intensified production in Latvia (Bechmann et al., 2014). Small catchments have been used as indicators on how changes in future climate may alter patterns of N losses, e.g. outside the growing season (Øygarden et al., 2014).

In a recent study evaluating the impact of climate change on trends in nutrient losses from 69 Nordic headwater catchments (agricultural, forested, natural), no clear pattern was found (de Wit et al., 2020). In general, there was slight decrease in N losses in the agricultural catchments, but few showed statistically significant trends, while there was a small but significant increase in P losses, although with contrasting patterns in different countries (de Wit et al., 2020). Those authors concluded that mitigation measures against N losses have had some effect, but not measures against P losses. A study evaluating the concentration-water discharge relationship (C-Q) for almost the same dataset found that land use characteristics dominated the control of nutrient export behaviour, followed by climate (Hashemi et al., 2020).

Time series of stream water data from small agricultural catchments in the Nordic-Baltic countries have been analysed for trends in e.g. N losses (Stålnacke et al., 2014) and P losses (Pengerud et al., 2015). However, the Mann-Kendall (MK) trend test (Hirsch and Slack, 1984; Libiseller and Grimvall, 2002) used in these studies identifies monotonous trends in the time series as a whole, but gives no information on the temporal dynamics. Further, the MK test is not valid if opposing trends occur in the dataset. For analysis of time series of data with complex dynamics, statistical models using smoothers, are more useful than conventional trend tests. While simple smoothers like LOWESS have the drawback of requiring equidistant data (Lloyd et al., 2014), generalised additive mixed models (GAMM) don't have this restriction and are more flexible (Hastie and Tibshirani, 1986; Wood, 2017). A visualisation tool has recently been developed to enable presentation of results for large numbers of sites analysed with GAMM (von Brömssen et al., 2021).

Specific objectives of the present study were to: (1) Assess the relationship between catchment characteristics and stream water quality in 34 agricultural monitoring catchments in the Nordic-Baltic region; (2) analyse temporal patterns in concentrations and transport of N and P in these 34 catchments using a GAMM technique; and (3) discuss the potential for reducing N and P losses based on catchment characteristics.

2. Material and methods

2.1. Agricultural monitoring catchments

Small agricultural catchments are currently being monitored for water quality, water discharge and nutrient loads within national agricultural monitoring programmes in five countries in the Nordic-Baltic region (Denmark, Norway, Sweden, Finland and Latvia), while Estonia and Lithuania performed such monitoring until 2011 and 2015, respectively (Table 3). In the present study, 34 small agricultural catchments (1–33 km^2) in the seven countries that were monitored at least during the period 2006–2011 were selected for further analysis (Fig. 1). The catchments were chosen to provide examples of various combinations of climate, soil type, hydrology and agricultural production system (Table 2).

In the selected dataset, Danish agricultural areas were represented by five catchments, two with coarse naturally drained soils, high precipitation (over 900 mm year^{-1}) and animal production based on grass ley and three with partly tile-drained loamy soils, lower precipitation and crop rotations dominated by annual crops (Blicher-Mathiesen et al., 2014a). The main agricultural areas in Norway were represented by nine monitoring catchments covering cereal production in the east, vegetables on coarse soil in the south coastal area, intensive dairy farming in the west and extensive grass production in the north and south mountain regions (Bechmann, 2014). Sweden was represented by eight catchments covering mixed crop production on sandy loam soils in southern coastal areas, dairy production on coarse soils in the southern highlands, cereal production on clay soil plains and irrigated crops on the island of Gotland (Kyllmar et al., 2014b). Finland was represented in the dataset by three catchments covering major agricultural production systems on clay soils in the west (Vuorenmaa et al., 2002). Estonia was represented by three catchments on sandy clay loam soils, two with production of cereals and one with grass (Iital et al., 2014). Latvia was represented by three catchments dominated by loam soils, with production of cereals in two of these catchments and grass and pasture in one (Lagzdins et al., 2012; Lagzdins et al., 2015). The three Lithuanian catchments in the dataset were selected along a transect from west to east, with catchments in west and east characterised by pasture and production of cereals in upland areas, whereas the catchment in central Lithuania is situated in a flat area with loam soils and production of cereals and sugar beet (Povilaitis et al., 2014) (Table 2).

Table 2
Characteristics of the 34 Nordic-Baltic agricultural monitoring catchments selected for this study (source: Kyllmar et al., 2014a).

Country/ Catchment	Area (km^2)	Agric. land[a] (%)	Dominant soil texture class on arable land According to USDA	Drained area(arable land) (%)	Production	Livestock density[b] (AU ha^{-1})	Temp. (°C)	Prec. (mm)
DENMARK (DK)								
Højvads Rende	9.8	65	Loamy sand	72	Cereals, sugarbeet	0.3	9.4	739
Lillebæk	4.7	89	Loamy sand	8	Cereals	1.0	9.3	833
Bolbro bæk	8.2	99	Sand	0	Cereals, grass, forage crops	1.3	8.9	1106
Horndrup bæk	5.5	82	Loamy sand	0	Cereals	1.2	8.5	919
Odderbæk	11.4	98	Sand	10	Cereals, grass, forage crops	1.4	8.4	939
NORWAY (NO)								
Skuterud	4.5	61	Clay loam, silt loam	100	Cereals	0.2	6.3	930
Mørdre	6.8	62	Silt, silt loam	100	Cereals	0.1	5.3	762
Kolstad	3.1	68	Loam, loamy sand	100	Cereals	1.3	4.4	751
Vasshaglona	0.86	65	Silt loam, loamy sand	100	Vegetables, potatoes	1.7	8.2	1429
Time	1.0	86	Loamy sand	100	Grass, pasture	2.3	8.5	1278
Skas-Heigre	29.3	84	Loamy sand	100	Grass, cereals	–	8.4	1237
Volbu	1.7	43	Loamy sand	100	Grass	0.4	2.9	587
Hotran	19.4	58	Silty clay loam, silt loam	100	Cereals, grass	–	6.1	997
Naurstad	1.5	35	Peat on loamy sand	100	Grass, pasture	0.6	5.2	1258
SWEDEN (SE)								
M42	8.2	92	Sandy loam, loam	100	Cereals	<0.1	7.7	709
M36	7.9	86	Clay, sandy loam	88	Cereals, grass, potatoes	0.3	7.6	719
N34	13.9	85	Sandy loam, silt loam	93	Cereals, grass, potatoes	0.4	7.2	886
F26	1.8	71	Sandy loam		Grass	0.9	6.2	1066
O18	7.7	92	Clay	100	Cereals	0.1	6.1	655
E21	16.3	89	Sandy loam	95	Cereals	0.2	6.0	506
I28	4.8	78	Sandy loam	99	Cereals, grass, potatoes	0.3	6.9	587
C6	33.1	59	Clay loam	95	Cereals	<0.1	5.5	623
FINLAND (FI)								
Haapajyrä	6.1	58	Clay, peat	–	Cereals	<0.1	4.5	545
Löytäneenoja	5.6	77	Clay, sand	–	Cereals, potatoes, sugar beet	<0.1	5.1	604
Savijoki	15.4	39	Clay, loamy sand	–	Cereals	<0.1	5.8	644
ESTONIA (EST)								
Räpu	24.9	61	Sandy clay loam, loamy sand, peat	80	Cereals, oilseeds, grass	0.5	5.3	717
Rägina	21.1	53	Sandy clay loam, peat	100	Cereals, oilseeds, grass	0.2	5.6	662
Jänijõgi	18.4	59	Sandy clay loam, sandy loam	–	Grass, cereals	–	5.8	705
LATVIA (LV)								
Vienziemite	5.9	78	Sandy loam	100	Grass, pasture	0.5	5.7	715
Berze	3.7	98	Silty clay loam	100	Cereals, oilseeds	–	7.4	589
Mellupite	9.6	69	Loam	100	Cereals, grass	0.1	6.4	666
LITHUANIA (LT)								
Lyžena	1.7	97[c]	Sandy loam	100	Pasture, cereals	0.6	6.5	706
Graisupis	14.2	69[c]	Loam	100	Cereals, sugar beet	0.9	7.3	561
Vardas	7.5	73[c]	Loamy sand	100	Pasture, cereals	0.4	7.2	661

[a] Agricultural land with harvested crops.
[b] Animal units per hectare (1 AU = one cow, three pigs, 10 sheep or 100 hens).
[c] Including permanent pasture.

2.2. *Catchment monitoring methods*

The monitoring methods used in the selected catchments during the study period were similar (for details, see Kyllmar et al., 2014a). In short, water discharge was measured continuously (hourly) at defined stream cross-sections at the stream outlet in all catchments except EST-Jänijõgi, where area-specific water discharge was assumed to be the same as in a neighbouring stream. Flow-proportional composite water samples were taken in 32 of the 34 catchments, mostly biweekly, whereas in EST-Jänijõgi and LV-Vienziemite the sampling strategy was monthly grab samples. Water samples were analysed for concentrations of TN, nitrate-N and TP using international standard methods or comparable national standard methods (see also Kyllmar et al., 2014a). Transport loads of TN, nitrate-N and TP at the stream outlet were calculated by multiplying the concentration for a defined period (composite samples) by water discharge for the same period. For discrete data (grab samples), linear interpolation was used to achieve daily concentration values, which were multiplied by daily water discharge values to obtain daily transport loads. Water discharge and transport of TN and TP were summarised to monthly and annual area-specific values (mm and kg km^{-2}), enabling comparison to other catchments and to precipitation level (mm). Flow-weighted mean annual concentrations were obtained by dividing total transport by total water discharge. Annual surveys of agricultural field management were conducted in catchments in Denmark, Norway, Sweden and Latvia, and occasionally in the other countries, during the selected monitoring period.

Fig. 1. Location of 34 agricultural monitoring catchments in the Nordic-Baltic region.

2.3. Visualisation of trends

Temporal dynamics in trends in time series of annual flow-weighted concentrations and annual loads of TN and TP were visualised using a GAMM approach (Hastie and Tibshirani, 1986; Wood, 2017), which is not limited to any prior definition of the shape of the trend curve. A thin plate spline was used to model the trend curve and a continuous autoregressive process of lag 1 (AR(1)) was included to account for autocorrelation. The first derivatives of the smoothed trend were computed by finite differencing and the corresponding confidence 95% bands were determined (Monteith et al., 2014; Simpson, 2019). Trends were taken as significant at a specific time point if the computed confidence band did not cover zero. Trend analysis was performed for each time series and the results were visualised using trend screening plots developed by von Brömssen et al. (2021). In these, each time series was represented by a horizontal bar, with time fraction of increasing, decreasing or no trend marked by different colours. The aim of the trend screening plots is to reveal the overall pattern of changes in time series, rather than to quantify the magnitude of these changes (von Brömssen et al., 2021). Statistical analysis was performed in R v 4.2.1 (R Core Team 2022), using the package *mgvc* (Wood, 2019) for fitting the GAMM and the package *gratia* (Simpson, 2019) for computing derivative function and confidence intervals.

3. Results and discussion

3.1. Spatial variations in water discharge and in concentrations and transport of nitrogen and phosphorus

Water discharge (mm) varied widely between the catchments, from 125 mm in DK-Højvads Rende in central Denmark to > 1000 mm in NO-Naurstad in northwest Norway (Table 3). Most of the Norwegian catchments were characterised by high water discharge (Fig. 2), due to high precipitation but also the undulating landscape where water is transported on the soil surface and in drainage systems, rather than infiltrating to deeper groundwater. The opposite occurs in western Danish catchments, where the landscape is flat and water percolates through the permeable coarse soils to the groundwater. Beside the visible differences in topography, the soil texture beneath the topsoil may also vary due to geological history, especially in Denmark and in western Sweden. For example in SE-N34, windborne sands partly overlay a clay layer which prevents free percolation to groundwater (Kyllmar et al., 2005). The size and location of a catchment in the landscape can also affect water discharge, e.g. large lowland headwater catchments can receive discharging groundwater originating from outside the catchment, while small catchments located on higher land can lose drainage water to groundwater discharged further downstream in the landscape. In general, this difference is reflected by greater base flow and slower response to precipitation (flashiness) in larger catchments (Deelstra et al., 2014). Relatively high area-specific water discharge (mm) in the similarly large catchments EST-Räpu, EST-Jänijögi and FI-Savijoki (24.9, 18.4 and 15.4 km^2, respectively) (Fig. 2) can be explained by contributions of groundwater from outside the catchments.

The TN concentrations in stream water also varied widely, from < 3 mg L^{-1} in five catchments to > 10 mg L^{-1} in three catchments. The catchments with the lowest TN concentrations were dominated by clay soils (SE-C6 and FI-Savijoki), had pasture and grass as the main agricultural land use (NO-Naurstad and LV-Vienziemite) or was undrained and with pronounced reduction of nitrate in shallow groundwater (DK-Bolbro bæk) (Petersen et al., 2021). The catchments with the highest TN concentrations in stream water (NO-Kolstad, LV-Berze and LT-Graisupis) were all dominated by loam soils and production of cereals, but with contrasting climate, e.g. low annual water discharge in LV-Berze and LT-Graisupis (129 and 177 mm, respectively) and mild winters that provide favourable conditions for mineralisation of organic N. The high TN concentration in NO-Kolstad was unexpected, since its colder winter climate and relatively high water discharge (426 mm) could be expected to decrease N mineralisation rate and dilute N concentrations in stream water, respectively.

The contrasting climate in the three catchments with high TN concentrations were reflected in TN transport in the streams. NO-Kolstad had the highest TN transport of all catchments (>5000 kg km^{-2}), whereas LV-Berze and LT-Graisupis had < 2000 kg km^{-2} (Table 3). Among the six catchments with the greatest TN transport, five were Norwegian (mainly due to high water discharge) and one was Swedish (SE-N34). Total N transport < 1000 kg km^{-2} was found in five catchments located in all countries except Norway and Lithuania. High TN losses from mineral soils are in general related to coarse permeable soils (such as sands and sandy loams) that are tile-drained and have high water discharge (Shrestha et al., 2010). Mild winters and crop rotations with annual crops and high manure application rates are also associated with an increased risk of TN leaching (Shepherd and Newell-Price, 2013). In addition, high organic content (peat soils) increases the risk of TN leaching (Cameron et al., 2013; Kreyling et al., 2015). Low TN transport is typically associated with clay soils, where denitrification decreases the amount of N available for leaching (van der Salm et al., 2007; Colombani et al., 2020).

Concentrations of TP in stream water were highest ($\geq$0.45 mg L^{-1}) in catchments NO-Mørdre, NO-Hotran and SE-O18 (Table 3), all characterised by erosive soil (silt, silty clay loam and clay), relatively high water discharge (360, 406 and 393 mm, respectively) and crop rotations dominated by cereals. The lowest TP concentrations ($\leq$0.07 mg L^{-1}) were found for seven catchments with permeable soils (sand and sandy loam), most of which were used for pasture/forage leys or less intensive agriculture (EST-Rägina) or had calcareous soil (SE-E21) (Table 3).

Total P transport was highest (221 kg km^{-2}) in SE-O18, followed by

Table 3

Mean annual water discharge and flow-weighted concentration and transport of total nitrogen (TN), nitrate-N (NO_3-N) and total phosphorus (TP) at the stream outlet in the 34 Nordic-Baltic catchments in the period 2006–2010.

Catchment	Water discharge (mm)	Concentration ($mg L^{-1}$)			Transport ($kg km^{-2}$)			Monitoring (start–end)
		TN	NO_3N	TP	TN	NO_3N	TP	
DK-Højvads Rende	125	8.9	7.7	0.12	1100	944	17	1989-
DK-Lillebæk	232	7.0	6.4	0.15	1617	1489	36	1989-
DK-Bolbro bæk	523	1.4	0.7	0.07	730	392	44	1990-
DK-Horndrup bæk	283	4.0	3.6	0.08	1142	1008	24	1989-
DK-Odderbæk	234	5.9	5.0	0.17	1376	1171	38	1989-
NO-Skuterud	632	5.5	3.6	0.24	3464	2303	151	1995-
NO-Mørdre	360	5.3	3.6	0.53	1921	1332	189	1992-
NO-Kolstad	426	12.2	9.5	0.10	5226	4106	39	1991-
NO-Vasshaglona	857	5.3	4.1	0.19	4542	3416	162	1992-
NO-Time	637	7.2	4.6	0.15	4326	2764	100	1995-
NO-Skas-Heigre	715	5.4	4.1	0.14	3879	2974	103	1995-
NO-Volbu	318	3.8	2.8	0.07	1201	873	23	1993-
NO-Hotran	406	4.7	3.7	0.45	2046	1607	168	1992-
NO-Naurstad	1009	1.2	0.4	0.12	1146	347	117	1994-
SE-M42	295	8.4	7.3	0.13	2367	2053	38	1992-
SE-M36	296	5.7	5.1	0.19	1662	1431	55	1989-
SE-N34	391	8.2	7.3	0.11	3192	2811	43	1995-
SE-F26	533	3.0	2.2	0.12	1622	1194	62	1994-
SE-O18	393	4.4	3.3	0.56	1797	1299	221	1988-
SE-E21	196	8.4	7.6	0.07	1636	1478	13	1988-
SE-I28	181	9.3	8.3	0.15	1641	1465	30	1989-
SE-C6	238	2.6	2.1	0.21	619	489	52	1994-
FI-Haapajyrä	238	7.9	5.9	0.09	1900	1421	22	1997-
FI-Löytäneenoja	267	5.6	4.8	0.17	1578	1380	44	1981-
FI-Savijoki	346	2.4	1.6	0.20	817	519	72	1981-
EST-Räpu	371	7.7	6.2	0.08	2556	2083	27	2000–2011
EST-Rägina	235	3.2	2.1	0.04	761	502	9	2000–2011
EST-Jänijõgi	365	5.9	5.1	0.03	2246	1942	9	2002–2011
LV-Vienziemite	278	2.2	1.3	0,04	582	333	8	1995-
LV-Berze	129	13.2	12.0	0.09	1452	1319	13	1995-
LV-Mellupite	242	5.5	4.2	0.08	1306	974	16	1995-
LT-Lyžena	271	3.9	3.1	0.03	1063	861	9	1997-2015[a]
LT-Graisupis	177	11.8	9.5	0.12	1899	1509	20	1996-2015[a]
LT-Vardas	255	4.0	2.4	0.07	1019	606	19	1996-2015[a]

[a] Except 2011 and 2013.

NO-Mørdre, NO-Hotran and NO-Vasshaglona (Table 3). High TP concentrations, high water discharge and crop rotations dominated by cereals or vegetables were prominent characteristics shared by these catchments. A positive relationship between TP losses and soil clay and silt content, high water discharge and arable rotations with annual crops has been found in previous studies in the Nordic-Baltic countries (e.g. Rankinen et al., 2016). When water flows through the soil, on the surface or in the streams in areas with arable land dominated by erosive soils, small soil particles that are typically rich in P content due to their mineral structure are transported. When these soil particles are deposited as sediment in stream beds, release of P (internal loading) can occur due to anoxic conditions (Zhang et al., 2021). The origin of P in erosive soils can vary (Frossard et al., 2000; McDowell, 2012). One fraction of soil P content probably derives from previous P fertilisation in excess amounts to cover future crop demand or to long-term application of manure in large amounts (Griffin et al., 2003; Pagliari et al., 2013). The natural content of P in clay and silt soils can be an additional source of P released from sediments in stream beds, e.g. the Nordic and Baltic soils are young in a global perspective and may have a natural P content that has not been accounted for to date. Methods have been developed for analysis of soil P from an agronomic perspective, where P availability to crops in a short and long-term perspective is of interest (Edmeades, 2003). In a recent study, Sandström et al. (2020) found no correlation between P content in arable soils measured as ammonium lactate/acetic acid-extractable P (P-AL) and P in the stream water of 11 Swedish agricultural monitoring catchments, but observed a correlation between clay content and stream water P content. Large variations in concentrations and losses of P between clay soils and sandy loam soils were also observed by Bergström et al. (2015), indicating that legacy P is not the only source in soils with fine mineral particles.

Although patterns in stream water characteristics emerged among the 34 catchments, averages based on 10 years instead of five years (2006–2010) would have been preferred to achieve robust values normalised for weather variations within and between years. Precipitation, temperature and water discharge normally vary widely within each time series, which determine the crops grown, yield and hence nutrient losses.

3.2. Trend analyses and temporal variations

Time periods with statistically significant trends (in any direction) were found for flow-weighted annual concentrations of TN or TP in about half of the 34 catchments (Fig. 3a and Fig. 3b). Fewer time periods with statistically significant changes were found for annual nutrient transport, which can be explained by larger inter-annual variation due to the direct dependence on water discharge.

For annual flow-weighted TN concentrations, time periods with decreasing trends were found for seven catchments, whereas eight catchments had periods with increasing trends (Fig. 3a). Opposing trends, with decreasing TN concentrations until 2010 and increased trends after 2013, were found for four of the Swedish catchments. A general pattern for the whole dataset was for decreases to occur before 2010 and increases after 2010. Time periods with statistically significant trends in TN transport coincided in most cases with the trends in TN concentrations, with the exception of the increasing trends in TN transport seen in NO-Skuterud and NO-Vasshaglona (Fig. 3a).

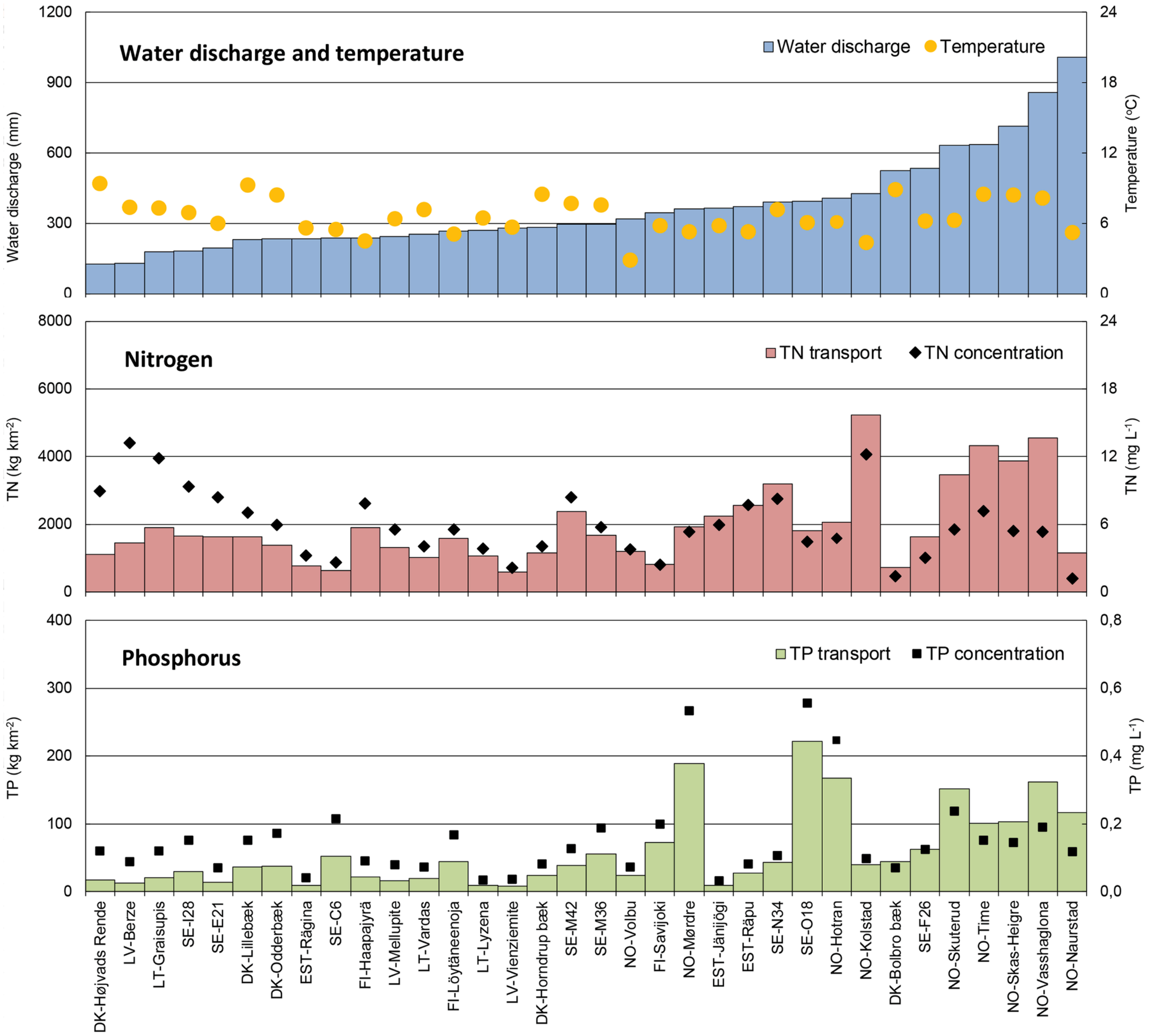

Fig. 2. Water discharge, transport and flow weighted concentrations of TN and TP as annual average (2006–2010) at catchment stream outlet in 34 catchments. Temperature from nearby climate stations.

Decreasing TN concentrations detected in four of the five Danish catchments (DK-Lillebæk, DK-Bolbro bæk, DK-Horndrup bæk and DK-Odderbæk) corresponded to decreasing trends in nitrate-N concentrations reported for these catchments (Petersen et al., 2021) due to implementation of intensive mitigation programmes to reduce N leaching from agricultural land. NO-Skas-Heigre and NO-Naurstad also showed decreasing trends, for the whole period and after 2012, respectively. Previously until 2011, NO-Skas-Heigre has shown a tendency for decreasing TN concentrations whereas NO-Naurstad showed a tendency to increasing TN concentrations explained by less mitigation measures against N losses than P losses (Stålnacke et al., 2014).

In Sweden, there have been intensive mitigation programmes to control N leaching, especially in southwest Sweden where the catchments in this study with decreasing trends in TN concentration are located (SE-M36, SE-N34, SE-F26 and SE-O18). Decreasing TN concentration trends have been detected previously in agricultural rivers in this region (Fölster et al., 2012). Increasing TN concentration trends in later years in seven out of the eight Swedish catchments are more difficult to explain. A smaller area of subsidised catch crops may be a partial explanation like a change in crop distribution to more cereals due to higher market prices. Another reason is probably weather variations, especially after the extremely dry season of 2018 when e.g. low soil water content could have enhanced mineralisation of organic N. In two of these Swedish catchments (SE-F26 and SE-O18), lower water discharge in later years also coincided with higher concentrations of TN (Fig. 3a). A similar pattern with decreasing water discharge and increasing TN concentrations was seen for FI-Löytäneenoja and FI-Savijoki (Fig. 3a).

Increasing TN concentrations in stream water in EST-Jänijõgi have been reported in previous studies covering the period 2006–2011 (Stålnacke et al., 2014; Iital et al., 2014), where they were attributed to intensified agricultural production and increased fertiliser use. Compared with results in another previous trend test (1995–2018) for the Latvian catchments, the trend pattern remains with increasing TN concentrations for LV-Mellupite and the opposite with decreasing TN concentrations for LV-Vienziemite (Siksnane and Lagzdins, 2020).

For TP concentrations, time periods of decreases were found in eight catchments, increases were seen in six catchments and one catchment

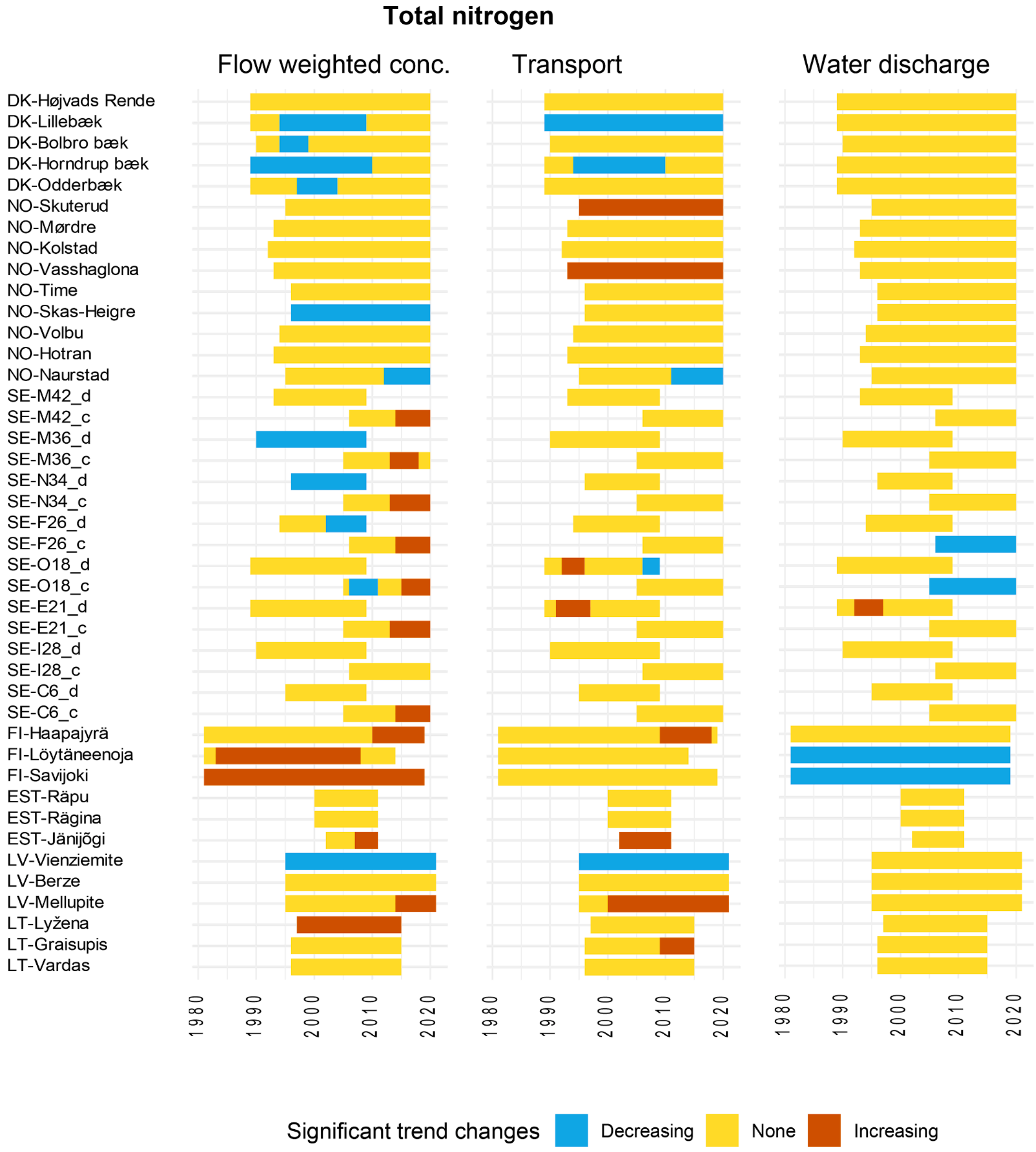

Fig. 3a. Trend analysis on annual flow-weighted concentrations and transports of total nitrogen and water discharge in 34 agricultural streams. Swedish catchments are divided into two time series depending on water sampling technique: c – composite sampling, d – discrete sampling. Decreasing (blue) and increasing (red) trends are defined by the 95 % confidence interval of the first derivative of the smoother in the GAMM analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

showed trends in both directions (Fig. 3b). An increasing trend in TP transport, but not in concentrations, was found in DK-Bolbro baek. In FI-Löytäneenija and LV-Mellupite, transport of TP decreased without any associated trend in concentrations. In FI-Löytäneenija, this was explained by decreased water discharge (Fig. 3b).

Decreased P application rates have been reported for seven of the catchments with downward trends in P concentrations: DK-Lillebæk and DK-Horndrup bæk (Blicher-Mathiesen et al., 2014b), NO-Vasshaglona and NO-Naurstad (Bechmann, 2014), SE-M36 and SE-E21 (Linefur et al., 2022) and LV-Berze (Lagzdins et al., 2012). Increased P concentrations could be explained by an increased P balance in NO-Time (Bechmann, 2014) and occurrence of a new point source in SE-I28 (unpublished data). The results indicated that improvements in P balance have had the desired mitigation effect in catchments with sand and loam soils or in parts of catchment where mitigation measures on sand soils dominate (SE-M36). In a previous study, however, few detectable trends were found in almost the same dataset (Pengerud et al., 2015). Longer time series in the present study indicates that the effect of mitigation measures against losses of P take longer time to detect in the streams than measures against leaching of N.

Examples of how GAMM were fitted to single time series are shown for six selected catchments in Fig. 4. For DK-Lillebæk, it was possible to fit a smoother to the annual flow-weighted concentrations of TN, showing a decreasing trend 1994–2008. In LV-Vienziemite where water sampling was as monthly grab samples, the TN concentrations were so variable so no smoother could be fitted. Here, only a linear trend for the whole period was revealed indicating a decline in TN concentrations. In SE-N34, a linear decline in TN was found for the first time period (up to 2010), which was based on grab sampling. The later period, which was based on flow-proportional composite sampling, showed an increase in TN in the last eight years (Fig. 4). For TP in NO-Time and NO-Skas-Heigre, smoothers were also fitted to the time series. Within small water courses, where water quality variations can be large over time, the composite sampling method gave concentrations with less variation than discrete grab sampling, and thus seems to be more appropriate for detection of trends within the time series.

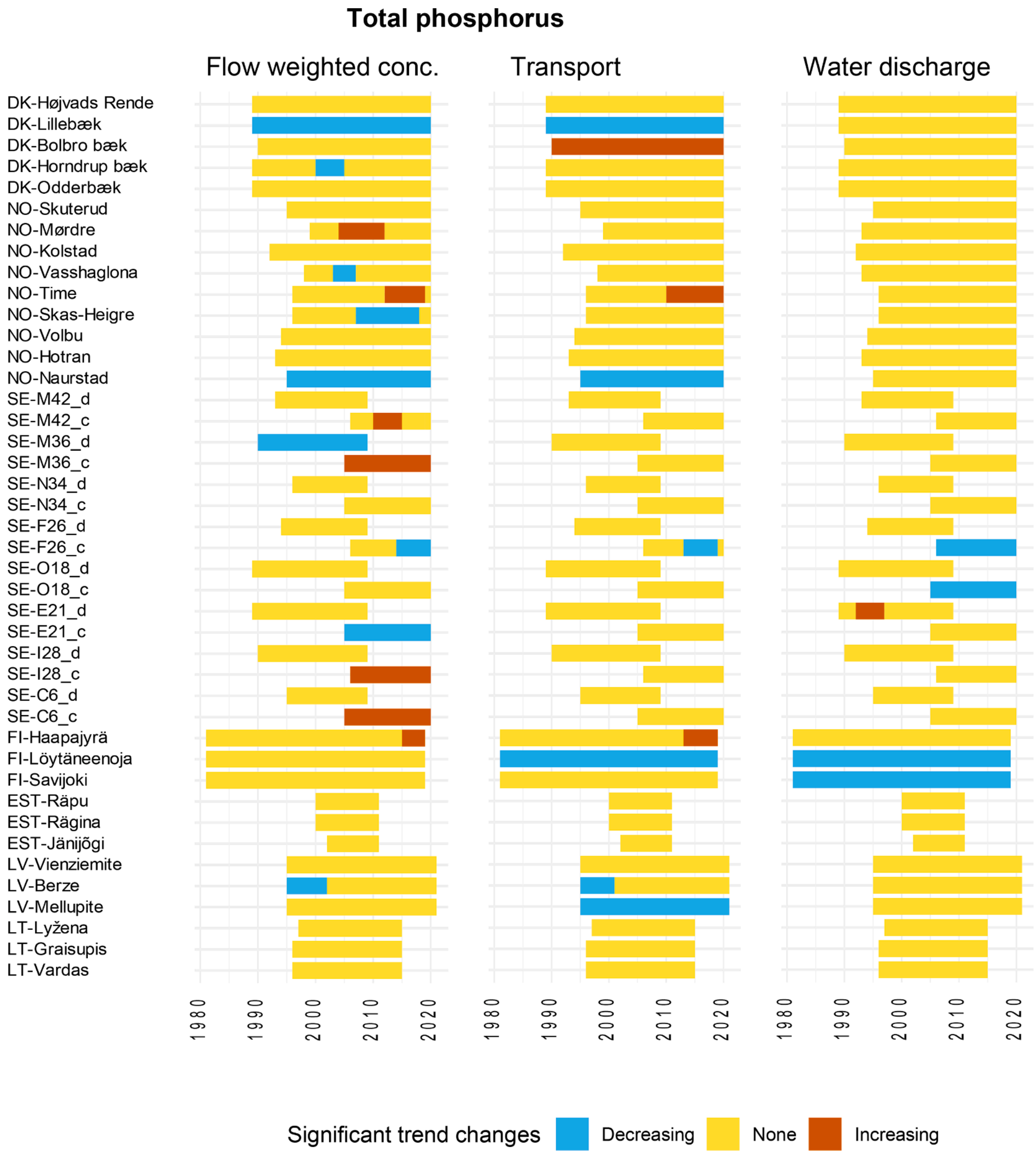

Fig. 3b. Trend analysis on annual flow weighted concentrations and transports of total phosphorus and water discharge in 34 agricultural streams. Swedish catchments are divided into two time series depending on water sampling technique: c – composite sampling, d – discrete sampling. Decreasing (blue) and increasing (red) trends are defined by the 95 % confidence interval of the first derivative of the smoother in the GAMM analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The GAMM-based trend screening plots proved to be a useful tool for visualising overall patterns in annual flow-weighted concentrations and transport of TN and TP. In some cases, significant trends were explained by documented changes in agricultural management in the catchments or by trends in water discharge. The GAMM screening plots also indicated periods that could be objective for further analyses, e.g. magnitude and directions of trends during different periods, and distinguished between weather variations, changes in climate and hydrology and changes in agricultural practices.

3.3. Potential for further mitigation measures

Evaluation of catchment characteristics and stream water quality together with trend analysis gave an indication of the potential of future mitigation measures. Nitrogen losses from agricultural land to waters mainly occur as leaching of soluble nitrate-N. In permeable soils, such as sands and sandy loams, nitrate-N is transported through the soil profile to the drainage system or directly to groundwater. Mitigation measures that prevent leaching of soluble N are therefore warranted and can give relatively rapid effects on N concentrations in drainage water. The decreasing TN trends seen in this study for Danish and Swedish monitoring catchments with sand and sandy loam soils indicate that the current national mitigation programmes have been effective in arable areas with these soil types. Most of these mitigation programmes have focused on measures at field level, such as adjustment of farm and field N balance, better utilisation of the nutrient content in manure, avoiding soil cultivation in late autumn and growing catch crops and winter-grown crops. For water leaving agricultural fields, wetlands are a key remediation measure and most Nordic-Baltic countries have policy programmes to increase the number of wetlands.

Reuse of drainage water for irrigation can also be a beneficial measure in several aspects, e.g. recirculation of drainage water prevents nutrients reaching water bodies and a secure water supply reduces the risk of limited nutrient crop uptake during dry periods and hence the risk for increased nutrient leaching afterwards. Mitigation measures targeted at drained fields with a high proportion of soil water flow to streams can

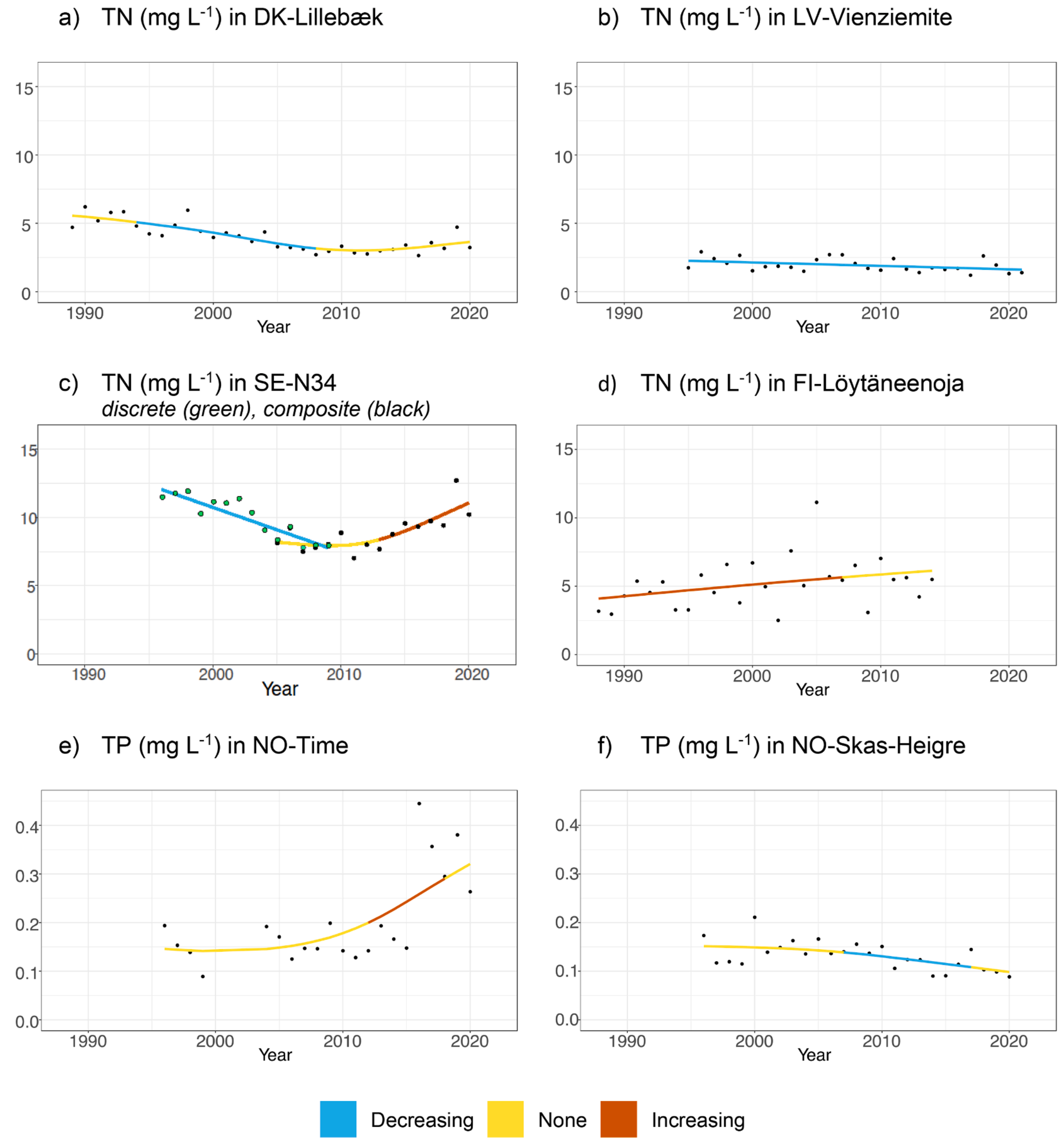

Fig. 4. Annual flow weighted concentrations of TN and TP and lines showing GAMM analysis. Decreasing (blue) and increasing (red) trends are defined by the 95 % confidence interval of the first derivative of the smoother in the GAMM analysis.

also be more effective than when applied to fields that have reduction of N in groundwater aquifers. In a review of mitigation measures targeting agricultural drainage waters as wetlands, controlled drainage, denitrifying bioreactors, saturated buffer zones and integrated buffer zones it was found that they reduce losses of N but that the result for P varied (Carstensen et al., 2020).

At regional scale, reductions in livestock density, better distribution of manure to farms without animals and production of biogas from manure can be considered. Technical solutions for fractionation of manure into fertilisers and biogas are under development, which will hopefully enable better utilisation of manure, at least at local scale. Similar development is underway on fractionation of grass biomass into high-quality proteins for animal fodder (Jørgensen et al., 2021), but also for biogas production (Bedoić et al., 2019). In a fossil-free society the need for biomass production on agricultural land will increase (Vermaat et al., this issue) and model calculations show that there is potential to increase the area of ley in agricultural landscapes (Mårtensson et al, this issue). Long-term leys have smaller losses of N than most other agricultural crops (Johnsson et al., 2019) and a larger areal coverage will hence probably further decrease N losses from agriculture.

In soils that form aggregates, such as clay soils, nitrate-N is partially trapped and reduced to gaseous forms (N_2O and N_2). Nitrogen leaching from these soils is lower than from drained coarser soils, but effective crop management is still very important to reduce N leaching to streams and to prevent greenhouse gas emissions (Abdalla et al., 2019; Plunge et al., 2022).

Soil P losses can roughly be divided into losses of dissolved reactive P (DRP) and particulate P (PP). In coarse soils, DRP is the main fraction of concern, whereas PP often dominates in clay soils (Johnsson et al., 2022). Coarse soils that have received excess P for decades can be saturated with P and hence can leach P for many years. Clay soils can contain such legacy P too, and probably also natural P. The soil particles that are eroded from fields accumulate as stream sediments, where internal loading due to anoxic conditions can release P. Information about the natural P content of soils in the Nordic-Baltic countries is limited, due to the previous strong focus on P available for crop production. If there is a considerable amount of natural P in certain soil types, e.g. clay soils with no calcareous fraction, this is important information for water authorities seeking to reach defined water quality goals. Knowledge on the natural P content in soil may not exclude (or even alter) the need for mitigation measures, but can help set reasonable goals. In a recent study comparing how reference values for agricultural lowland streams are defined in the Nordic countries, it was found that the methods differed and that harmonisation is needed (Skarbøvik et al., 2020).

Improved field P balances, better utilisation of manure and a longer crop season are important measures to reduce P losses from soil (Heathwaite et al., 2003). On erosive soils, measures that reduce soil erosion on the soil surface, within the soil and in drainage systems should be a high priority. The basis is often good soil structure, where water can percolate slowly through the soil without shortcuts in cracks. Sedimentation ponds, filtration areas where sediments are allowed to settle and reuse of water for irrigation are other measures that should be considered to reduce transport of soil particles (and associated P) to downstream recipients. Renovation of subsurface drainage systems to prevent soil being lost through damaged tile-drains to stream should also be considered.

To further reduce N and P losses, the optimal combination of measures in crop production, soil, drainage system and stream must be identified for each field, farm and catchment (Heathwaite et al., 2000). Integration of research results on measures and on processes in the crop-soil–water system, modelling of various scenarios, local knowledge on field function and already implemented measures and finally results from monitoring in streams can provide good support for local decision-making on the most appropriate combination of measures. Small intensively monitored catchments scattered over the Nordic and Baltic countries constitute a matrix that show the relation between N and P losses to different combinations of soils, climate, hydrology and agricultural production systems. They also provide basis for further understanding of system functioning, for upscaling to other agricultural land where information is less detailed or through calibration and validation of modelled data.

4. Conclusions

Mean annual water discharge 2006–2010 varied widely among the 34 selected Nordic-Baltic catchments, from 125 mm in central Denmark to 1009 mm in northwest Norway. This variation was explained by differences in catchment topography, climate and geohydrology. Annual TN concentrations also varied widely, from < 3 mg L^{-1} in five catchments to > 10 mg L^{-1} in three catchments.

The catchments with the lowest TN concentrations were dominated by clay, had pasture and grass leys as the main agricultural land use or were undrained and showed a pronounced reduction in nitrate concentrations in shallow groundwater. The highest TN concentrations were found in catchments dominated by loam soils and cereal production.

Concentrations of TP were highest ($\geq$0.45 mg L^{-1}) in catchments characterised by erosive soils, relatively high water discharge and crop rotations dominated by cereals. The lowest TP concentrations ($\leq$0.07 mg L^{-1}) were in seven catchments with permeable soils and mainly with grass as the dominant crop.

Application of a GAMM-based visualisation tool for time trends indicated periods with decreasing trends in annual flow-weighted TN concentrations for seven catchments and increases for eight catchments. Opposing trends, with decreasing TN concentrations until 2010 and increasing concentrations after 2013, were found for four (Swedish) catchments. Decreasing TN concentrations until 2010 seen in four Danish and four Swedish catchments corresponded to implementation of mitigation programmes to reduce N leaching from agricultural land. A declining rate of improvement after 2010 was seen for the Danish catchments, indicating that additional measures are needed to achieve the further decreases required by the EU WFD. Extreme weather, with more frequent dry periods during the past decade, can also be the explanation for changes in the trends, especially in Sweden.

For TP concentrations, decreases were found in eight catchments and increases in six catchments, while one catchment displayed trends in both directions. Overall, the results indicated that improvements in P balance had given benefits in catchments with sand and loam soils.

Few trends were found in water discharge, which means that changes in concentrations also indicates changes in loads. Concentration averages, especially if based on flow-proportional water sampling, varies less between the years compared to loads, which enhances identification of temporal trends.

To further reduce N and P losses, the optimal combination of measures must be identified for each combination of soil, climate, geohydrology and agricultural production system. Small intensively monitored catchments scattered over the Nordic and Baltic countries act as indicators on how N and P losses are related to natural conditions, agricultural practices and production systems, and changes in these over time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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