



# Assessment of agricultural water protection strategies at a catchment scale: case of Finland

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## Abstract

For decades, water quality monitoring programmes, agri-environment schemes and environmental permits for animal farms have targeted a decrease in agricultural loads. These have been supplemented with more recent policies related to nutrient recycling and a circular economy. However, eutrophication of surface water bodies remains a widespread problem. In this paper, we focus on the nutrient loading and recycling in the catchment of Eurajoki River, Finland. We statistically examine the generation of nutrient loading and its variation on a sub-catchment scale. We extend this examination to the factors behind the loading and estimate the impact of nutrient recycling on it. Our analysis reveals shortcomings in the availability and collection of data on the agricultural nutrient loadings and the parcel-specific data on the presence and application of manure and fertilisers. Nine sub-catchments were responsible for roughly half of the TP loading from the 46 sub-catchments studied. To reveal such hot spots and to better target agricultural water protection measures, we recommend short-term water quality sampling campaigns. Judging from our data, the rate of manure recycling is not high enough to reduce the regional P surplus to manageable levels. Therefore, we suggest facilitated collaboration between animal and crop farms to decrease the nutrient surplus. We also propose setting up a national database containing parcel-specific information, for example, on soil P content, manure and fertiliser application, agricultural practices and the presence of acid sulphate soils. We also suggest an independent soil fertility sampling to provide valid baseline soil P data for field parcels.

**Keywords** Agri-environment scheme · Eutrophication · Manure · Water quality · Recycling · Sub-catchment

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## Introduction

Eutrophication remains a widespread problem in aquatic environments worldwide. As wastewater management has gradually become increasingly efficient, the role of agricultural non-point source loading has become dominant (Mateo-Sagasta et al. 2017; Xie et al. 2022). The European Environment Agency (2021) reported that in 2016–2021, the diffuse pollution from agriculture affected 22% of surface water bodies and 28% of groundwater areas across Europe, thus downgrading the continent's overall ecological and chemical status. In Finland, diffuse runoff originating from human activities contributes to around 50–75% of the total phosphorus (TP) and total nitrogen (TN) contamination of waters (Tattari et al. 2015; HELCOM 2018; Fleming et al. 2021).

Various measures have aimed at reducing the agricultural nutrient loads flowing to water bodies. In the European Union (EU), several policies and instruments are intended to mitigate this problem. Among others, the Nitrates Directive

(EEC 1991), the Water Framework Directive's (WFD's) regional River Basin Management Plans (EC 2000) and the Marine Strategy Framework Directive (EC 2008) aim to improve the condition of surface waters. Additionally, HELCOM's Baltic Sea Action Plan sets country targets for nutrient reduction in this sea area (HELCOM 2020). Furthermore, reducing nutrient loads by 50%, resulting in at least 20% less fertiliser usage by 2030, has recently been incorporated in the EU's Green Deal in the Farm to Fork Strategy (EC 2020) and Biodiversity Strategy 2030 (EC 2021).

Currently, the rising costs and threatened availability of energy, raw materials for fertilisers and other inputs in agricultural production have acted as further drivers towards more efficient use of nutrients (Prado et al. 2023). However, the regional segregation of crop and livestock production in EU countries has resulted in spatially unstable demand and supply of manure and its nutrients (Ylivainio et al. 2014; Akram et al. 2019; Laakso and Luostarinen 2019; van Leeuwen et al. 2019; Niskanen 2020). Consequently, recycling nutrients is often perceived as a solution to the excess manure in regions with intensive animal husbandry (e.g. Spiegel et al. 2020; Köninger et al. 2021). In Finland, for instance, enhancing the recycling of nutrients has received significant attention and funding (Finnish Government 2019). Thus, technologies and practices towards improved solutions for regional-scale sustainable nutrient management are needed (Daniel-Gromke et al. 2017; Luostarinen et al. 2020; Salminen et al. 2022; Lemola et al. 2023).

Since Finland joined the EU in 1995, the attempts of the Finnish agri-environment authorities to control nutrient loads of the agricultural sector have mainly focused on limiting the acceptable phosphorus (P) and nitrogen (N) amounts that can be applied in fertiliser and manure per hectare of field (Marttinen et al. 2018). The success of mitigation measures can be monitored in two ways: first, by monitoring water quality (i.e. nutrient concentrations) (Räike et al. 2003) and second, by monitoring nutrient use and concentrations in agricultural soils (Sharpley 1995; Hyvönen et al. 2020; Rankinen et al. 2021). The total nutrient loads from Finland to the Baltic Sea are quantified by monitoring water quality in major rivers (Knuuttila et al. 2016). Another monitoring programme aims to quantify the changes in non-point source nutrient loads but includes only a few small agricultural sub-catchments (Tattari et al. 2017).

At the farm level, the fertility of agricultural soils in Finland has been monitored as one of the practices of the agri-environment schemes (AESs) since the country joined the EU in 1995 (Miettinen 2019). The farmers are required to take soil samples of their field parcels and have these analysed at an accredited laboratory for soil-test P (STP), among other physical and chemical variables. STP is used as a proxy for the P loading potential (Uusitalo and Aura

2005; Uusitalo et al. 2007; Ni et al. 2020), and together with the soil type and cultivated plant, the AESs set a limit to the allowed use of P fertilisation (Turtola et al. 2021). For larger animal shelters, an environmental permit is required, which sets the minimum agricultural area onto which the manure from the farm can be spread (Miettinen 2019).

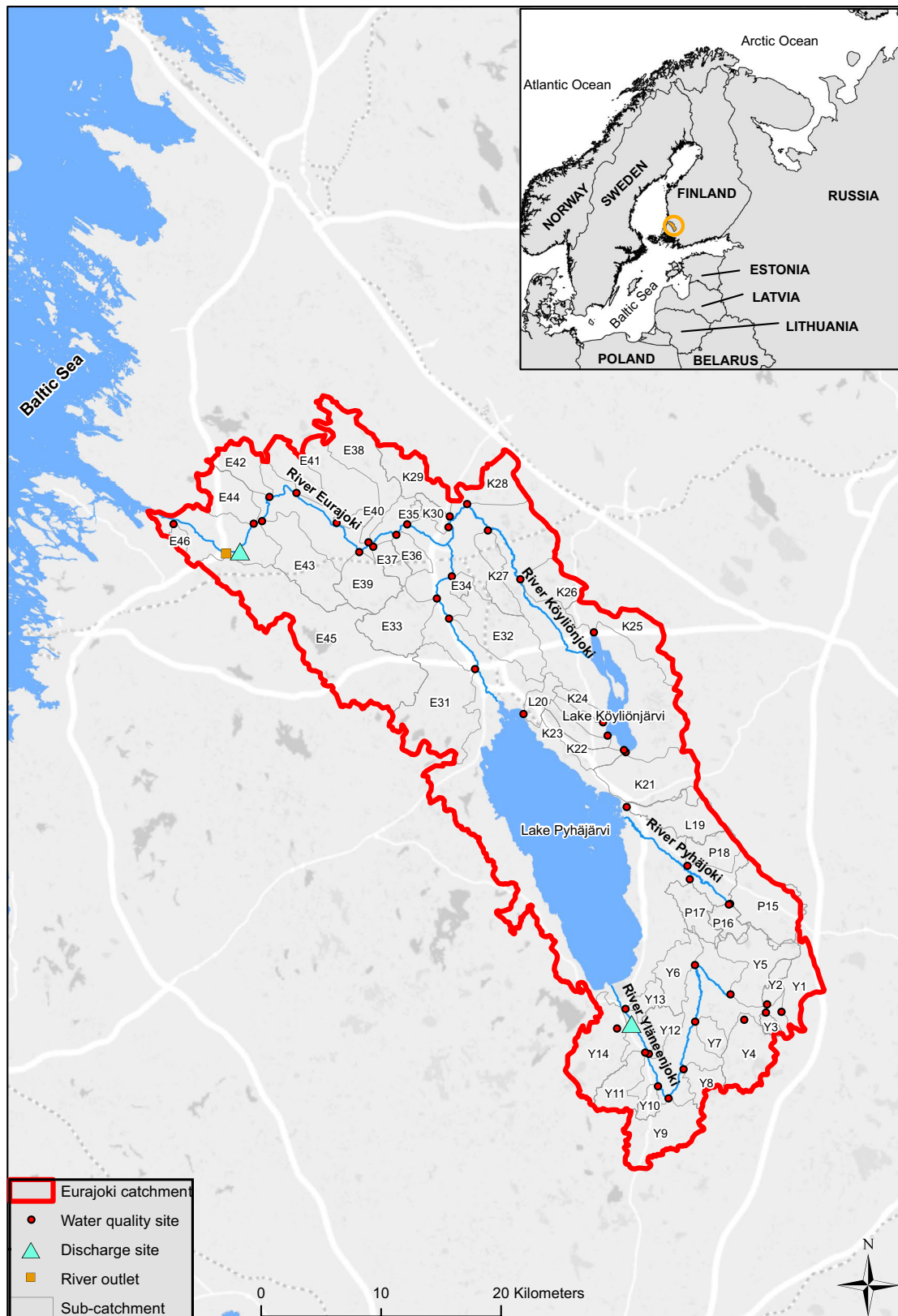
Despite the above attempts, the eutrophying nutrient loss from agriculture has not decreased substantially in Finland (Räike et al. 2003; Räike et al. 2020). Climate change, resulting in increased winter thaws in the northern latitudes (e.g. Tattari et al. 2017; HELCOM 2018; Rankinen et al. 2020), poses additional challenges to the abatement of agricultural nutrient loads. For example, Räike et al. (2020) estimated that in southern Finland, more than half of the annual TP export from river flows occurred within a couple of weeks between December and January over the first decade of the twenty-first century. Due to the current challenges, there is an evident need for developing further agri-environmental actions, whose implementation must be backed by a knowledge base of sufficiently high quality.

Our aim is thus to examine the factors influencing nutrient fluxes, based on multi-dimensional data on a river sub-catchment scale. We evaluate the sufficiency of regional data on the water quality, the agricultural soil fertility, the acreage of cultivated crops and the volumes of manure P and manure N generated, applied and recycled in the area under study. We then provide recommendations on how the availability and quality of such spatial data could be improved.

## Materials and methods

### Case study area

The Eurajoki catchment covers 1335 km<sup>2</sup> in southwestern Finland (Fig. 1). In the upper reaches, Yläneenjoki and Pyhäjoki Rivers discharge into Lake Pyhäjärvi (155 km<sup>2</sup>), which flows into the Baltic Sea via Eurajoki River. Note that Eurajoki is the name of both the entire catchment and the river between Lake Pyhäjärvi and the Baltic Sea (Fig. 1). Köyliönjoki River originates from Lake Köyliönjärvi and enters Eurajoki River in its middle part. The ecological state of most of the water bodies in the area was below the good level required by the WFD (Finnish Environment Institute 2019). The land use in the catchment is distributed among arable lands (23%), forests (47%), sparsely vegetated areas and bare rocks (9%), marshes and peat bogs (2%), lakes and rivers (13%) and constructed areas (6%; CLC 2018). Topographically, the area is rather flat, ranging from the sea level to a height of 140 m. The coastal regions are prone to the formation of active acid sulphate (AS) soils (GTK 2019). These soils contain high amounts of sulphidic materials, which may be oxidised, resulting in the formation of



**Fig. 1** The locations of the studied area in southwestern Finland, water sampling sites and discharge measurement stations. The 46 independent sub-catchments are located along Yläneenjoki River

(Y), Pyhäjoki River (P), Lake Pyhäjärvi (L), Lake Köyliönjärvi and Köyliönjoki River (K) and Eurajoki River (E)

sulphuric acid, in turn leading to adverse effects on aquatic ecosystems (Virtanen 2015). Furthermore, these soils have been associated with reduced P mobility since P forms poorly soluble complexes with iron (Fe) and aluminium (Al) found in these soils (Haynes 1982).

The mean annual temperature and precipitation in 2008–2019 were 5.7 °C and 593 mm, while the 30-year (1981–2010) mean values were 4.8 °C and 614 mm, respectively (Finnish Meteorological Institute, Kokemäki Station: N 61.25°, E 22.35°). Its share did not undergo significant change between 2006 and 2018 (Online Resource 1).

## Hydrology

Runoff was approximated by utilising the daily discharges measured at two stations located at Yläneenjoki River (Vanhakartano Station) in the upper reaches and at Eurajoki River (Pappilankoski Station) in the lower reaches of the Eurajoki catchment (Fig. 1). The data were obtained from the open HERTTA environmental information system (CC BY 4.0 International; [https://www.syke.fi/en-US/Open\\_information/Open\\_web\\_services/Environmental\\_data\\_API](https://www.syke.fi/en-US/Open_information/Open_web_services/Environmental_data_API)) operated by the Finnish Environment Institute and the Centres for Economic Development, Transport and the Environment. The discharge was converted into daily runoff ( $\text{ls}^{-1}\text{km}^2^{-1}$ ) and annual mean runoff ( $\text{ls}^{-1}\text{km}^2^{-1}$ ), calculated for each year under study (Online Resource 2).

Additionally, mean runoff was calculated for each sub-catchment, consisting of daily runoff values for each day of water quality sampling.

## Water quality data

Agricultural nutrient loads were estimated using a dataset consisting of 1948 records on ditch water quality, collected by the Pyhäjärvi Institute in 2008–2019. Comprehensive data were available for 46 sub-catchments, which were located in 5 catchments: (i) 14 sub-catchments in the Yläneenjoki River catchment (Y1–Y14), (ii) 4 in the Pyhäjärvi River catchment (P15–P18), (iii) 2 sub-catchments discharging directly into Lake Pyhäjärvi (L19–L20), (iv) 10 in the Köyliönjoki River catchment (K21–K30) and (v) 16 along Eurajoki River (E31–E46; see Fig. 1). Each of these sub-catchments contains one water quality sampling site (Fig. 1). Of the 1948 total records, 1759 were used from these 46 sub-catchments. The delineation of the 46 sub-catchments was performed by the GIS-based VALUE tool (Finnish Environment Institute 2015). Thereafter, the outcome was reviewed to correct mismatches caused by tile drainage. The 46 sub-catchments cover about 52% of the total area of the Eurajoki catchment.

Additional water quality data were retrieved from the HERTTA database for Yläneenjoki River and for the

Eurajoki River outlet discharging into the Baltic Sea because these data represent almost the entire Eurajoki catchment (Online Resource 3). Sample numbers per site are given in Online Resource 3. Nutrient loads of point-sources (2008–2017) for the sub-catchments were acquired from the database of the Finnish Pollutant Release and Environmental Enforcement Register (Finnish Environment Institute 2022).

The water quality data included turbidity, conductivity, total suspended solids and pH, as well as the concentrations of TP, dissolved reactive phosphorus (DRP) and TN. Analyses were conducted in laboratories accredited by the Finnish Accreditation Service (FINAS).

## Calculation of nutrient loads

Water quality data were combined with runoff information, after which flow-weighted annual mean concentrations ( $\mu\text{g l}^{-1}$ ) were calculated for TP, DRP and TN for the sub-catchments. These were multiplied by the annual mean runoff to obtain nutrient loss estimates ( $\text{kg km}^2^{-1} \text{ year}^{-1}$ ) for each variable. This methodology has previously been described by Frisk and Kylä-Harakka (1981).

## Farms and their animal numbers and the use of arable land

Information on the farms was obtained from the Integrated Administration and Control System (IACS) administered by the Finnish Food Authority. In total, 794 and 626 farms were located in the Eurajoki catchment area and the 46 sub-catchments, respectively. For each farm, the data on animal numbers, field parcels (hectares) and crops (87 different types) in 2017 were obtained from the IACS (Online Resource 4). These data were utilised to assign each farm a primary production line classification based on the numbers of raised animals and cultivated crops. Our production line classification describes 14 agricultural production types: 7 relating to crop production and 7 to animal husbandry (see Online Resource 5).

## Field parcel-specific data on soil fertility and soil types

STP concentrations, based on extraction with an acidic ammonium acetate buffer (pH 4.65; Vuorinen and Mäkitie 1955), and soil types were acquired from Eurofins Agro Testing Finland Ltd and the Finnish Food Authority. Only the most recent STP value was utilised for each parcel in case there were several results for a parcel. In total, 3695 parcels (11,228 ha) were located on the 46 sub-catchments under study. Based on the data, area-weighted averages of STP were defined for each sub-catchment.

Soil types were classified into six categories: clay, silt, coarse mineral soils, gytja, organic soils (soil organic content: 20–40%) and peat (organic content: over 40%). As the soil type tends to vary in the same parcel, soil type distribution was calculated for each parcel and subsequently averaged for each sub-catchment.

### Data on manure generation, spreading scenarios and recycling

The mass of manure generated on the animal farms located across the entire Eurajoki catchment and the 46 sub-catchments were calculated by multiplying the farm-specific animal numbers (37 different types) by animal-type-specific (Online Resource 6), animal-to-manure ratios obtained from a previous study (Luostarinen et al. 2017). Masses were converted to manure-P and manure-N by using the coefficients also provided by Luostarinen et al. (2017). These coefficients address N losses during storage. There is no available information on how and where the manure is actually applied to fields. Therefore, we envisioned three scenarios on how farms spread the manure they generated (Table 1).

Field application of unprocessed manure is considered economically feasible when the transportation distance is not more than 10 km. Even then, farmers tend to prefer the field parcels closest to the animal shelter, which is considered in scenario 3. We have assumed that a 10-km transportation distance equals an 8-km radius around the animal shelter.

In the area under study, poultry manure is recycled by a local company that manufactures secondary, recycled fertilisers and substrates for non-agricultural use (i.e. gardening). Data on the received poultry manure volumes (11,800 metric tonnes (tn) in total and 4700 tn originating from the studied area in 2014) were obtained from the company. The average total poultry manure quantity received by the company amounted to ca. 6900 tn in 2010–2018. Hence, the poultry manure volume used in this study represented the upper end of the range of the manure recycling volume in the region. As the recycled fertilisers produced are delivered to retail markets throughout the country, these nutrients were considered removed from the studied area. The company also delivers poultry manure to be used in crop farms and in growth media within the area.

### Land use data

The land use of the sub-catchments was calculated, based on the CORINE 2018 land cover data (CLC 2018), which was aggregated into five groups (agricultural land, forest, constructed area, miscellaneous land use and lake). Thereafter, we estimated the habitation in sparsely populated areas, based on the number of inhabitants of dwellings not connected to the municipal sewers (inhabitants km<sup>2</sup><sup>-1</sup>) using the data of the Building and Dwelling Registry 2019 provided by the Digital and Population Data Services Agency in Finland.

### Statistical analysis

To examine the dependencies among water quality, land use and soil and crop data, the annual area-specific loads for P and N (kg km<sup>2</sup><sup>-1</sup> year<sup>-1</sup>) were explained by a set of independent variables by using multiple linear regression (MLR) analysis. To explore the most relevant interaction effects between the independent variables, interaction terms between Field% and soil type percentages, Field% and Slope% and STP and ASS% were calculated. These interactions were chosen for further investigation since previous research indicated that soil types, STP and AS soils influenced nutrient loads. For the definitions of these variables, see Table 2. Sub-catchment L19 was excluded from the analysis, due to the low sampling frequency (Online Resource 3). MLR was thus run on a set of 45 sub-catchments.

The independent variables and their interactions were introduced in the model one by one, starting with exogenous variables, followed by land use and agricultural attributes. Analogous to the definition by Ekholm et al. (2015), “exogenous” variables are here defined as those independent variables that do not directly pertain to land use or the characteristics of agricultural land but may influence the nutrient loads. In our analysis, exogenous variables include the mean runoff in sampling days and the inhabitants of dwellings not connected to the municipal sewage network. At the inclusion of each variable in the model, Akaike information criteria (AIC), *R*<sup>2</sup> and regression coefficients were examined to determine if the variable was to remain in the model. The variables that did not

**Table 1** Three alternative scenarios on how the locally produced manure P and N was spread in the sub-catchments.

Scenario for manure spreading	Description of the scenario
1. On the spot manure P and N field application	All manure is spread across the same sub-catchment where the manure is generated. This scenario is indifferent to the actual location of the animal shelter in the sub-catchment
2. Equalised manure P and N field application	All manure is spread homogenously within an 8-km radius from the animal shelter
3. Tiered manure P and N field application	Three-fourths and one-fourth of manure are spread homogenously within 4-km and 4–8-km radii, respectively, from the animal shelter

**Table 2** Key variables of 46 sub-catchments and their mean, standard deviation (SD), minimum (Min) and maximum (Max) values

Independent variable	Abbreviation	Unit	Mean	SD	Min	Max
Exogenous						
Mean runoff in sampling days		l/s/km <sup>2</sup>	9.5	2.3	6.1	20.2
Inhabitants of dwellings not connected to municipal sewers		nr./km <sup>2</sup>	8	9	0	35
Land use						
Share of agricultural area in sub-catchment	Field%	%	28.4	17.3	3.7	87.8
Share of forested area in sub-catchment		%	62.4	16.8	8.6	93.0
Share of lakes and water bodies in sub-catchment	-	%	0.2	0.6	0.0	2.6
Share of constructed land in sub-catchment	-	%	4.4	3.3	0.3	13.2
Share of miscellaneous land use <sup>1</sup> on sub-catchment	-	%	4.7	2.8	0.8	13.3
Agricultural land-related						
Field soil mean electrical conductivity	-	mS/cm	1.4	0.4	0.7	2.7
Mean soil test-P concentration	STP	mg/l	18.5	9.8	5.3	48.7
Share of acid sulphate soils in sub-catchment	ASS%	%	23.5	31.0	0.0	83.4
Mean field slope percent	Slope%	%	1.8	0.9	0.8	6.1
Mean distance to nearest water body	-	m	227	84	55	472
Share of fields not involved in agri-environment scheme	-	%	2.7	2.8	0.0	10.9
Manure P field application, 3 different scenarios <sup>2</sup>	-	kg/km <sup>2</sup> /y	4490	8000	0.0	3410
Manure N field application, 3 different scenarios <sup>2</sup>	-	kg/km <sup>2</sup> /y	13,100	20,900	0.0	88,400
Organic matter content of mineral soils	-	%	10.5	4.7	4.6	23.5
Agricultural soil types						
Share of clay soils	Clay%	%	26.9	21.6	0.0	99.1
Share of silt soils	Silt%	%	11.2	9.5	0.0	37.2
Share of coarse mineral soils	Coarse%	%	49.1	24.5	0.0	99.6
Share of gytjtja soils	-	%	0.2	1.1	0.0	7.2
Share of organic soils	Organic%	%	11.0	14.6	0.0	56.0
Share of peat soils	Peat%	%	1.4	2.2	0.0	9.5
Crop types						
Share of cereals <sup>3</sup>	-	%	46	19	2	80
Share of special crops <sup>4</sup>	-	%	14	17	0	64
Share of environmental grasses <sup>5</sup>	-	%	6	5	0	20
Share of grasslands in production <sup>6</sup>	-	%	33	21	0	90

<sup>1</sup>Sparse forest, sandy beach, bare rock, wetland and bog. <sup>2</sup>The three scenarios are explained in Table 1. <sup>3</sup>Oat, barley, wheat, spelt, triticale, buckwheat, turnip rape, rapeseed and rye. <sup>4</sup>Sugar beet, caraway, fruits/berries, vegetables and root crops. <sup>5</sup>Nature management field, perennial environmental grass and buffer zone. <sup>6</sup>Cultivated grassland for silage and hay, perennial pastures in production

result in model improvement based on AIC and  $R^2$  were excluded, and the variance inflation factor (VIF) was used to diagnose intercollinearity. As more and more independent variables are added to a model, their intercollinearity may inflate their variances, potentially resulting in false positives (Dormann et al. 2013). When VIF values higher than 5–10 were found, the model was checked if any variables should be removed. Residual analysis was conducted via a visual examination, and residual distributions were corrected via log-transformation for TP and DRP loads. Statistical analysis was conducted using R (R Development Core Team 2019).

## Results and discussion

### Variation in nutrient loading on the sub-catchment scale

The nutrient loads from agricultural areas show a strong spatial variation, with a high proportion of the load coming from disproportionately small high-risk areas (Heckrath et al. 2007). Nevertheless, the load is typically monitored at river outlets (Räike et al. 2020) or representative small catchments (Ezzati et al. 2023; Liu et al. 2023), rather than within a catchment. We investigated the variations

in the nutrient loads of 46 sub-catchments in the Eurajoki catchment. Covering 5–12 years of observations, our analysis demonstrated that TP, DRP and TN loads varied up to two orders of magnitude among the sub-catchments (Online Resource 3). The spatial patterns of the nutrient loads remained similar across the years — that is, the sub-catchments that ranked high in loads did so consistently throughout the years in our dataset. To cite an example, 9 sub-catchments with the highest specific loads for TP (exceeding  $30 \text{ kg km}^{-2} \text{ year}^{-1}$ ) were responsible for about 50% of the total TP loading of the 46 sub-catchments (Online Resource 3).

Typically, to save costs, the number of sampling sites and thus the spatial extent of national water quality monitoring programmes have been reduced in Finland (Kipinä-Salokannel Mäkinen 2021). Consequently, the sub-catchment-scale water quality data are rarely available. Therefore, the data used in the present work are exceptional, enabling analyses that cannot be carried out based on the national monitoring programmes, which are designed to address national-scale reporting such as for HELCOM (2020).

We argue that relatively short-term water quality sampling campaigns on a sub-catchment scale, accompanied with runoff estimations, can help identify the areas that contribute most to local-scale nutrient loading. Thus, after an initial extensive sampling campaign, more detailed investigations can target the sub-catchments showing the highest nutrient loads and hence in most urgent need of nutrient abatement measures. Additionally, as pointed out by Marttila et al. (2020) and Kipinä-Salokannel Mäkinen (2021), monitoring small catchments provides a way to improve the essential understanding about the cause-effect relationships of agricultural management practices and loads of P and N.

### Factors behind the nutrient loading in the Eurajoki catchment

We used regression analysis to explain the variations in the loads of TN, TP and DRP among the sub-catchments. The explanatory variables, and their interactions, were included in the model one-by-one to help interpret and understand the changes in the parameter estimates and intercepts. For such an exploratory use of multiple regression analysis, see Ekholm et al. (2015).

Our analysis showed that Field%, ASS%, STP, Clay% and Organic%, together with interactions ASS%  $\times$  STP and Field%  $\times$  Clay%, provided the best explanatory power for TP loads (AIC = 57,  $R^2 = 0.7$ , Table 3). For DRP loads, Field%, ASS%, Clay%, STP, Organic% and Slope%, together with interactions ASS%  $\times$  STP, Field%  $\times$  Clay%, Field%  $\times$  Organic% and Field%  $\times$  Slope%, gave the highest explanatory power (AIC = 115,  $R^2 = 0.7$ , Table 3).

**Table 3** Multiple linear regression parameters for models found to best explain log TP, log DRP and TN loads. The full sets of candidate models are featured in Online Resources 7–9. Significance codes: \*\*\* = 0.001, \*\* = 0.01, \* = 0.05, · = 0.1; for multivariate models,  $R^2$  is adjusted to account for inflation. The dataset encompasses statistically independent sub-catchments ( $n = 45$ ). The symbol  $\times$  between variable names denotes interactions

	log TotP	log DRP	TN
Field%	0.01·	0.01	28.64***
ASS%	−0.02**	−0.04**	-
STP	−0.02·	−0.07*	-
Clay%	−0.01	−0.02	-
Organic%	−0.03***	−0.11***	-
ASS% $\times$ STP	0.00*	0.00**	-
Field% $\times$ Clay%	0.00*	0.00·	-
Slope%	-	−0.25	−44.98
Field% $\times$ Organic%	-	0.00**	-
Field% $\times$ Slope%	-	−0.02*	−5.58*
Silt%	-	-	9.38·
Coarse%	-	-	1.68
Peat%	-	-	−56.73*
Field% $\times$ Silt%	-	-	−0.32*
Field% $\times$ Coarse%	-	-	−0.17*
Field% $\times$ Peat	-	-	1.92**
Num.Obs.	45	45	45
$R^2$	0.746	0.768	0.887
$R^2$ Adj.	0.698	0.700	0.858
AIC	57.26	115.00	594.45

Although the models reached a high explanatory power, the results also suggest that multiple data sources and a wide variety of agri-environmental variables are needed to account for the variation in the nutrient loads in this catchment.

For example, Field% alone had a very low explanatory power for P loads (Online Resources 7–8). This finding contrasts with earlier studies (e.g. Röman et al. 2018), in which most of the variation in P loads was explained by Field% and lakes. Field% ultimately appeared as statistically slightly significant for P loads (Table 3) but only in combination with several other variables.

When the presence of AS soils (ASS%) was also introduced in the analysis (model 2 and onwards in Online Resource 7), it appeared as statistically highly significant and had a slightly negative slope, conforming with earlier studies showing lower P losses from AS soils (Nystrand et al. 2016; Kämäri et al. 2020; Yli-Halla et al. 2020). The interaction ASS%  $\times$  STP appeared as statistically significant as well. Surprisingly, the interaction suggests a relation in which a high ASS% and a high STP together seem to aggravate P loads. The reasons for the interaction are difficult to explain using the present dataset but may be attributed to

the fact that the AS soil survey data are based on a lower spatial resolution than the STP data, possibly resulting in inaccuracies. These may arise, as the national scale AS mapping is based on interpolation between dispersed sampling sites across large areas and does not specifically target AS prevalence on small parcels of cultivated land. This may lead to failure in detecting the existence of AS soils on the small parcels. Parcel-specific AS sampling within the Eurajoki catchment would mitigate this issue, but such data is unfortunately not available at present. Nevertheless, the AS soils appear to influence the P loads in the Eurajoki catchment, and their role should be further clarified.

Organic% with a negative slope (Table 3, Online Resources 7–8) was one of the variables that had a significant explanatory power for TP and DRP loads. For example, Ni et al. (2020) have concluded that organic matter increases P sorption capacity, although their lack of Al and Fe oxides may have an opposite effect (Peltovuori 2006). Organic soils also tend to have less P leaching potential by decreasing soil permeability and soil P bioavailability (Rankinen et al. 2020; Rääke et al. 2020).

The main effect between P loads and Clay% was statistically significant, as was the former's interaction with Field%. This was true for both TP and DRP. The direction of this interaction is in line with the present view that P loads increase with an increase in Field% and Clay%, clay soils being sensitive to erosion, thus tending to increase particulate P emissions (Kleinman et al. 2011, Kyllmar et al. 2014, Sandström et al. 2020). Similar results were observed for DRP as well, albeit with a weaker significance.

In DRP and TN models, Slope% was negative, in contrast to earlier research indicating that steeper fields, sensitive to erosion, often act as sources of nutrient losses (e.g. Shi and Schulin 2018). We assume that the negative regression coefficient in our model is a spurious effect because most fields in the studied area are relatively flat (Slope%:  $1.8 \pm 3.1$ ). The sub-catchments with the steepest slopes, located around the basin of artificial wetlands (Y10: 6.1%, Y11: 3.5%), had low Field% (3.7% and 5.0%, respectively; Online Resource 3).

The TN loads were best explained by Field%, Silt%, Coarse%, Peat% (organic content over 40%) and Slope%. In addition, interactions Silt%  $\times$  Field%, Coarse%  $\times$  Field%, Peat%  $\times$  Field% and Slope%  $\times$  Field% ( $R^2 = 0.86$ , AIC = 595) provided the best explanatory power, in line with previous findings (Ekholm et al. 2015; Rääke et al. 2020). In contrast to TP and DRP, Field% alone explained more than 50% of the variation in TN loss (Table 3). The effect of Field% on TN loss is consistent with previous findings, for example, by Rankinen et al. (2016), who reported that on average, 50% of the TN loss originated from agricultural areas when Field% exceeded 15%. In our analysis, we observed a negative regression coefficient between TN loads and Peat%. The verification of this relation merits further studies.

## Soil-test P and cultivated crops along agricultural production lines

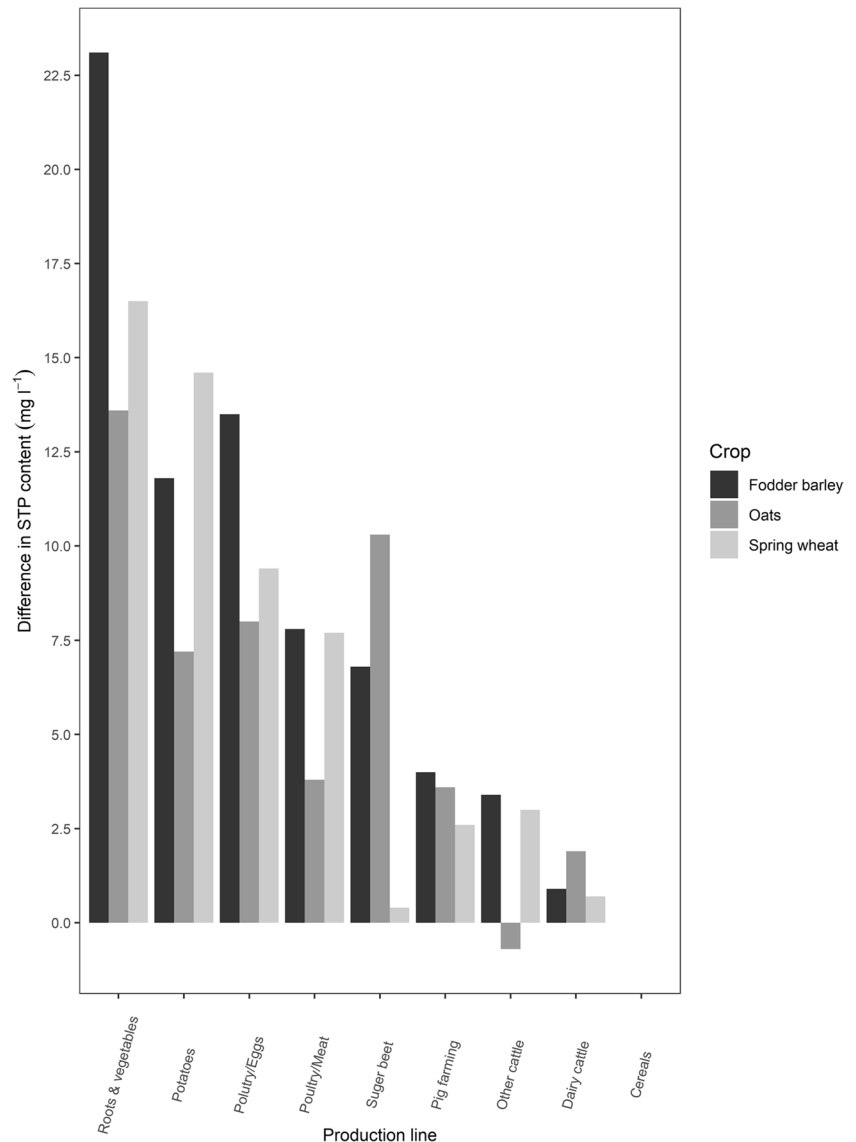
In these data, STP and ASS% together contributed to the explanation of TP and DRP loads. The link between STP and higher P loads in experimental setups on a field-parcel scale is well-documented (Yli-Halla et al. 1995; Uusitalo and Aura 2005; Uusitalo et al. 2007; Uusitalo et al. 2016). The existing literature also shows that the presence of ASS reduces leaching of P from agricultural soils since P forms complexes with Fe and Al (e.g. Mayakaduwege and Mosley 2021). However, STP alone did not appear as a variable explaining either TP or DRP loads — a similar observation was made by Ekholm et al. (2015) for major river catchments in Finland discharging to the Baltic Sea. The reasons for this may be provided in a recent study by Valve and Salminen (2022), who discussed biases attributed to soil fertility samples taken by the farmers themselves. Other factors may also blur the relation between STP and water quality. For example, DRP is affected by surface enrichment of P, not visible in STP values and typical of less intensive tillage systems, especially the no-till ones (Dodd and Sharpley 2016; Tian et al. 2017; Iho and Uusitalo 2018; Ni et al. 2020). Data on tillage practices were unavailable for the field parcels included in this study.

The STP data were further analysed with the crops ( $n = 87$ ) cultivated on each field parcel, together with the production lines ( $n = 14$ ) of the farms in 2017 (Online Resources 4 and 5). The highest average STP appeared mainly in the fields used for cultivation of roots, vegetables, annual herbs and potatoes. Among the production lines, the highest average STP values were recorded for farms cultivating roots and vegetables (mean STP: 32.0), berries and fruits (28.5) and potatoes (27.6), followed by farms raising poultry (meat: 25.7; eggs: 24.7) (Online Resource 5). These findings are in line with a previous study's results (Suojala-Ahlfors et al. 2021) — the fertiliser limits for these plants are markedly higher than those for cereal crops. The farms cultivating cereal and cumin covered about 45% of the agricultural land in the studied area, the average STP value being 15.4 (Online Resource 5).

Poultry farms ranked among the production lines with a high average STP (Online Resource 5). Examining the parcels of the poultry farms, where the top three cultivated crops (spring wheat, fodder barley and oats) were grown in 2017, revealed more relevant findings in this respect. For egg- and meat-producing poultry farms, the average STP values on these parcels were  $10.3 \text{ mg l}^{-1}$  and  $6.4 \text{ mg l}^{-1}$ , respectively, above the corresponding average in farms specialising in cereals and cumin (Fig. 2). Similar or even higher differences in the average values were recorded for farms specialising in the cultivation of roots and vegetables, potatoes and sugar beets.



**Fig. 2** Average STP concentrations in field parcels used for cultivation of spring wheat, fodder barley and oats in 2017 by the classification of the production line (*X* axis). Here, STP (*Y* axis) is expressed as the difference from the mean STP of the farm fields representing the cereal and cumin production line



The pattern in the average STP is partly explained by crop rotation — the parcels used for the cultivation of special crops (e.g. root crops, vegetables or potatoes) with higher STP values are regularly used for the cultivation of cereals as well. The higher average STP values in parcels of poultry farms might result from the spreading of poultry manure, which is rich in P. Unfortunately for nutrient load estimations, there is no available information on when, how much and where (i.e. which field parcels) manure is applied. The above findings suggest that certain production lines may be susceptible to the accumulation of nutrients in the soil. In the Eurajoki catchment, poultry farming is a particularly relevant production line — about 15% of all poultry animals in Finland are raised in this region — together with cultivation of special crops, such as roots, vegetables, potatoes and sugar beet. The nutrient accumulation problem may be shared by other regions

with intensified animal husbandry and cultivation of special crops.

The AES regulations limit fertiliser use based on soil fertility. There is growing interest in using organic fertilisers; at the same time, nutrient recycling is receiving more attention as a partial solution for reducing agricultural loading. A database including field parcel-specific information about soil fertility and applied inorganic and organic fertilisers (including manure) and yields would enhance the sustainable management of nutrient recycling, as suggested by some researchers (e.g. Akram et al. 2019; Valve and Salminen 2022). This would require the collection and documentation of data on manure application, which is not enforced at present. The data would facilitate effective supervision on manure application related to environmental permits and minimise unsustainable application of fertilisers. Similarly, independent sampling of soils for fertility analysis would

increase the reliability of STP data. To avoid excessively high costs, this could be limited to one occasion to generate baseline soil quality and fertility data against which STP could be monitored by using samples taken by farmers.

### Assessment of the impact of nutrient recycling

More efficient recycling of nutrients has been perceived as a solution to the problems related to the excess nutrients in manure in some areas in Finland (Lemola et al. 2023). We estimated the relevance of industrial and farm-to-farm manure recycling to the nutrient flows in the Eurajoki catchment using recycling data from the year 2014. The annual volumes of total manure and manure from poultry animals in the studied region were ca. 140,000 tn and 45,000 tn, respectively. Poultry animal manure is nutrient rich and thus contributed 84% and 70%, respectively, to the total manure-P and manure-N contents in the region. According to the 2014 recycling data, roughly up to 4800 tn of manure from poultry farms was used as raw materials for secondary fertiliser production, amounting to up to ca. 11% of the poultry manure volume and up to 9% and 7% of the total manure-P and manure-N, respectively, generated in the region. The produced secondary fertilisers are for retail sale and utilised elsewhere. Hence, this amount can be taken as removed from the area. Additionally, up to ca. 1200 tn (2.6%) of poultry manure was relocated within the area (from poultry farms to crop farms). It should be noted that the volume of poultry manure recycling in 2014 represented the upper end of the overall range of recycled volumes (period 2010–2018).

Earlier, Kirkkala (2017) estimated approximately 13 tn of annual surplus in P use in the upper reaches of the Eurajoki catchment, that is, Yläneenjoki River, Pyhäjoki River and Lake Pyhäjärvi sub-catchments (see Fig. 1), when different streams' P contents, such as from virgin fertilisers and P removed from agricultural products, are all summed up. Judging from our data, the recycling activity had a rather limited capacity for the eutrophication mitigation in the region. The volumes of poultry manure recycling were not high enough to level down the P surplus.

In the current global context, it is particularly important to focus on the sustainable recycling of nutrient surpluses to produce food, as well as energy, by developing an industrial-scale manure processing and recycling capacity. Expanding the use of animal manure on the farms cultivating cereals would support a more even distribution of manure-P and manure-N among the production lines in the region, where several food-processing companies acquire their raw materials through contract farming. As a result, manure would replace non-manure fertilisers, lowering the overall volume of fertilisers applied. Excess application of manure on certain field parcels, as indicated in Fig. 2, could also be avoided. These actions would jointly reduce the nutrient

surplus in the area. However, this would decrease the STP of the fields (Uusitalo et al. 2016) and hence the P loading in the region at a slow pace only. The companies are also largely committed to the water protection programmes in the region and — in some cases — have signed the national water stewardship commitment (Sojamo et al. 2021). In this regard, the more even distribution of animal manure to field plots could be implemented through intensified collaboration among the companies committed to water stewardship. In that case, companies operating with contract farms could facilitate and set targets for the donation and reception of animal manure to achieve a more balanced application of manure.

### Conclusions

We analysed the data on water quality, land use, soil fertility and manure generation and recycling on a regional scale to assess the knowledge base used in the agricultural eutrophication abatement strategies practised in Finland. We found several potential reasons why these strategies had failed to reduce the eutrophying loading from agriculture in Finland. Primarily, the measures had not sufficiently targeted the risk areas. Our analysis showed that P and N loads from agriculture varied substantially among the 46 sub-catchments under study. Nine sub-catchments with the highest loads contributed approximately 50% to the total load, and this pattern among the sub-catchments remained largely similar from year to year. In conclusion, short-term water quality sampling campaigns and the related calculations of nutrient loads would help in finding hot spots of nutrient loads on a sub-catchment level in river catchments. Consequently, additional investigations and abatement measures could be prioritised for these sub-catchments to improve the measures' cost-effectiveness.

Our results identified STP as a variable that explained the DRP or TP loads, albeit at a reduced level of statistical significance in comparison to previous findings. Besides STP and AS soils, the interaction between the two was identified as contributing to nutrient loads in the catchment. Contrary to previous studies, the interaction between STP and ASS seemed to increase P loads. Further studies are required to explore this relation.

Our analysis demonstrated that manure from poultry farms and to a lesser extent, from pig farms, was clearly related to elevated STP in the region. Our analysis also showed that the volume of nutrient recycling was low compared to the total volume of manure nutrients in the region. Based on these findings, we conclude that in addition to the intensification of industrial processing and recycling of manure nutrients, farm-level collaboration would constitute a potential way to allocate manure from poultry and pig

farms to farms cultivating cereals and to decrease the use of fertilisers and nutrient surplus in the area. In practice, manure that is currently applied excessively on field parcels cultivated by poultry and pig farmers would be used on fields that presently receive non-manure fertilisers. Here, we identified companies operating with their contract farmers and committed to water stewardship as additional players to set goals and facilitate this collaboration. However, a more sustainable use of P in manure is observed in only a gradual decrease in STP and thus in the P load (Uusitalo et al. 2016).

To date, there is no available information on when, how much and where (i.e. which field parcels) manure is applied. Moreover, the data on STP, analysed in the samples taken by farmers, may be somewhat biased. We conclude that independent soil sampling would strengthen the reliability of the data and could thus be included in future monitoring of STP in agricultural soils. We also suggest setting up a database containing parcel-specific information on soil fertilities, application of fertilisers and manure, volumes of harvested crops and the prevalence of AS soils. Data production, collection and analyses would jointly facilitate compliance monitoring of the AES and environmental permits, sharing of more accurate information for agri-environmental policy and guidelines, and more effective targeting of agricultural water protection measures in Finland.

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