Drainage for forestry increases N, P and TOC export to boreal surface waters

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Abstract

More reliable assessments of nutrient export to surface waters and the Baltic Sea are required to achieve good ecological status of all water bodies. Previous nutrient export estimates have recently been questioned since they did not include the long-term impacts of drainage for forestry. We made new estimates of the total nitrogen (N), total phosphorus (P) and total organic carbon (TOC) export from forests to surface waters at different spatial scales in Finland. This was done by formulating statistical equations between streamwater concentrations and climate, soil, forest management and runoff variables and spatial data on catchment characteristics. The equations were based on a large, long-term runoff and streamwater quality dataset, which was collected from 28 pristine and 61 managed boreal forest catchments located around Finland. We found that the concentrations increased with temperature sum (TS), i.e. from north to south. Nitrogen, P and TOC concentrations increased with the proportion of drained areas in the catchment; those of N and TOC also increased with the proportion of peatlands. In contrast, with the increasing concentrations of N and TOC with time, P concentrations showed a decreasing trend over the last few decades. According to our estimates, altogether 47,300 Mg of N, 1780 Mg of P and 1814 Gg of TOC is transported from forest areas to surface waters in Finland. Forest management contributes 17% of the N export, 35% of the P export and 12% of the TOC export. Our new forest management export estimates for N and P are more than two times higher than the old estimates used by the environment authorities. The differences may be explained by the long-term impact of forest drainage. The spatial results indicate that peatland forests are hotspots for N, P and TOC export, especially in the river basins draining to the Gulf of Bothnia.

Keywords: Catchment, fertilization, forest management, nutrient concentrations, peatland, streamwater

1. Introduction

In general, the ecological status of surface waters in Finland is good according to the standards set by the EU Water Framework Directive (WFD, https://ec.europa.eu/environment/water/water-framework/index_en.html). The exception, however, is the poor status of the rivers draining to the Baltic Sea (State of the surface waters, https://www.ymparisto.fi/en-US/Waters/State_of_the_surface_waters). The target set by the WFD demands that measures be taken to maintain or achieve good ecological status of all water bodies in Europe. In addition, the Helsinki Commission (HELCOM) has set country-specific nutrient input reduction targets to stop the eutrophication of the Baltic Sea (https://helcom.fi/baltic-sea-action-plan/nutrient-reduction-scheme/targets/). In this context, it is of the utmost importance to be able to make reliable assessments of the nutrient export from forestry land to surface waters and the Baltic Sea. Further, it is important to understand the difference between natural and anthropogenic factors affecting nutrient transport from forest ecosystems so as to be able to evaluate and plan appropriate water protection measures. In Finland, forestry land covers 77% of the land area; 70% of that land is managed (Päivänen and Hånell 2012, Vaahtera et al. 2018). The nature of forest management may thus contribute remarkably to the surface water quality in Finland (Finér et al. 2020, Räike et al. 2020).

In the Baltic Sea drainage basin there are a total of 19.5 Mha of mires (i.e. peatlands), of which 10 Mha have been drained to improve forest growth (Piirainen et al. 2017). The drainage has been intensive, particularly in Finland, where 4.7 Mha of peatlands and 1.3 Mha of mineral soil sites have been drained, mostly in the 1960–1970s (Päivänen and Hånell 2012, Vaahtera et al. 2018). Pristine peatland areas have not been reclaimed for forestry since the 1990s, and current drainage activity is focused exclusively on the maintenance of existing ditches. So far, only short-term, 10-year-long

68 impacts following the first-time forest drainage operation have been included in nutrient export
69 assessments (Kenttämies 2006). Justification for including only short-term impacts was based on a
70 single catchment study where the changes in total nitrogen (N) and total phosphorus (P)
71 concentrations were monitored after forest drainage: the concentrations returned close to the level
72 prior to the drainage within 10 years after the operation (Ahtiainen and Huttunen 1999). In contrast
73 to first-time drainage, ditch network maintenance has been reported to have no significant impact
74 on N concentrations, while the export of P has been associated with the transport of suspended
75 solids (Joensuu et al. 2001, Joensuu 2002, Nieminen et al. 2010). Recently, the existing nutrient load
76 assessments concerning forestry in Finland have been seriously questioned, since they ignore the
77 long-term, pronounced impacts of forest drainage on water quality (Nieminen et al. 2017, 2018). The
78 existence of long-term impacts is also suggested by observations at large geographical scales which
79 show statistically significant relationships between forest drainage and an increasing trend in N
80 concentrations and export in Finnish river basins (Räike et al. 2020). Consequently, the existing
81 assessments need to be revised to include nutrient exports from old drainage areas.
82
83 Current nutrient load assessments (*Vesistöjen kuormitus ja luonnon huuhtouma,*
84 https://www.ymparisto.fi/fi-FI/Kartat_ja_tilastot/Vesistojen_kuormitus_ja_luonnon_huuhtouma)
85 and HELCOM nutrient reduction targets consider only the N and P load to the Baltic Sea (HELCOM
86 2018). They do not include estimates of the total organic carbon (TOC) load. Further, they do not
87 consider changes caused by climatic drivers. Changing environmental conditions (including
88 increasing temperatures), changes in hydrology and flow paths, decreasing acid deposition and
89 changes in land use all cause between-year-variations in nutrient and TOC export to surface waters
90 (e.g. Monteith et al. 2007, Clark et al. 2010, Øygarden et al. 2014, Meyer-Jacob et al. 2019). New
91 research results and changes in environmental conditions surely call for the development of both
92 TOC and new N and P export assessments concerning forestry land in Finland, and for their

93 introduction to the large-scale nutrient loading models used in the national implementation of the
94 WFD (e.g. Huttunen et al. 2016).
95
96 Several methods have been applied for assessing nutrient export from forestry land to surface
97 waters at national level. In Finland, the methods based on land-use specific export coefficients (e.g.
98 Lepistö et al. 2006, Finér et al. 2010), multiplied by the area of different land-use types retrieved
99 from official statistics (Kenttämies 2006, Finér et al. 2010), or from satellite-based GIS-datasets
100 (Lepistö et al. 2006) have been widely used. The export coefficients have been based on empirical
101 paired-catchment studies for the excess N and P export caused by different forest management
102 practices. The advantage of this method is that it can show the relative importance of different
103 practices; its weakness, on the other hand, is that the export coefficients are not available for all
104 forestry practices, including long-term impacts of forest drainage. Another method for assessing
105 nutrient export is to use statistical equations explaining the nutrient export as a function of different
106 factors such as climate, forest type, soil, forest management regime, etc. That method requires data
107 on water quality and must include explaining factors. Since a mosaic of a high number of treatment
108 areas is typical in forestry and treatment areas vary temporally from year to year (with impacts of a
109 single treatment lasting from a couple of years up to tens of years), data are not available for
110 producing equations that would separate the impacts of different forestry practices. The two above-
111 mentioned approaches are simple and logical, and the limited input requirements make them useful
112 for assessments at catchment or national scales (e.g. Johnes and Butterfield 2002). The third
113 methodological approach is nutrient export modelling. Models are increasingly used to support
114 assessments of the ecological status of water bodies and of the recovery options that could be
115 implemented. Modelling examples include: the Moneris model for simulating nutrient emissions
116 (Venohr et al. 2011); the PolFlow model, which simulates the transport of nutrients as a function of
117 soil, lithology and runoff (de Wit 2001); and the N_EXRET model for simulating N export from
118 different sources and N retention in lakes and peatlands (Lepistö et al. 2006). The N_EXRET model

119 includes all major N sources including forestry and background export. Models focusing on nutrient
120 transport and retention over large spatial scales include: the HBV-N model applied to Swedish
121 catchments (e.g. Arheimer and Brandt 1998); the HYPE model developed for the entire Baltic Sea
122 catchment area (Donnelly et al. 2011); and the VEMALA model for all large Finnish catchments
123 (Huttunen et al. 2016). However, these models are generic; N, P and TOC exports solely from
124 forestry land are typically acknowledged in only a limited way. Although several approaches and
125 methods have been developed for assessing nutrient export from forest areas to surface waters,
126 there is still a clear demand for further development of large-scale nutrient export modelling
127 methods, and particularly so for forestry land.
128
129 Our main aim was to assess N, P and TOC export from managed and pristine forest land to surface
130 waters at different spatial scales in Finland. This was done by taking into account the long-term
131 impacts of forest drainage, and changing hydro-meteorological conditions and catchment
132 characteristics in the N, P and TOC export assessments. Our approach was to formulate statistical
133 equations between streamwater N, P and TOC concentrations and climatic, soil and forest
134 management factors, runoff and spatial data on catchment characteristics. The formulation of the
135 equations was based on a sizeable, long-term runoff and streamwater quality dataset collected from
136 28 pristine and 61 managed boreal forest catchments distributed across Finland.
137
138

2. Material and methods

2.1 Catchment data

The study was based on long-term monitoring data collected over 45 years from 1973 to 2018 from the outlet streams of 89 forested headwater catchments in Finland (Fig. 1, Table 1). The data were derived from the national databases maintained by the Finnish Environment Institute (SYKE) (https://www.syke.fi/en-US/Open_information/Open_web_services/Environmental_data_API) and the Natural Resources Institute Finland (Luke)(http://kartta.luke.fi/vesidata/). The catchment dataset was selected to meet the following criteria: 1) water had been sampled for N, P and TOC concentrations at minimum eight times per year during at least three years, 2) there was either data on runoff or the runoff values could be estimated using nearby stations for the water quality monitoring period and 3) the chemical analysis methods used were comparable. The aim with the first two criteria was to reduce the impact of seasonal, very high or very low flow events, or to reduce the domination of a hydrologically very extreme year on streamwater concentrations.

The length of the time series of the water quality data varied: there were 14 catchments for N and 15 catchments for P where the number of water quality monitoring years was ≥ 30; 21 with 11–29 years; and 54 catchments with 3–10 years, respectively. For TOC there were 15 catchments with ≥ 20 monitoring years and 58 with ≤ 10 monitoring years. The N and P analyses started from 1973, and the TOC analyses from 1982. From the late 1970s the number of monitored catchments, and therefore also the available data for our study, increased in the Finnish monitoring programmes (supplementary Fig. A1). The peak in the total number of monitored catchments and data was in 1994; since then it has decreased.

The dataset comprised a total of 89 catchments, on 61 of which forests were managed; 28 catchments were pristine without any human impact significantly affecting the quality of runoff water during the monitoring period. Forest management operations had been carried out with period-specific practices including wood harvesting, forest regeneration, soil scarification, fertilization and forest drainage operations. The pristine catchments were located in national parks or in other protected areas. Peatlands covered on average 31% of the area of the managed catchments and 44% of the pristine catchments (Table 1), which agreed well with the average peatland percentage of 33% on forestry land in Finland (Vaahtera et al. 2018, supplementary Fig. A2 a). On average 24% of the area of the managed catchments was drained, which was comparable to the average of 23% in Finland as a whole (supplementary Fig. A2 b. There were very few lakes (average 0.4%, md 0.0%, max 5.9%) or agricultural fields (0.3%, md 0.0%, max 5.1%) in the catchments (Table 1). Agricultural lands cover 8% and lakes 10% of the total area of Finland (Vaahtera et al. 2018).

All chemical analyses were performed on unfiltered samples. Determination of P was performed by the molybdenum blue method with ascorbic acid as a reductant and digestion with potassium peroxodisulphate. Nitrogen determination was initiated by digestion with peroxodisulphate, followed by reduction of NO_3 with a Cd amalgam and determination of NO_2 by the azo colour method. The TOC samples were sparged after acidification in order to remove the inorganic carbon. TOC was then oxidized to carbon dioxide by combustion and determined by infrared spectrometry. In the chemical analyses the detection limit of N varied from 5 to 10 µg/L, that of P from 3 to 5 µg/L and the detection limit of TOC was 0.5 mg/L. In most cases the analysis results were above the detection limits (Table 1).

189 Runoff was continuously recorded at a V-notch weir and water level recorder. On 26% of the
190 catchments runoff was missing from one or more years. Runoff was complemented by using the
191 runoff from nearby forest catchments of the same type. The annual export of N, P and TOC was
192 calculated for the monitored catchments with the periodic method, in which the temporally nearest
193 concentration observation is multiplied by the discharge observation of each day (e.g. Rekolainen et
194 al. 1991, Kauppila and Koskiaho 2003).
195
196 Data on variables characterizing the climate, land use and forest management in the catchments
197 were collected to be used as explaining variables in the concentration equations. The criterion in
198 selecting these variables was that they should be easily available. The list of variables included:
199 annual precipitation, mean annual temperature, temperature sum (TS) (i.e. the sum of mean daily
200 temperatures exceeding 5°C during the growing season, percentage of peatlands and percentage of
201 forests drained for forestry. Climate characteristics were calculated or estimated from three
202 different types of raw data. Initially, long-term average annual TS (supplementary Fig. A3) and
203 precipitation (1961–1990) and annual values until the year 2006 were estimated with the model
204 created by Ojansuu and Henttonen (1983) using the weather station data of the Finnish
205 Meteorological Institute. Later years were covered by gridded data on a 10x10 km or 1x1 km
206 resolution obtained from the Finnish Meteorological Institute (Venäläinen et al. 2005). The nearest
207 grid point relative to each catchment area was used. The land-use information was collected from
208 the databases of SYKE and Luke, from scientific publications and reports or the topographic database
209 of the National Survey of Finland (Topographic database,
210 https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/expert-users/product-
211 descriptions/topographic-database). Peatland area in the database was based on the soil type and
212 the composition of surface vegetation. According to the Finnish system, sites are classified as
213 peatland sites if the soil type is peat or if ≥ 75% of the ground layer of the surface vegetation was

214 covered by mire plant species (mainly *Sphagnum* spp.) when the site was in a pristine state
215 (Vasander and Laine 1988).
216

217 ## 2.2 Concentration equations and spatial estimations

218

219 ### 2.2.1 Concentration equations

220

221 Mean annual streamwater N, P and TOC concentrations were used as dependent variables in the
222 equations; they were calculated for the catchments by weighting them with the runoff. The
223 independent factors used during the formulation of the equations were the mean annual
224 temperature, TS, annual precipitation, percentage of peatlands of the total catchment area (peat%),
225 percentage of drained forests of the total catchment area (drained%), the calendar year of the water
226 sampling during the monitoring period and forest management status (FM), i.e. whether a
227 catchment had been managed by forestry operations or not (0/1). The significant independent
228 variables were selected for the final equations. The independent variables are known to be
229 correlated with the streamwater quality parameters; in addition, they were easily available for other
230 catchments to facilitate the use of equations in spatial export assessments.
231
232 Equations for N and P concentrations were formulated as linear equations using a mixed-model
233 approach. Transformations on the given independent variables were done to linearize their
234 relationships between the dependent variable:
235

236 $$N, mg\ L^{-1} = \alpha_1\,\mathrm{TS} + \alpha_2\,\mathrm{TS}^2 + \alpha_3 \mathrm{drained\%} + \alpha_4\,\mathrm{peat\%} + \alpha_5\,\mathrm{year} + \alpha_6\,\mathrm{year}^2 +$$

237 $$\alpha_7\,[\mathrm{FM}\,(\mathrm{TS}/1000)^3)] + \mathrm{u}_i + \mathrm{e} \qquad (1)$$

238

$$P, mg\ L^{-1} = \beta_1\ \mathrm{TS} + \beta_2\ \mathrm{peat\%} + \beta_3 \mathrm{drained\%} + \beta_4\ [\mathrm{FM}\ (\mathrm{TS}/1000)]^{3} + \beta_5\ [\mathrm{drained\%} \times \mathrm{year}] + \mathrm{u}_i + \mathrm{e} \quad (2)$$

Both linear and polynomial equations were explored for TOC as well, but turned out they did not fit very well with the data. Eventually, a growth curve was formulated on the temperature sum for the TOC equation:

$$y = \alpha_0[1 - \exp(\alpha_1 TS)]^{\alpha 2} \quad (3)$$

The α0 parameter (the asymptote of the curve) was replaced with a sub-model adjusting the level of the growth curve according to multiple selected variables. Furthermore, variables were also tested outside the growth curve for additive independent effects. As a result, the final equation had a relatively complex formulation:

$$TOC, mg\ L^{-1} = 3 + [\ \alpha_{10} + \alpha_{11}\ \mathrm{drained\%} + \alpha_{12}\ \mathrm{year} + \alpha_{13}\ \mathrm{year}^{2} + \alpha_{14}\ \mathrm{FM} + \alpha_i] \times [1 - \exp(-0.007\ \mathrm{TS})]^{\alpha 2} + \beta\ \mathrm{peat\%} + \mathrm{e} \quad (4)$$

All equations were formulated with a mixed variance structure, and the parameters were solved within the R-program using the nlme-module (Pinheiro et al. 2020). The notations in the equations were:

α, β	parameters for fixed effects
u_i and a_i	parameters for random effects of the observation year i
e	the residual error
drained%	proportion of drained area of the total catchment area (%)

peat%	proportion of peatland area of the total catchment area (%)
TS	temperature sum, d.d.°C (threshold value 5°C)
year	calendar year of water sampling
FM	dummy variable, in which 0=managed catchment and 1=pristine catchment.

The relative performance of different equation formulations and variable combinations was validated with the Akaike criterion. The variable monitoring year was used as a random effects variable describing the annual variation in the dataset. Additionally, the year variable was also included as a fixed effects variable for generalized time trends. When the equations were used for predictions, it was done with the fixed effects variables without random effects.

2.2.2 Spatial N, P and TOC export estimations

Nitrogen, P and TOC exports to streamwater from pristine forest land (background export) and land available for forestry were calculated at national and regional scales. Nitrogen, P and TOC exports were estimated as the product of concentrations calculated with the formulated equations, estimated long-term runoff, and total forest area (including all forestry land) and forest area available for forestry separately for 5448 catchments covering the whole mainland of Finland. The excess export caused by forest management was estimated as the total export from forest land available for forestry minus the background export. The exports were further aggregated to larger area units, i.e. to all Finnish counties (19) and to the whole mainland of Finland. The national N, P and TOC export estimates were based on the total forest area of 25.9 Mha, with 22.2 Mha available for forestry and 5.2 Mha of that area influenced by forest drainage.

289 As input to the concentration equations, the TS and annual precipitation for the 5448 catchments
290 was calculated as for the monitoring catchments presented in Section 2.1. The background export
291 for the entire forest area was obtained using a drained% of 0.5–2% when estimating streamwater
292 concentrations because a small number of natural streams are always present and included in the
293 drained% when it is determined from the topographic data. Data on total forest area (including all
294 forestry land), forest area available for forestry and area covered by peatlands were obtained from
295 the GIS-based national multi-source forest inventory data of the Natural Resources Institute Finland
296 (MNFI 2020, http://www.metla.fi/ohjelma/vmi/vmi-moni-en.htm), and the area covered by drained
297 peatlands from the GIS-based topographic data of the National Survey of Finland (Topographic
298 database 2020). The borders of the 5448 catchments were obtained from a SYKE open spatial
299 database (https://www.syke.fi/en-
300 US/Open_information/Spatial_datasets/Downloadable_spatial_dataset).

301 The mean long-term runoff for the 5448 catchments was estimated with an equation formulated by
302 using SYKE's runoff monitoring data recorded at 212 small catchments during 1981–2010
303 (Hydrological observations 2020,https://www.ymparisto.fi/en-
304 US/Maps_and_statistics/Hydrological_observations) (Appendix 1). The explaining variables in the
305 equation were TS, annual precipitation and the proportion of lakes (lake%) in the catchment. The TS
306 and annual precipitation were obtained for the 5448 catchments as described in Section 2.1, and the
307 lake% from the GIS-based topographic database of the National Survey of Finland (Topographic
308 database 2020).

309 Finally, soil type-specific N, P and TOC export coefficients (kg/ha) were calculated for the following
310 categories: mineral soils, undrained peatlands and drained peatlands. A three-step simulation on the
311 export values from the 5448 catchments was used to produce the export coefficients. First, a base
312 level export value (i.e. export coefficient for mineral soils) was extracted using zero drained% and
313 zero peat%; it was expressed per hectare. Secondly, the peatland effect ((peatland – no peatland)/ha

314 of peatland) was added to the base level, resulting in the coefficient for the peatlands. And finally,
315 the drainage effect ((drainage – no drainage)/ha of drainage area) was added to the peatland
316 coefficient to produce the drained peatland coefficient. The original dataset contained no other
317 information about forestry practices except for drainage. Therefore, the coefficients refer only to the
318 effects of forest drainage as presented in the streamwater concentration equations.
319

3. Results

3.1 Relationships between streamwater quality and catchment characteristics

The parameters of the statistical equations constructed for N, P and TOC concentrations are presented in Table 2. When formulating the equations no predefined conceptual relationships were assumed between the N, P and TOC concentrations; therefore, all three equations were clearly different from each other. The most important explaining variable was the TS, mainly describing the catchment area location on a gradient from southern to northern Finland (Fig. 2a, b and c, supplementary Fig. A3). For P, the effect of TS was linear with the estimations decreasing slightly from south to north. For N, the decrease was stronger and slightly curved. The relationship for TS and the estimated TOC was also curved, but with distinctly high concentrations in southern Finland, low concentrations and small variation in northern Finland. The drained% was the second most important variable in all equations. The largest effect of drained% on the estimated concentrations was observed for P (Fig. 2d) and the smallest for TOC (data not shown). Most of the variables in the TOC equation interacted with the TS, so their effects on the estimated concentrations changed along the geographical gradient. Interaction terms were included for some variables in the other equations as well. All equations included a dummy variable indicating whether the catchment was managed or not. The dummy variable had a significant interaction with the TS in the N and P concentration equations, indicating smaller concentration differences between pristine and managed catchments in the north compared to the south. The peat% was the only completely independent factor in all equations. Nitrogen and TOC concentrations increased with peat%, whereas those of P decreased. Since the 1990s a decreasing trend in the P concentrations (Fig. 3b)

344 and an increasing trend in the N and TOC concentrations were observed with time (Fig. 3a, c). The
345 time-related trend was dependent on the drained% for P, but not for N and TOC. Therefore, P
346 concentrations were simulated for pristine conditions (Fig. 3b).
347
348 Temperature sum, drained%, peat%, the year of sampling and the forest management status
349 (dummy variable) explained from 60 to 80% of the variation in the average concentrations of the
350 studied parameters among the catchments. Based on the comparison between measured and
351 estimated concentrations (residual graphs) (Fig. 4), all equations were relatively unbiased both on
352 annual and average catchment levels. However, the validation showed that the equation for N
353 concentrations provided much better estimations than the equations for P and TOC.
354

355 ### 3.2 Spatial estimates of N, P and TOC export

356

357 Nitrogen, P and TOC exports from forests to streamwater were calculated at national and regional
358 scales. At national scale the mean long-term excess export caused by forest management was 17%
359 of total N, 35% of total P and 12% of total TOC export (Table 3). Based on changes in the
360 concentrations during a calculation period of the last 25 years, the increase in N export was
361 estimated to be about 8%, the increase in TOC 23% and the decrease in P 15%, respectively.
362
363
364 The background export of N and P was highest in the south and decreased towards the north,
365 whereas the background export of TOC was highest in the catchments draining to the Gulf of
366 Bothnia, western Finland, and in parts of east-central Finland; decreasing also towards the north
367 (Fig. 5). The excess export caused by forest management was highest in the catchments draining to
368 the Gulf of Bothnia. Those catchments typically have a flat topography and thus high coverage of

drained peatlands. In the north and in the lake-district in the central and south-east parts of Finland the impact of forestry was lowest.

Nitrogen, P and TOC export coefficients (kg/ha) for mineral soils, for undrained peatlands and for drained peatlands are shown in relation to the TS (> 5°C d.d.) in Figure 6. All export coefficients showed that N, P and TOC export increased with TS on all three soil type categories (Fig. 6). The only exception was the P export, which had no relationship with the TS on drained peatland category. The N and TOC exports were highest from drained peatlands followed by undrained peatlands, and lowest from mineral soils. Phosphorus export was lowest from undrained peatlands, i.e. lower than from mineral soils.

4. Discussion

4.1 Forest drainage and other factors affecting streamwater N, P and TOC concentrations

4.1.1 Geographical factors and peatland coverage

Nitrogen, P and TOC concentrations were found to increase with TS, i.e. from north to south, as found also in previous studies carried out in Finland (Kortelainen and Saukkonen 1998, Kortelainen et al. 1997, Mattsson et al. 2003, Mattsson 2010). Nitrogen and P are mostly leached in organic form, correlating considerably with the leaching of TOC in boreal streams (e.g. Kortelainen and Saukkonen 1998, Kortelainen et al. 1997, Mattsson et al. 2003, Lepistö et al. 2008). Therefore, the geographical pattern in concentrations may reflect the higher biomass and input of organic matter from forests to streamwaters in the south (Mattsson et al. 2003).

393 Both N and TOC concentrations increased with peat%, supporting previous results showing that
394 peatlands are important contributors to N and TOC concentrations in streamwater (e.g. Hemond
395 1990, Dillon and Molot 1997, Kortelainen et al. 1997, 2006, Aitkenhead et al. 1999, Mattsson et al.
396 2005, Sarkkola et al. 2009, 2012). Due to high water levels in peatlands throughout the year, surface
397 runoff is dominant, which facilitates the leaching of organic matter. Phosphorus concentrations were
398 found to decrease together with peatland percentage. In previous studies, no significant correlation
399 was observed between peatland percentages and leaching of P (Kortelainen and Saukkonen 1998,
400 Mattsson et al. 2003, Kortelainen et al. 2006). Our results indicated that P is in low supply and tightly
401 retained in catchments with pristine peat soil (see Fig. 6b), as previously suggested by Väänänen et
402 al. (2008).

403

404 ### 4.1.2 Impacts of climate and deposition

405

406 The results showed an increasing trend in the concentrations of N and TOC. The increase in TOC
407 concentrations was 23% during a significant calculation period of 25 years from the 1990s to 2010s.
408 Nitrogen concentrations also increased, but there was more fluctuation, with a clearer increase from
409 the early 1990s towards the early 2010s. Increasing trends in TOC concentrations have been
410 reported in numerous studies from northern Europe and North America (e.g. de Wit et al. 2016). In
411 Finland, increasing TOC concentrations have been detected in small forest streams in eastern Finland
412 (Sarkkola et al. 2009), in small lakes (Vuorenmaa et al. 2006) and in large rivers flowing to the Baltic
413 Sea (e.g. Lepistö et al. 2008, 2014, Räike et al. 2016, Asmala et al. 2019). Changing climate,
414 decreasing acid deposition and changes of land use have most probably contributed to the increased
415 concentrations, while also interacting with each other (e.g. Monteith et al. 2007, Clark et al. 2010,
416 Meyer-Jacob et al. 2019). Climate change can affect organic carbon (OC) and nutrient cycling in
417 multiple ways. Increased temperature enhances the mineralization of soil organic matter and

418 decomposition of peat soils (Freeman et al. 2001). In addition, hydrological conditions and processes
419 are undergoing major changes due to climate warming. Large areas are becoming warmer and
420 wetter in the boreal region and these trends are expected to continue in the future (Arheimer et al.
421 2005, Huttunen et al. 2015, de Wit et al. 2016). This is resulting in increasing runoff, accelerating
422 biogeochemical processes and leaching of elements (Mellander et al. 2018). Climate change-related
423 factors have already contributed to increasing nutrient fluxes (e.g. Øygarden et al. 2014).
424
425 During the past few decades atmospheric deposition of sulphate has decreased considerably, which
426 has potentially increased mobilization of soil OC (Kalbitz et al. 2000). Based on time series data from
427 lakes and streams in North America and Europe, Monteith et al. (2007) showed that rising trends in
428 dissolved organic carbon (DOC) concentrations between 1990 and 2004 can be explained by changes
429 in deposition chemistry and catchment acid sensitivity. Increases of DOC appeared to be unrelated
430 to climatic factors in their study, but, however, closer integration of research into pollutant and
431 climatic impacts was urged.
432
433 Oni et al. (2013) ascribed some of the change in DOC concentrations at a long-term monitoring site
434 in northern Sweden to the subtle effects of declines in acid deposition. In contrast, Sarkkola et al.
435 (2009) found that hydro-meteorological factors were more important than declining acid deposition
436 in predicting TOC trends in boreal headwater streams in eastern Finland located in a low deposition
437 area. In 28 large Swedish river catchments, decline in anthropogenic sulphate deposition was related
438 to increased organic matter in streamwater, but explaining organic matter variability flow emerged
439 as an even more important driver (Erlandsson et al. 2008). Both changing climate and decreasing
440 acid deposition were found to affect the increase in long-term C and N concentrations when looking
441 at a subset of 12 catchments of our dataset with 41-year-long monitoring data (Lepistö et al. 2020);
442 further analysis is currently being done (Lepistö et al. unpubl.).
443

4.1.3 Forest fertilization and drainage

Phosphorus concentrations decreased in contrast to those of N and TOC during the measurement period, an occurrence only found, however, on managed catchments. Since runoff did not significantly change during the measurement period (Korhonen and Kuusisto 2010, Räike et al. 2020), the export of P had also significantly decreased since the 1970s. The decrease in P concentrations was contrary to the results of Nieminen et al. (2017, 2018), who found an increase in P concentrations by drainage age. Drainage age increased during the measurement period, since most of the peatland drainage in Finland took place in the 1960s–1970s (Päivänen and Hånell 2012). One reason for the decrease in P concentrations could be the diminished impacts of P-fertilization on peatland forests. In Finland, forest fertilization started in the 1950s, was at its highest in the mid-1970s (250,000 ha/year), decreased close to zero in the early 1990s and is now again gradually increasing (Vaahtera et al. 2018). During the 40-year period from 1950 to 1990 a high proportion of peatland forests were fertilized (e.g. Keltikangas et al. 1986). That was done mainly with P-fertilizers that may result in elevated P concentrations in streamwater for more than 15 years (Nieminen and Ahti 1993, Nieminen et al. 2018). The use of wood ash fertilization replaced other P-fertilizers in the late 1990s. As opposed to other P-fertilizers, ash fertilization does not notably increase the leaching of P to streamwaters if not deposited in ditches (Piirainen et al. 2013). The decreasing trend in P concentrations could thus be partly explained by the disappearance of the effects of P-fertilization on peatland forests (Tattari et al. 2017, Nieminen et al. 2018). The high specific P export coefficients from drained peatlands compared to undrained peatlands or mineral soils also indicated that P-fertilization has had a strong impact on P concentrations in streamwater. Another explanation for the decrease in P concentrations and export could be the increased retention of P to forest biomass, something which has been suggested as a factor affecting the decreasing P concentration trends found in boreal lakes in Sweden (Huser et al. 2018).

We found a clear increase in the concentrations of N, P and TOC and the proportion of drainage area in the catchments. The increase in the concentrations of N with the proportion of drainage area was in accordance with the conclusions of Nieminen et al. (2018). However, they did not find a significant relationship between P concentrations and the proportion of drained peatlands, while Nieminen et al. (2017) did not find it either for N or P concentrations. Instead, drainage age was a significant factor in explaining N and P concentrations in their studies (Nieminen et al. 2017, 2018). Although we expected the drainage age to increase during the measurement period, we did not have exact data on the drainage age of the catchments, and in our study the proportion of drainage can also include the impacts of other forestry practices on the catchments, since no data separating all forest management practices exists. However, drainage for forestry has been shown to contribute to the increasing trends of OC and N fluxes in large river basins (Asmala et al. 2019, Räike et al. 2020). Drainage increases decomposition of surface peat and mineralization of organic matter as well as soil erosion, and therefore also the export of elements in both dissolved and particulate forms (Ahtiainen and Huttunen 1999). These drainage impacts have been suggested to last – or even increase – over several decades after drainage (Nieminen et al. 2017, 2018).

4.2 Nitrogen, P and TOC export in different spatial scales

New national N, P and TOC export estimates were produced, and they also included the impacts of forestry drainage. We also created, for the first time, maps to show the spatial variation in background export and excess export caused by forestry practices in Finland. Our total N and P export estimates from forests to surface waters were of the same order of magnitude as earlier ones: 41,000–48,000 Mg/year for N, 1400–2300 Mg/year for P and 1.5–1.8 Gg/year for TOC (Sallantaus 1985, 1988, Kortelainen et al. 1997, Kortelainen and Saukkonen 1998, Lepistö et al. 2006, Finér et al. 2010, 2018). In the estimates describing the excess export caused by forestry practices

there is much more variability. The excess export estimates of N have varied from 1600 to 14,600 Mg/year and those of P from 130 to 1100 Mg/year (Lepistö et al. 2006, Kenttämies 2006, Kenttämies and Haapanen 2006, Finér et al. 2010, 2018, Nieminen et al. 2017, 2018): our estimates fell within those ranges. The large variation in the previous excess export estimates may have been caused by the differences in the datasets, time periods and estimation methods. The lowest estimates (Kenttämies 2006, Kenttämies and Haapanen 2006, Finér et al. 2010) did not include the impact of old drainage areas in contrast to the largest estimates (Lepistö et al. 2006, Nieminen et al. 2017, 2018, Finér et al. 2018). Compared to the previous estimates, our concentration equations were formulated using a larger dataset, and with better temporal and biogeographical coverage. When comparing our estimates to the official estimates (*Suomen virallinen tilasto* 2018, http://www.doria/handle/10024/67152), the percentage of forestry's contribution to the total anthropogenic export of N to Finnish watercourses more than doubled, from 6% (3250 Mg/year^{-}) to 12% (8200 Mg/year), and that of P from 8% (230 Mg/year) to 14% (620 Mg/year).

In this study, we could not separate out the effects of different forest management practices on streamwater quality, but we conclude that the drainage effect was much bigger than the combined effect of the other forestry practices on the catchments. That conclusion is based on the comparison of our results with those of Finér et al. (2010), who estimated that in 2006 the excess export of N caused by forest regeneration, ditch network maintenance and forest fertilization together was only 1600 Mg/year, and that of P 130 Mg/year. Those excess export estimates are only 20% of our total N and P export estimates; most of the difference may be explained by the export from the drained forests, which cover 23% of the forest area in Finland. Our conclusion also agrees with the results of Nieminen et al. (2017, 2018), who showed that drainage areas contribute significantly more and for longer to the export of N and P than previously known (Ahtiainen and Huttunen 1999, Kenttämies 2006). These new results totally change the earlier understanding of the short-term impact of forest drainage.

Our N concentration equation explained well the variation in the data, whereas the unexplained variation was relatively high for P and TOC. The equations may be improved by adding more data from pristine catchments located in southern Finland and managed catchments in northern Finland. Since the forests are less intensively managed in the north and land use generally is intensive in the south, there were a small number of monitored managed catchments in the north and pristine catchments in the south. The equations could also be improved by adding more explaining variables, e.g. those related to soil, tree stand and forest management (Mattsson et al. 2003, Kortelainen et al. 2006). In this study, we were able to use only a small number of explaining variables, since we had to limit them to those which are easily available for use in assessing N, P and TOC export for all Finnish forest catchments. The trends that we observed in N, P and TOC concentrations also suggest that the concentration equations should be continuously updated when used for assessing the export from forests to surface waters.

Conclusions

We assessed N, P and TOC export from forests to surface waters at different spatial scales. The national estimates are useful for the implementation of the EU's WFD and for reporting to HELCOM. The regional estimates identify the differences in export levels and facilitate their use in developing water protection measures in forestry. The background export increases in general from north to south, and the N and TOC exports are also high in the areas with high peatland percentage. Forest management increases the export of N and TOC, and in particular that of P. The impacts of forest management, mostly due to the old drainage areas, are largest in the catchments draining to the Gulf of Bothnia. That particular finding can be of potentially great use in targeting water protection measures for these catchments; it also highlights the importance of water protection particularly on

peatlands drained for forestry. New water protection measures need to be developed – in addition to those already in use in ditch network maintenance operations – in order to decrease the load from old drained peatlands. Our results also call for continuous monitoring of water quality, as well as an increase in the understanding of the mechanisms controlling the leaching of N, P and TOC from pristine and managed forest catchments.

Acknowledgements

This study was funded by the Finnish government´s analysis, assessment and research activities, and supported by the projects FRESHABIT LIFE IP (LIFE14/IPE/FI/023) and BIOWATER Nordic Centre of Excellence (Nordforsk, project number 82263).

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Tables

Table 1. The characteristics of the catchments. Temperature sum, the amount of precipitation and runoff are long-term (1961–1990) annual values. Nitrogen, P and TOC concentrations and exports are calculated from the annual catchment data. For N the number of annual data was 893, for P 885 and for TOC 666.

	Managed catchments, n=61				Pristine catchments, n=28			
Variable	$\overline{x}$	md	min	max	$\overline{x}$	md	min	max
Surface area, ha	501	69	4	5322	403	90	6	4209
Temperature sum, d.d.°C	1077	1124	639	1340	976	965	554	1335
Precipitation, mm	561	562	439	625	564	578	428	625
Runoff, mm	305	279	193	503	357	358	244	485
Peatlands, % of area	31	33	0.0	75	44	41	6	95
Drainage, % of area	24	24	0.0	75				
Agricultural fields, % of area	0.5	0.0	0.0	5.1	0.0	0.0	0.0	0.5
Lakes, % of area	0.6	0.0	0.0	3.4	0.0	0.0	0.0	5.9
N, mg/L	0.61	0.58	0.05	1.96	0.37	0.33	0.12	0.95
P, mg/L	0.027	0.024	0.003	0.106	0.011	0.009	0.003	0.050
TOC, mg/L	22.1	20.3	2.4	49.8	17.6	13.6	4.1	45.9
N, kg/ha	1.85	1.71	0.16	7.69	1.29	1.14	0.37	4.01
P, kg/ha	0.084	0.072	0.006	0.424	0.041	0.031	0.006	0.209
TOC, kg/ha	67.5	60.5	7.2	227.2	62.2	56.4	11.4	176.9

Table 2. Fixed and random factors for the equations explaining the relationships between streamwater N, P and TOC concentrations and temperature sum (TS.), peatland percentage (peat%) and percentage of drained peatlands (drained%) out of the total catchment area, year of sampling (year), FM=dummy variable, 1 for pristine and 0 for managed catchments. The equations are presented with R^2 and RMSE values, and the significance of individual variables with t-values and related probabilities. The R^2 and RMSE values are presented separately including annual variation (Annual) and for catchment averages (Catchment).

	Variable	Parameter	Value	t-value	p-value		Annual	Catchment
N	*fixed effects*							
	TS	α1	-0.00105	-3.10	0.002	R^2	0.71	0.80
	TS**2	α2	1.00E-06	5.83	0.000	RMSE	0.15	0.11
	drained%	α3	0.005042	11.41	0.000	RMSE%	27.5	21.4
	peat%	α4	0.00162	4.86	0.000	N	1126	89
	year	α5	-0.00113	-1.87	0.068			
	year**2	α6	6.59E-07	2.29	0.027			
	FM* (TS/1000)**3	α7	-0.08621	-6.51	0.000			
	random effects							
	year (σ)	ui	0.028197					
		e	0.155613					
P	*fixed effects*							
	TS	β1	1.69E-05	20.11	0.000	R^2	0.51	0.60
	peat%	β2	-0.00011	-5.20	0.000	RMSE	0.01	0.01
	drained%	β3	0.015974	5.39	0.000	RMSE%	50,1	40.4
	FM * (TS/1000)**3	β4	-0.00255	-2.56	0.011	n	1115	88
	drained% * year	β5	-7.7E-06	-5.21	0.000			
	random effects							
	year (σ)	ui	0.001874					
		e	0.012479					
	fixed effects							
TOC		α10	-65261.9	-3.28	0.001	R^2	0.55	0.64
	drained%	α11	0.220008	8.53	0.000	RMSE	6.56	6.22
	year	α12	64.90536	3.26	0.001	RMSE%	31.1	28.6
	year**2	α13	-0.01613	-3.24	0.001	n	866	83
	FM	α14	-3.01291	-2.64	0.008			
		α2	522.9988	9.79	0.000			
	peat%	β	0.120611	7.53	0.000			
	random effects							
	year (σ)	ai	1.945588					
		e	6.628324					

800 Table 3. Total N, P and TOC excess export from all forest areas in mainland Finland divided into
801 excess export caused by forest management and background export. Estimates are calculated with
802 the concentration equations, long-term runoff and land-use data.

803

	Excess export by forestry	Background Export	Total
N, Mg/Year			
	8200	39,000	47,300
P, Mg/Year			
	620	1160	1780
TOC, Mg/Year			
	222,000	1,592,000	1,814,000

804

805

806

Figure captions:

Fig. 1. Location of the managed (n=61) and pristine (n=28) catchments used for assessing total (N), total (P) and total organic carbon (TOC) export to surface waters in Finland.

Fig. 2. Relationships between average measured concentrations of a) N, b) P and c) TOC and temperature sums (>5°C) on managed (filled circles) and pristine (empty circles) catchments. Additionally, subfigure d) shows measured (empty circles) and estimated (filled circles) P concentrations as a function of drained%. The regression lines represent estimated concentrations based on the equations given in Table 2.

Fig. 3. Mean annual measured and estimated concentrations of a) N, b) P and c) TOC during the observation periods. The time-related trend was dependent on the drained% for P but not for N and TOC, and therefore the trends in P concentrations are shown separately for pristine and drained catchments.

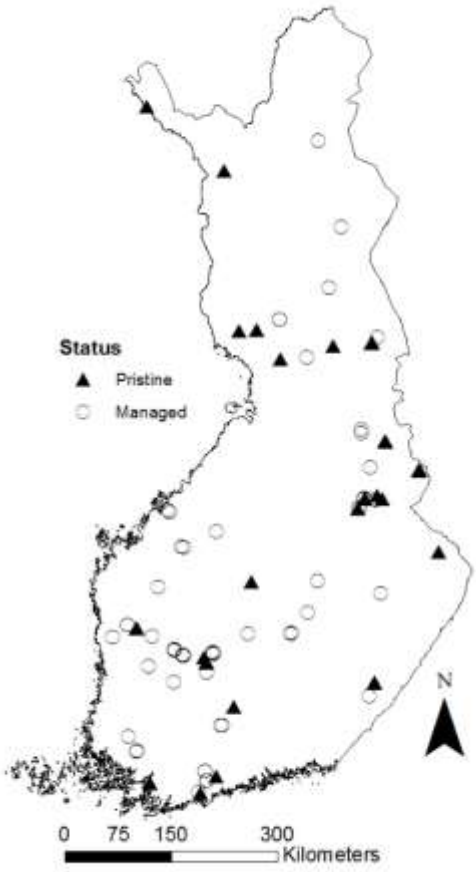
Fig. 4. Relationships between the observed streamwater a) N, b) P and c) TOC concentrations and those estimated with the equations presented in Table 2. Filled circles show the mean values of the annual concentrations on each of the catchments and the empty circles all individual annual concentrations for the measurement years on the catchments.

Fig. 5. Background export of a) N, b) P and c) TOC, and excess export caused by forest management calculated for 5448 catchments covering the whole of mainland Finland. The size of the symbols in the excess export maps are scaled to the proportion of drained peatlands on the catchment.

832 Fig. 6. Nitrogen, P and TOC export coefficients (kg/ha) for drained peatlands, pristine peatlands and
833 mineral soils shown in relation to the temperature sum (> 5^{o}C, d.d.). Coefficients are calculated by
834 the concentration equations (1–4) and long-term runoff on the area of each soil category. Each dot
835 represents an average value calculated for Finnish counties (n=19, supplementary Fig. A3).
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838 # Figures, revisions in a separate file

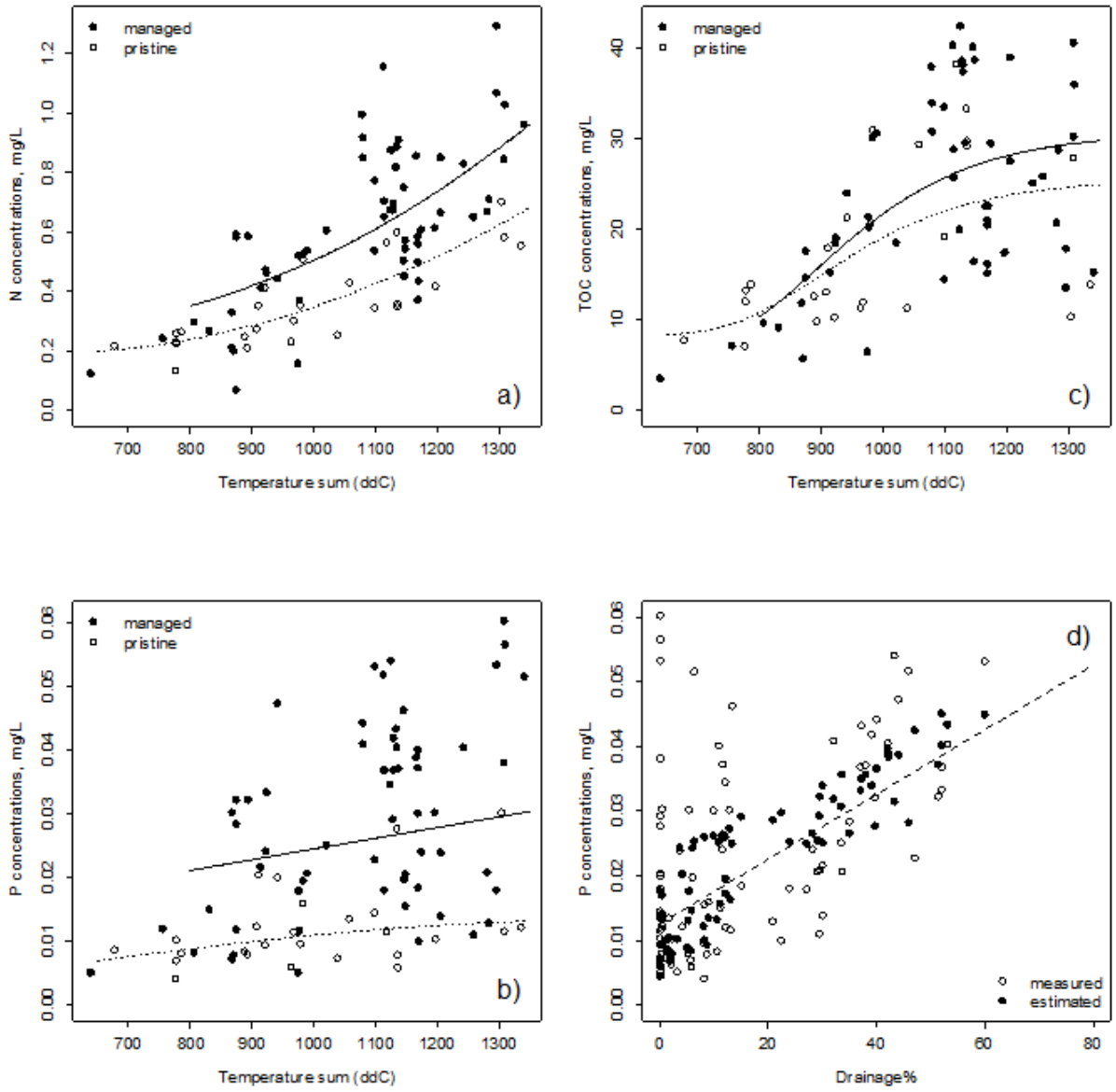
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841 Fig. 1.

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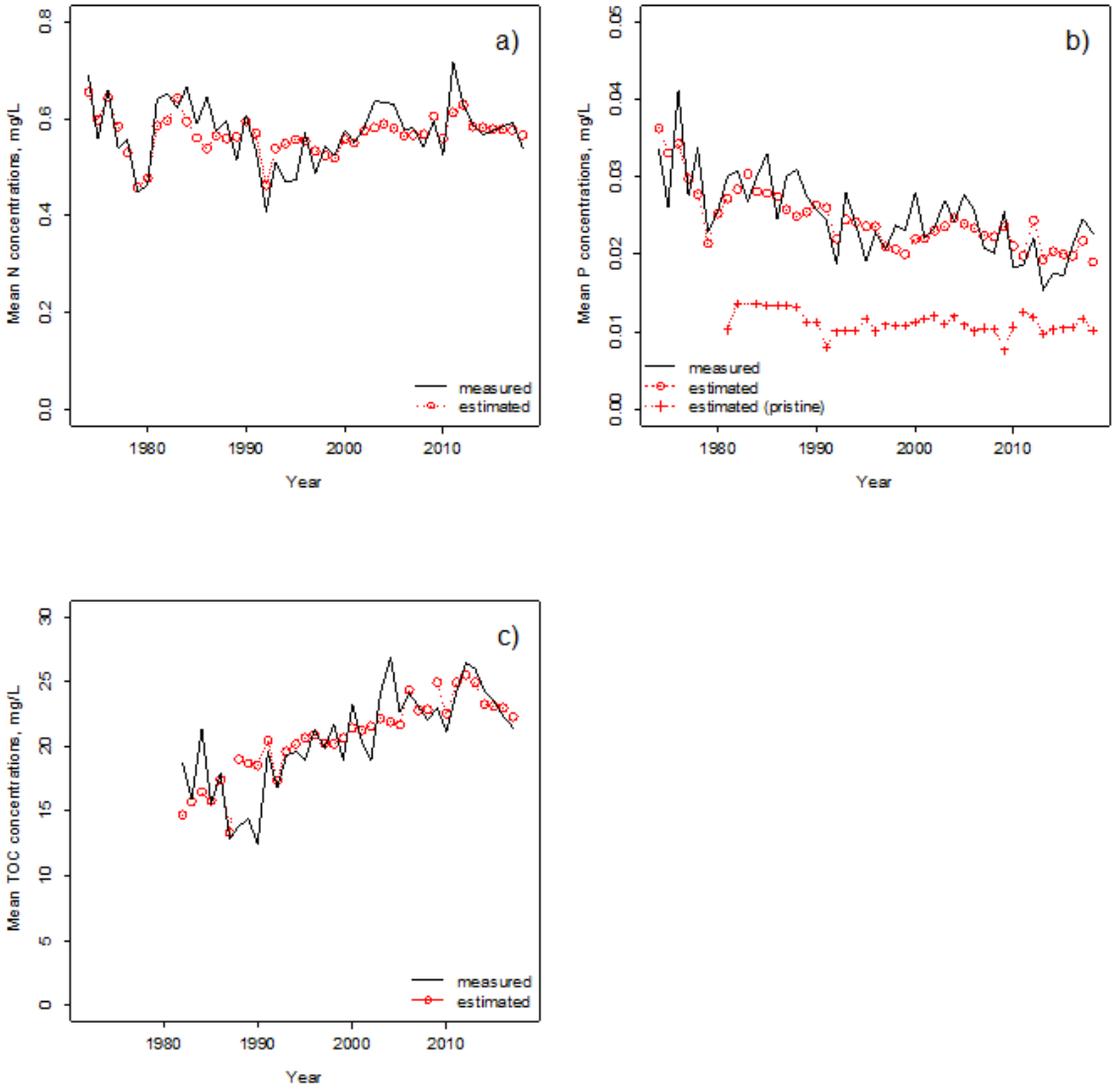


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845 Fig. 2

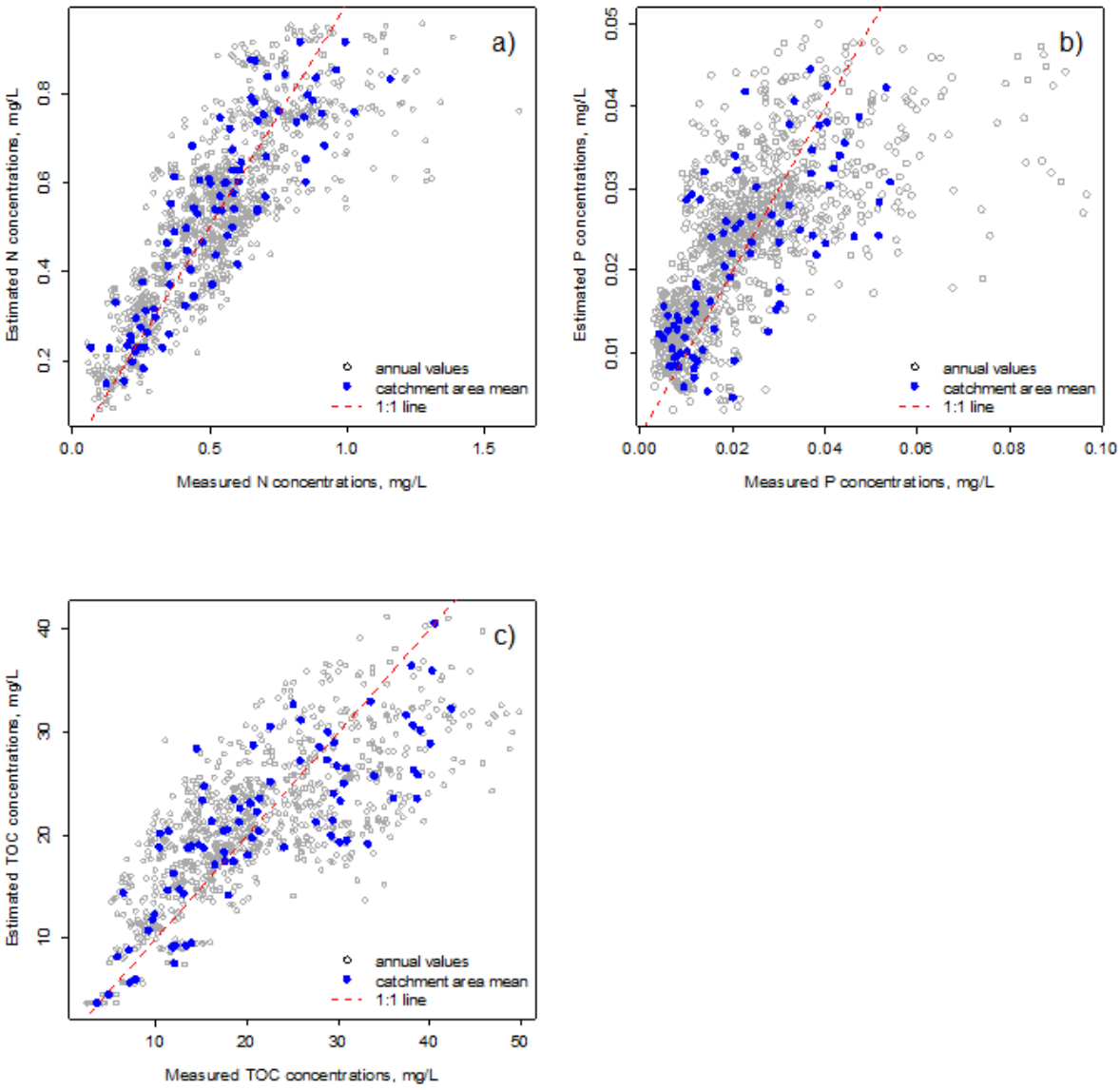
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848 Fig. 3

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851 Fig. 4

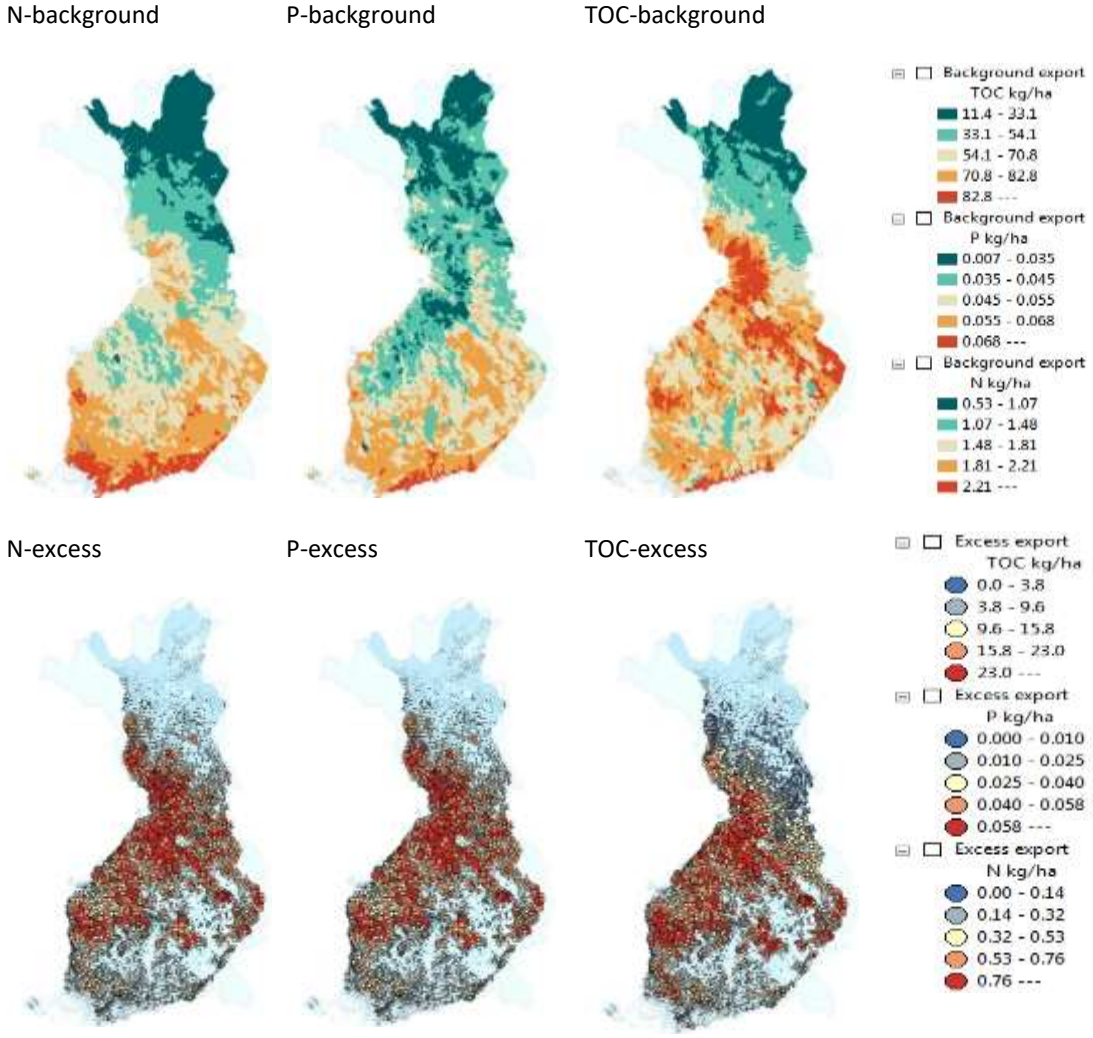
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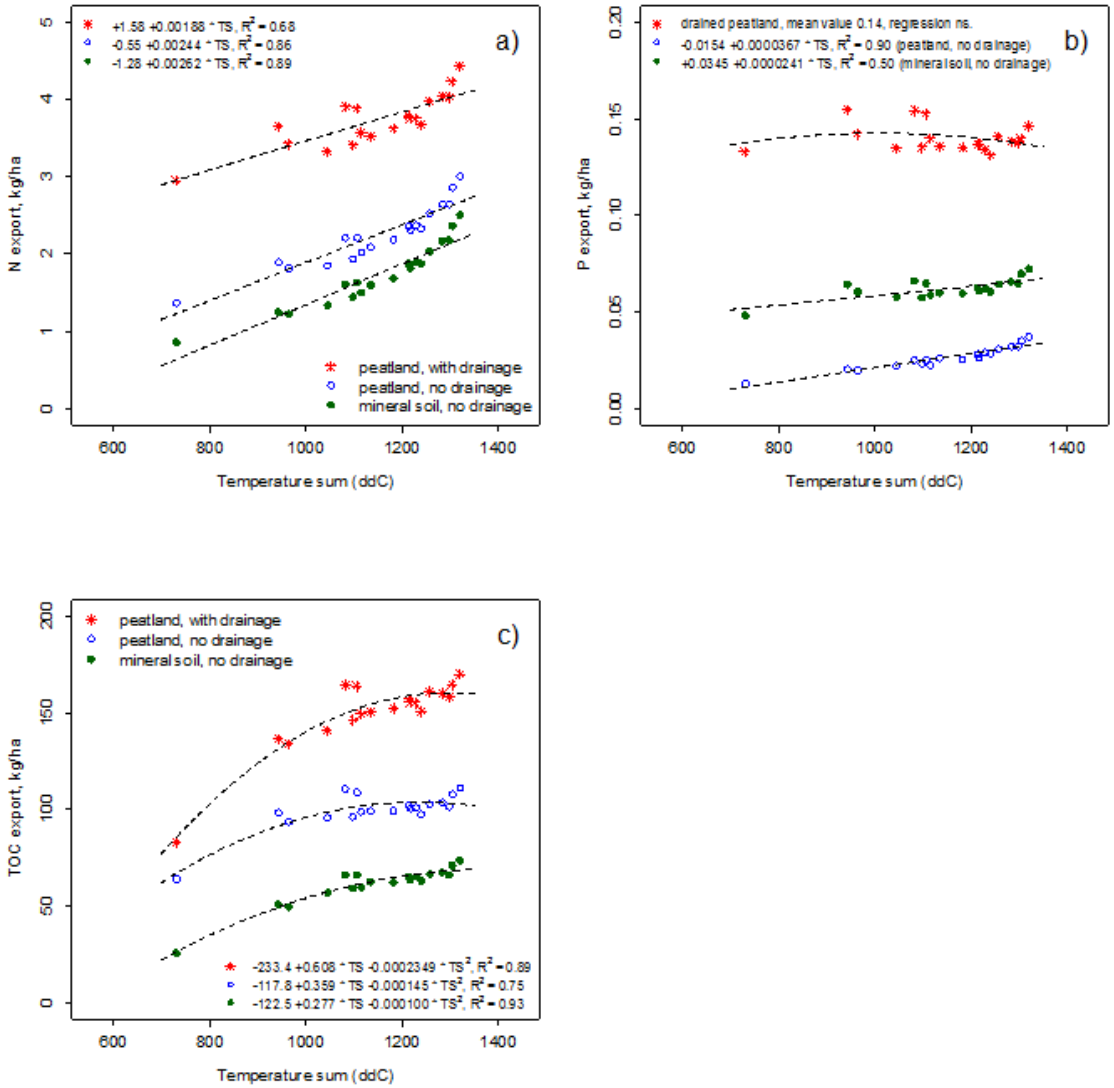
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859 Fig. 5

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863 Fig. 6

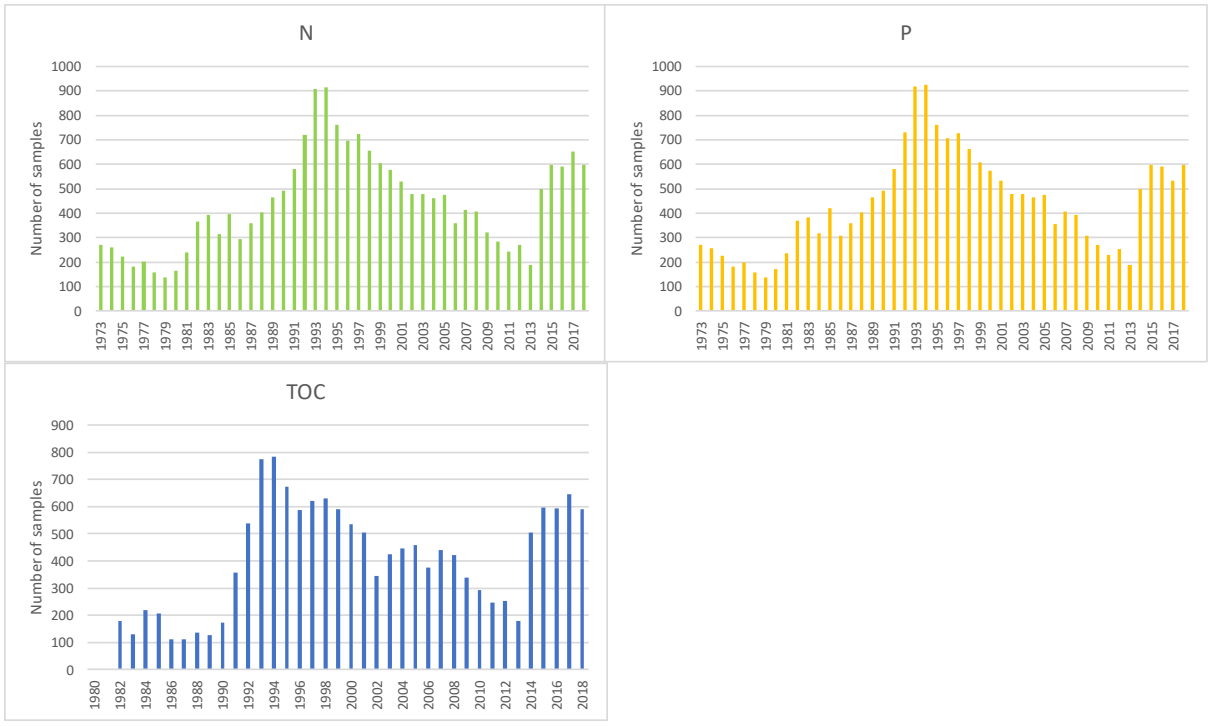
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866 **Supplementary material, Please see separate file for the revisions**

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870 Fig. A1. Number of water quality samples from 1973 to 2018 for N and P, and from 1982 to 2018 for

871 TOC.

872

873

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875

876 **Appendix 1**

877 **Method for estimating runoff to all Finnish catchments**

878 The dataset for streamwater flow contained mean discharge (MQ, m^3s^{-1}) as the main variable. MQ
879 was divided by the catchment area (km^2) and used as the dependent variable (qkm) in a mixed linear
880 model with the independent variables temperature sum (*TS*), precipitation (RS) and proportion of
881 lakes (lake%):

882 $$qkm = \alpha_0 + \alpha_1 TS + \alpha_2 \mathrm{RS} + \alpha_3 \,\mathrm{lake\%} + \mathrm{u}_i + \mathrm{e} \quad \text{(A1)}$$

883

884 where α = fixed effects parameters, u_i = random effects and e = residual error

885 The data consisted of 212 catchment areas within 49 main catchment areas. The main catchment
886 was entered as a random effects variable (region). Predictions were made using the region-specific
887 parameters (including random effects) for catchments when possible. Catchment areas without
888 region-specific parameters received predicted values from fixed effects variables only. The random
889 effects are described with the standard deviation (σ in Table A2); the region-specific parameters are
890 not presented. The predicted values were converted to annual water volume for generalized export
891 calculations, and also to runoff values (mm) for data presentation mainly. Figure A2 shows the
892 residual plot for the equation (A1) and the runoff shown in relation to the temperature sum of the
893 catchment.

894

Table A1. Estimated parameters and validation characteristics for the equation (A1) explaining the relationship between discharge ($m^3/s\ km^2$) and temperature sum (TS), precipitation (mm) and proportion of lakes (lake%).

Variable	Parameter	Value	t-value	p-value	Model validation	
fixed effects						
(Intercept)	α_0	0.015317	8.87	0.000	R^2	0.74
TS	α_1	-7.7E-06	-7.05	0.000	RMSE	0.0011
RS	α_2	7.18E-06	2.01	0.046	RMSE%	10.3
lake%	α_3	-6.9E-05	-3.77	0.000	N	212
random effects					Groups	49
region (σ)	u_i	0.001571				
	e	0.001226				

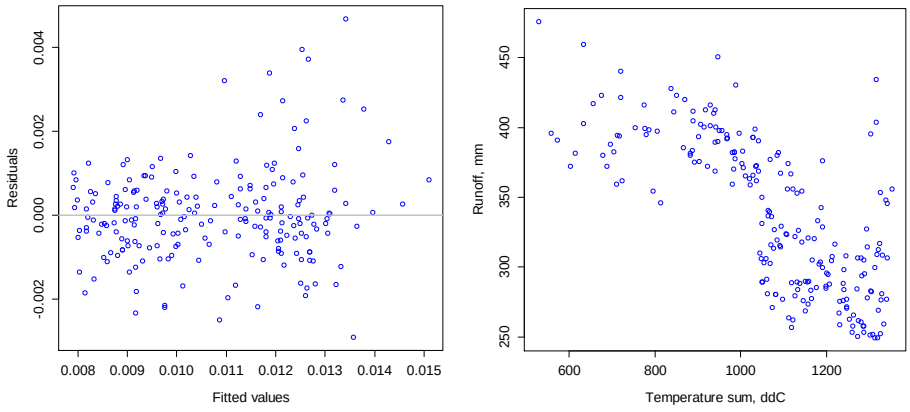


Fig. A2. Residual plot for the equation (A1) (left), and the estimated values converted to runoff and shown in relation to temperature sum of the catchment area (right).