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Combined use of satellite image analysis, land-use statistics, and land-use-specific export coefficients to predict nutrients in drained peatland catchment

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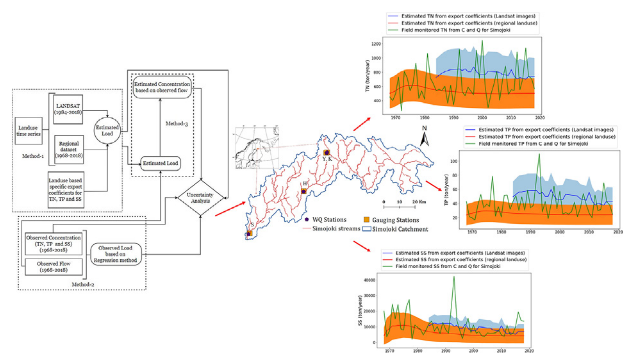
HIGHLIGHTS

- Nutrient and SS estimations were predicted by comparing different approaches.
- Peatland drainage strongly affected TN, TP, and SS loads and concentrations.
- Uncertainty in estimates captured 29–90% of measured TN, TP, and SS values.
- The uncertainty in export coefficients decreased with catchment size.

GRAPHICAL ABSTRACT



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ABSTRACT

Maintaining and improving surface water quality requires knowledge of nutrient and sediment loads due to past and future land-use practices, but historical data on land cover and its changes are often lacking. In this study, we tested whether land-use-specific export coefficients can be used together with satellite images (Landsat) and/or regional land-use statistics to estimate riverine nutrient loads and concentrations of total nitrogen (TN), total phosphorus (TP), and suspended solids (SS). The study area, Simojoki (3160 km^2) in northern Finland, has been intensively drained for peatland forestry since the 1960s. We used different approaches at multiple sub-catchment scales to simulate TN, TP, and SS export in the Simojoki catchment. The uncertainty in estimates based on specific export coefficients was quantified based on historical land-use changes (derived from Landsat data), and an uncertainty boundary was established for each land-use. The uncertainty boundary captured at least 60% of measured values of TN, TP, and SS loads or concentrations. However, the uncertainty in estimates compared with measured values ranged from 7% to 20% for TN, 0% to 18% for TP, and 13% to 43% for SS for different catchments. Some discrepancy between predicted and measured loads and concentrations was expected, as the method did not account for inter-annual variability in hydrological conditions or river processes. However, combining historical land-use change estimates with simple export coefficients can be a practical approach for evaluating the influence on water quality of historical land-use changes such as peatland drainage for forest establishment.

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1. Introduction

Boreal catchments often comprise a mosaic of water systems and land-use patterns, which poses challenges when evaluating the effects of human activities and ecosystem processes on water quality (Meynendonckx et al., 2006; Sliva and Williams, 2001). Knowledge of cause-effect relations between land-use change activities and ecological status and water quality is needed to inform and direct catchment-scale and soil management operations (Turner et al., 1990). Increased runoff and elevated nutrient concentrations and loads have been commonly observed in the Nordic region in recent years (Marttila et al., 2018). Climate change and intensified land-use pressures are suggested to result in increasing trends in dissolved organic carbon (DOC) and nitrogen (N) exports to boreal rivers (Asmala et al., 2019; Lepistö et al., 2008). In Finland, studies also suggest legacy effects from past land-use changes on peatlands (Nieminen et al., 2018b). For instance, forest clear-cutting can immediately increase nutrient and sediment loads, although the effect attenuates with time (Palviainen et al., 2014). Peatland drainage and ditch maintenance are other activities causing loading in peatland-dominated catchments (Ahtiainen and Huttunen, 1999; Kreutzweiser et al., 2008). Further, recent findings suggest a decadal influence, especially from old drainage areas (Ojanen et al., 2019). This confirms the importance of evaluating both the current status and previous history of peatland forestry (Nieminen et al., 2017). There is a particular need for spatiotemporal information on nutrient loads within and across catchments (Finér et al., 2021; Palviainen et al., 2016).

Estimating nutrient and sediment exports using process models is data-intensive, computationally expensive, and relies on large numbers of parameters. This decreases the practical applicability for predicting relative effects of land-use operations such as peatland drainage, which is common in boreal regions. Land-use-specific export coefficients are frequently used as a simple and practical approach to estimate nutrient load and sediment export at catchment, regional, and national levels (Finér et al., 2010; Johnes and Butterfield, 2002; Lepistö et al., 2006). Export coefficient values are typically obtained in long-term, small-scale experiments in which discharge and water quality are monitored after specific land-use practices (Launiainen et al., 2014). The values represent annual load from given forestry or land-use practice per unit area of the load source. The use of export coefficients is easy, robust, and requires significantly fewer input data than use of physically–based, distributed, and semi-distributed nutrient export models (Pechlivanidis et al., 2011). However, export coefficients are static in time and lack catchment-specific information (Launiainen et al., 2014), e.g., on leaching and retention processes or inter-annual hydrological variability. The use of specific runoff coefficients is a valuable tool for assessing land-use effects on nutrient runoff, especially in remote areas, but the method needs to be upscaled for assessment of river basin scale land-use changes and related changes in water quality.

In this study, we built an assessment framework based on land-use-specific export coefficients and historical and current land-use data extracted from Landsat images (1984–2018) and regional statistics (1968–2018). The aim was to compared predictions of nutrient load and sediment export against measured total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) loads in the peatland-dominated Simojoki catchment in northern Finland and its sub-catchments. Specific objectives were to: (1) determine annual load and annual mean stream water concentrations and their uncertainties, (2) investigate whether land-use information derived from different sources can predict load and concentration patterns and trends, and (3) introduce uncertainty ranges for land-use-based estimates of loads and concentrations of TN, TP, and SS.

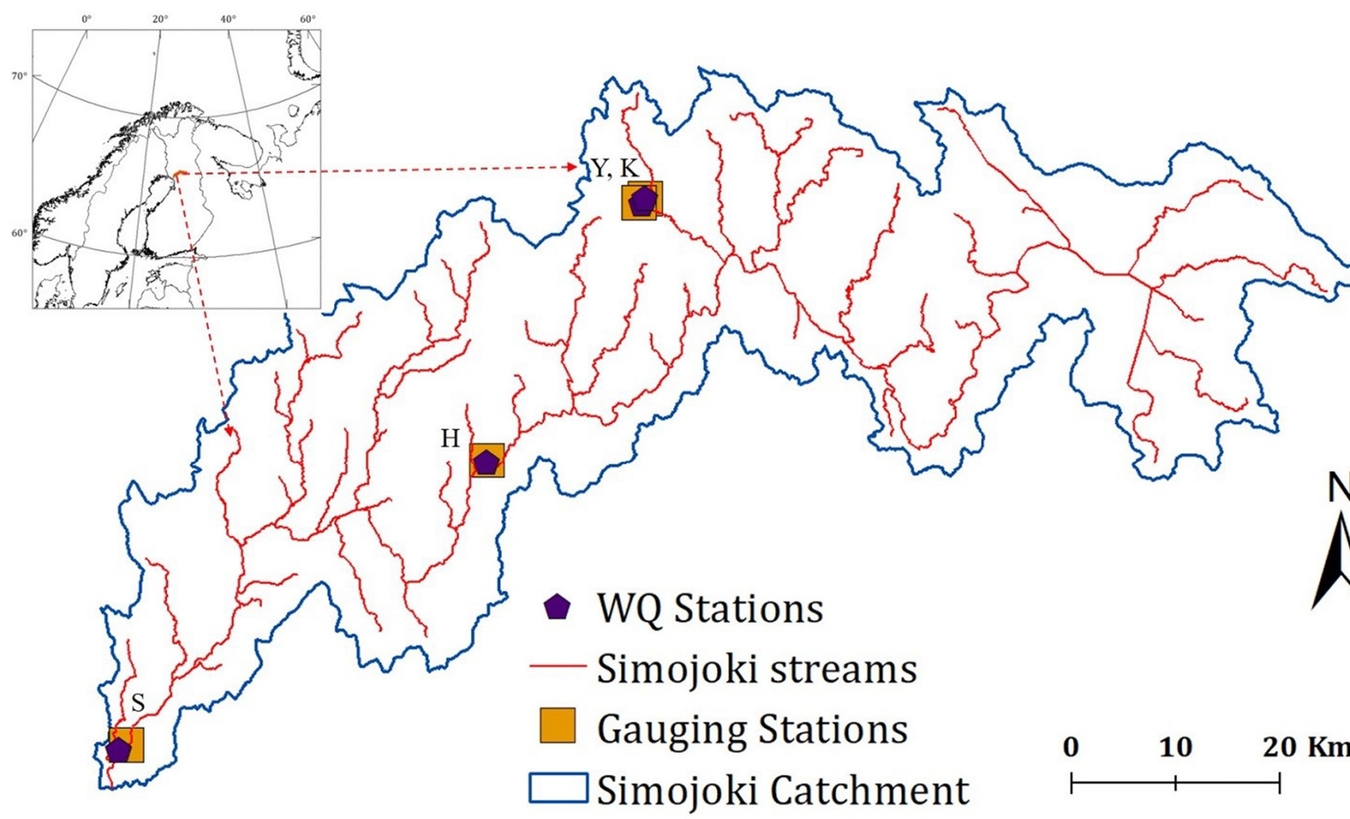

Fig. 1. Map of the Simojoki catchment showing the four gauging and water quality measurement stations in different sub-catchments. Stations Y and K represent headwater conditions of Ylijoki (Y) and Kotioja (K) catchments, Hosionkoski (H) is a medium-size catchment, and station S covers the entire Simojoki catchment.

2. Materials and methods

2.1. Simojoki study site

Simojoki is a northern boreal river catchment (3160 km^2) where peatlands and forests (53%) dominate. The major human impact is forest management, including peatland drainage, ditch network maintenance, and forest clear-cutting and replanting (Lepistö et al., 2014). Drained peatlands cover more than 30% of the catchment (Rankinen et al., 2006). Settlements and agricultural areas, located mainly along the river corridor, cover only around 3% of the catchment area (Perkkiö et al., 1995). The mean annual precipitation in the region is 700 mm and mean annual temperature is 1 °C, with 170–180 winter days per year (Rankinen et al., 2006). The Simojoki river typically freezes at the end of October, and the ice cover lasts until mid-May.

We estimated nutrient and sediment loads and concentrations at four different locations in the Simojoki catchment (Fig. 1). The two upstream sub-catchments, Ylijoki (Y) (56.27 km^2) and Kotioja (K) (18.11 km^2) represent headwater conditions in the catchment (Table A.2 in Supplemental materials (SM)). We also used one river station at the outlet of Hosionkoski (H) catchment (1981 km^2 area) and another station (S) near the outlet of the Simojoki catchment (Fig. 1).

2.2. Materials

Specific export coefficients that represent annual loading values of TN, TP, and SS per unit area for different land-use categories or land management practices were obtained from the literature (Launiainen et al., 2014; Palviainen et al., 2016) (Fig. 2). Data on current and historical land-uses in the Simojoki catchment were collected from different sources and analyzed (GEE, 2020; METLA, 2014). We then estimated loads and concentrations using the coefficients and land-use data, and compared the values with values measured at the streamflow and water quality monitoring stations in the different sub-catchments within the Simojoki catchment. Finally, we assessed uncertainties related to land-use analysis, export coefficients (Table A.1 in SM), and available data sources (Table A.2 in SM) for all steps in the workflow (Fig. 2).

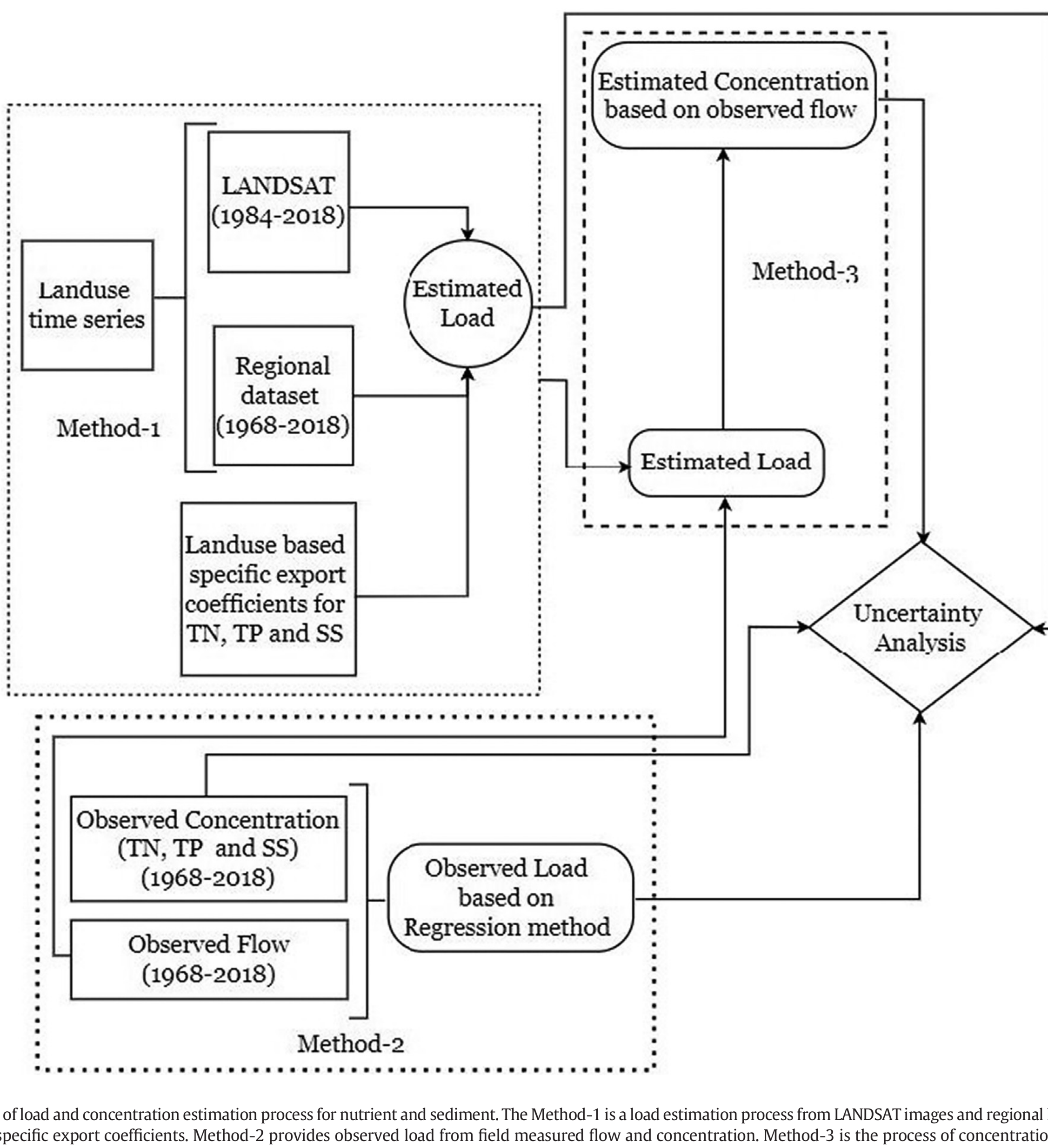

Fig. 2. Flowchart of load and concentration estimation process for nutrient and sediment. The Method-1 is a load estimation process from LANDSAT images and regional land-use database using available specific export coefficients. Method-2 provides observed load from field measured flow and concentration. Method-3 is the process of concentration estimation. The uncertainty analysis is the last step that analyzes all the methods.

2.3. Method-1: load estimation by the specific export coefficient approach

To estimate annual nutrient load and sediment export, we first obtained export coefficients (kg/ ha yr^{-1}) for TN, TP, and SS for available land-use category. For different land management practices, we used national land-use specific export coefficients originating from empirical field studies as mentioned by Launiainen et al. (2014) and Palviainen et al. (2016). We aggregated these land-use classes with the land-use categories specified in the database of specific export coefficients (Table A.1 in SM). In computation, we followed the steps summarized by Launiainen et al. (2014) and the succeeding research continued by Palviainen et al. (2016).

We then used two different data sources to assess land-use changes in the Simojoki catchment:

- land-use data source-I: land-use classification from Landsat image analysis (GEE, 2020)
- land-use data source-II: land-use classification from the Finnish Statistical Yearbook (METLA, 2014)

Specifically, we included both export coefficient uncertainty and land-use estimation-related uncertainty (relative uncertainty 10–20% depending on the data source) in our analysis. In addition to land-use, we also included nutrient deposition to water bodies and background

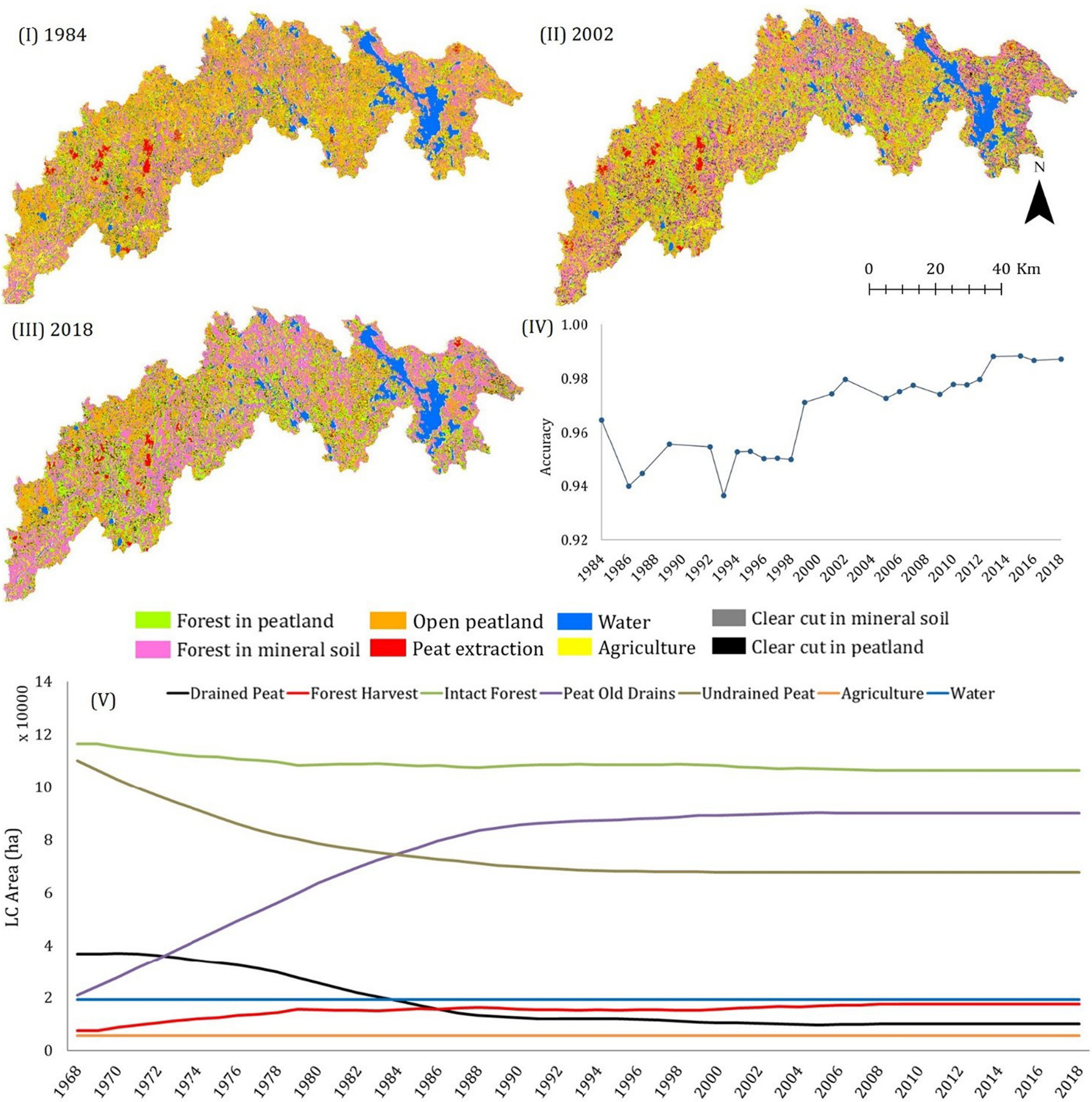

Fig. 3. Spatiotemporal distribution of land-use classes analyzed from Landsat images: sample results of (I) 1984 (II) 2002 and (III) 2018 for the entire Simojoki catchment. (IV) Accuracy with which each pixel was defined by Random Forest Classifier in GEE script. (V) Temporal changes in land-use classes based on the regional land-use database.

flux from intact forest land, but ignored point sources such as households as these are a minor contributor to loading in the Simojoki catchment (Rankinen et al., 2006).

2.3.1. Land-use data source-I

We analyzed Landsat images to infer annual land-use from 1984 to 2018. A script was developed (see Appendix-B in SM) based on the built-in functions in the Google Earth Engine (GEE) platform (GEE, 2020; Gorelick et al., 2017). We used three different versions of Landsat Thematic Mapper (TM) images: Landsat 5 (1/1/1984–31/12/1998), Landsat 7 (1/1/1999–31/12/2012), and Landsat 8 (4/11/2013–31/12/2018). We did not find any image for the Simojoki catchment before 1984. We chose a spatial resolution of 30 m × 30 m, with a cloud cover of less than 10%. The script considers:

- A simple composite function that computes Landsat top-of-atmosphere (TOA) composite from a collection of raw Landsat scenes for each year. The composites are built from orthorectified scenes, using computed TOA reflectance, as described by Chander et al. (2009)
- Standard TOA calibration, and then assigns a cloud score to each pixel using a simple Landsat cloud score algorithm (GEE, 2020)
- It then computes per-band percentile values from the accepted pixels.

We used Random Forest (RF) classifier (Pal, 2005) to train the samples. We trained the classifier on a collection of features, using the specified numerical properties of each feature as training data. In the last section of the script, all required functions to integrate possible land-use classes along with the classification accuracy score were provided. The accuracy of classified images was assessed based on the ratio between the number of correctly classified pixels and the total number of pixels in the image, using the confusion matrix function in GEE. Accuracy assessment of the image for each year was useful for understanding the RF Classifier for each specific land-use type, as mentioned by Rwanga and Ndambuki (2017).

2.3.2. Land-use data source-II

Readily available land-use data were taken from the Finnish Statistical Yearbook (METLA, 2014) (hereafter "regional land-use database"). The land-use classes were based on regional land-use statistics from 1968 onwards, which were further downscaled to the Simojoki catchment using the approach proposed by Kenttämies (2006). Nutrient loads and SS exports based on these land-use data were estimated only for the outlet of the Simojoki catchment (station S in Fig. 1).

2.4. Method-2: load estimation from measured data

To calculate the annual load of TN, TP, and SS from measured streamflow and concentration data, we applied a regression method (Walker, 1996) on the daily streamflow and concentration data measured at each selected monitoring station. Frequent sampling and strong concentration-streamflow (C-Q) relationships are required for accuracy (Walker, 1996). In our case, the slope of concentration-discharge (C/Q) relationship was sufficiently strong (e.g., $R^2 > 0.8$ at the Simojoki outlet (station S)), allowing us to use this method. Data on stream water concentrations were taken from the Hertta database (SYKE, 2020). Before 1982, the sampling frequency at the outlet of the Simojoki catchment was 4–5 samples per year, after which it increased to 10–25 samples per year (Lepistö et al., 2014).

2.5. Method-3: estimation of mean annual stream water concentrations

We divided annual load estimated using specific export coefficients by annual discharge at the monitoring stations, to estimate mean annual stream water concentrations of TN, TP, and SS. As two different land-use data sources were considered for the Simojoki catchment, we obtained two different time series of estimated concentrations for TN, TP, and SS. For the sub-catchments, only land-use data from Landsat images were used to estimate mean annual stream water concentrations.

2.6. Uncertainty analysis

Uncertainty analysis was used to assess how well the boundary zone of the load estimates based on specific export coefficients captured the measured loads. The uncertainty boundary was defined as the percentage of uncertain factors associated with export coefficients (Table A.2) and land-use classes. We used relative uncertainty for each specific land-use type and export coefficient, as described for the specific export coefficient method, to estimate load variation (minimum to maximum range) for each year. The uncertainty boundary approach was also used for the comparison of estimated concentrations with measured

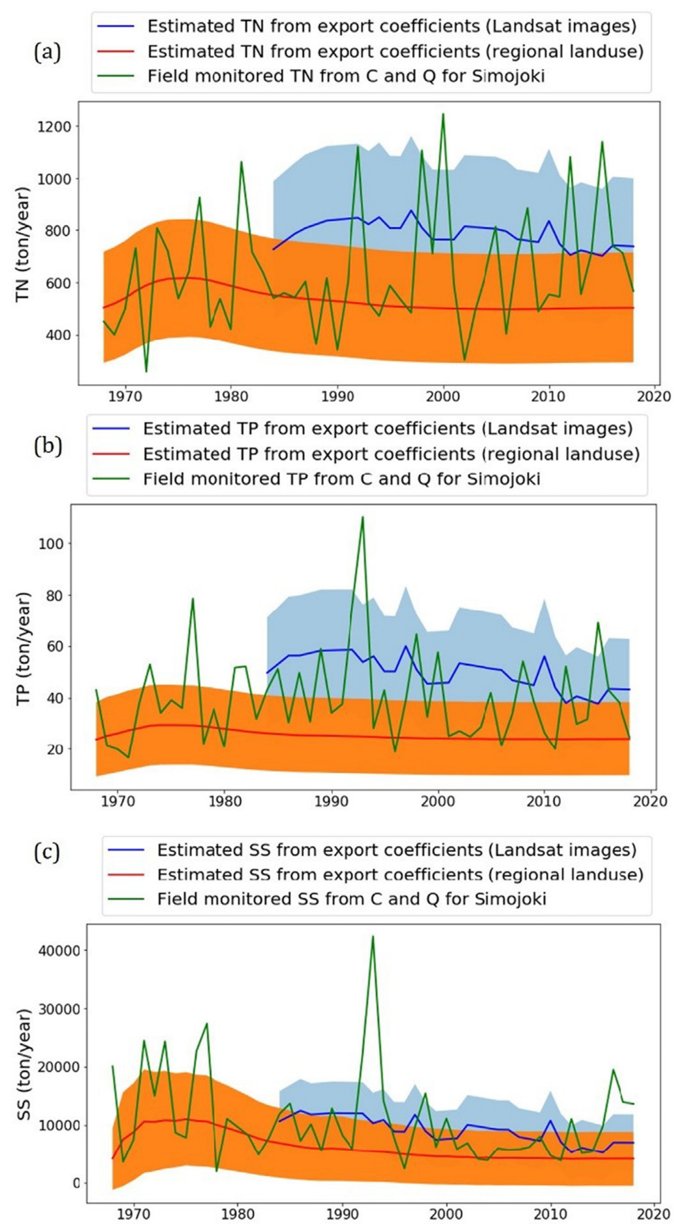

Fig. 4. Estimated and measured loads of (a) total nitrogen (TN) (b), total phosphorus (TP), and (c) suspended solids (SS) in the Simojoki catchment. For regional land-use data (1968–2018), the red line shows the estimated load and the orange shaded area is the uncertainty boundary. For Landsat land-use data, the blue line shows the estimated load and the blue shaded area is the uncertainty boundary based on Landsat land-use data 1984–2018. The green line shows measured load 1968–2018.

concentrations at field monitoring stations. To analyze trends in measured and/or estimated annual load and explore whether the export coefficients can reveal long-term field measurements, we tested for monotonic increasing or decreasing trends using the nonparametric Mann-Kendall test. The statistical significance of trends was tested following the approach presented by Salmi et al. (2002).

3. Results

3.1. Historical land-use changes in the Simojoki catchment

Analysis of Landsat images confirmed that peatlands and forests dominate in the Simojoki catchment. Other land-use types occupied less than 12% of the catchment area. A rapid change in land-use was observed during the study period (1984–2018), with a clear transition towards more forested areas (Fig. 3), with forest cover on former peatland reaching >30% in 2018 (Table C.1 in SM). The area of open peatland decreased with time (Fig. 3). No change was observed in the extent of agricultural areas, except in a small area downstream in the catchment. Forest regeneration (i.e., clear-cut) areas were scattered across the catchment, with no major spatial change throughout the period. For other land-use classes, only minor variations were detected throughout the study period. Detailed analysis of temporal land-use changes 1984–2018 for Simojoki and its sub-catchments scale are provided in Table C.1, Appendix-C.

For Landsat images used in land-use change assessment, the accuracy varied from 0.94–0.97 (Fig. 3IV) before 1999, but then improved as Landsat 8 images from 2013 to 2018 showed better accuracy. In 1986 and 1993, there was a sudden drop in accuracy, even though we followed the same procedure to classify images.

In contrast to trends based on Landsat images, those based on regional land-use statistics indicated a large change from "undrained peatlands" to "old drains". As undrained peat area started to decrease from 1968, the extent of old peat drains increased (Fig. 3V). By 1984, total drained area exceeded the area of undrained peat. For drained peat, we observed a progressive decrease for the first 18 years of the study period. All other land-use types remained almost constant throughout the period, except for some changes early in the period.

3.2. Accuracy of estimation of nutrient and SS loads

With the specific export coefficient approach, 64% of the measured TN load in the Simojoki catchment fell within the uncertainty boundary of estimates obtained from Landsat land-use analysis (land-use data

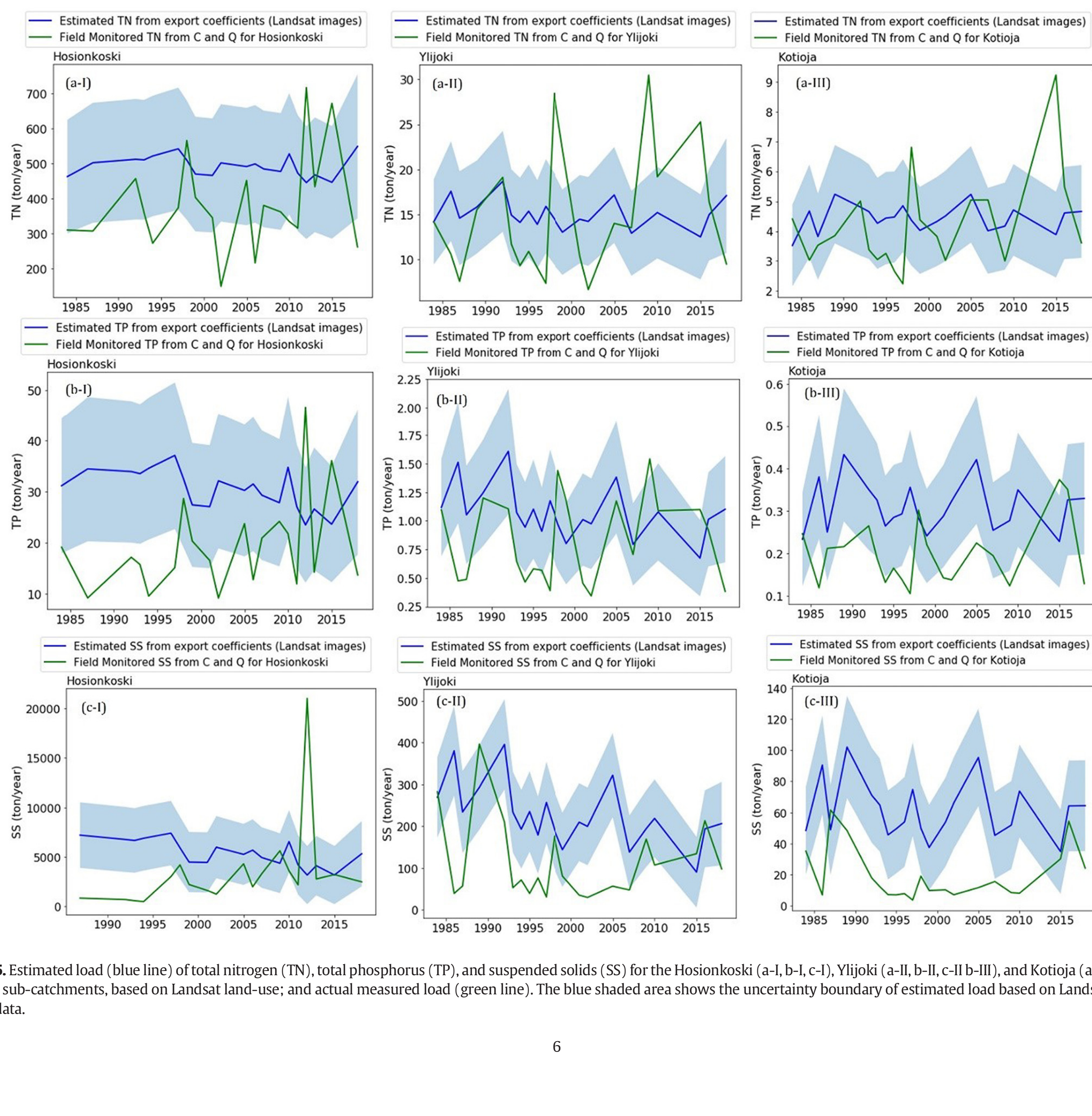

Fig. 5. Estimated load (blue line) of total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) for the Hosionkoski (a-I, b-I, c-I), Ylijoki (a-II, b-II, c-II b-III), and Kotioja (a-III, b-III, c-III) sub-catchments, based on Landsat land-use; and actual measured load (green line). The blue shaded area shows the uncertainty boundary of estimated load based on Landsat land-use data.

source-I, blue shaded area in Fig. 4), and 76.5% of the measured TN load fell within the uncertainty boundary of estimates obtained from regional land-use data (land-use data source-II, orange shaded area in Fig. 4). For TP load, the corresponding percentages were 60% and 58.8%, respectively, while for SS load, they were 68% and 62%, respectively (Fig. 4). For detailed results, see Table D.1 (Appendix-D in SM).

The export coefficient approach gave larger annual differences for the sub-catchments than for the entire Simojoki catchment. At the Hosionkoski (H) outlet, the average difference between estimated and measured load during 1984–2018 was 109 ton/year for TN, 11 ton/year for TP, and 1953 ton/year for SS. In the same period, the proposed uncertainty boundary from the export coefficient approach captured 57.1% of measured TN load, 38.1% of TP load, and 28.6% of SS for the Ylijoki sub-catchment (Fig. 5). For the smallest sub-catchment (Kotioja), 76.2% of the measured TN load, 35% of TP load, and 19.1% of SS load fell within the proposed uncertainty boundary estimated from export coefficients (for detailed load results, see Tables D.2–D.4 in SM).

3.3. Concentrations

Consideration of existing export coefficients and uncertainty boundary functioned better to capture measured concentrations than measured load at the Simojoki catchment outlet (station S). When using regional land-use statistics, 70.6% of measured TN load, 86.3% of TP load, and 90% of SS load fell within the uncertainty boundary of estimates based on specific export coefficients. However, during 1984–2018, the estimated concentration based on Landsat land-use data was higher than the measured concentration (Fig. 6). For detailed concentration results, see Table E.1 (Appendix-E in SM).

For the small Kotioja sub-catchment, estimated TN concentration showed a similar pattern to measured concentration, but concentrations of TP and SS were overestimated. For the Kotioja sub-catchment, 67% of measured TN concentration fell within the uncertainty boundary of the estimates, whereas the percentage was lower for the Ylijoki (62%) and Hosionkoski (55%) sub-catchments (Fig. 7). The Hosionkoski sub-catchment uncertainty boundary captured 35% of measured TP concentration and 42% of measured SS concentration, which were the highest values for all sub-catchments (Tables E.2–E.4, Appendix-E in SM).

3.4. Accuracy of the method in capturing long-term trends

During 1968–2018, measured loads and concentrations of TP and SS at the Simojoki catchment outlet (station S) followed downward trends, while those for TN showed increasing trends ($p < 0.001$). However, for individual sub-catchments, the trends based on measured data showed increases for TN, TP, and SS in some cases (where p is at least <0.05). For estimated load and concentration (regional or Landsat land-use data), significant downward trends ($p < 0.001$) for some time series were found, whereas the actual measured data showed increasing trends (Table 1).

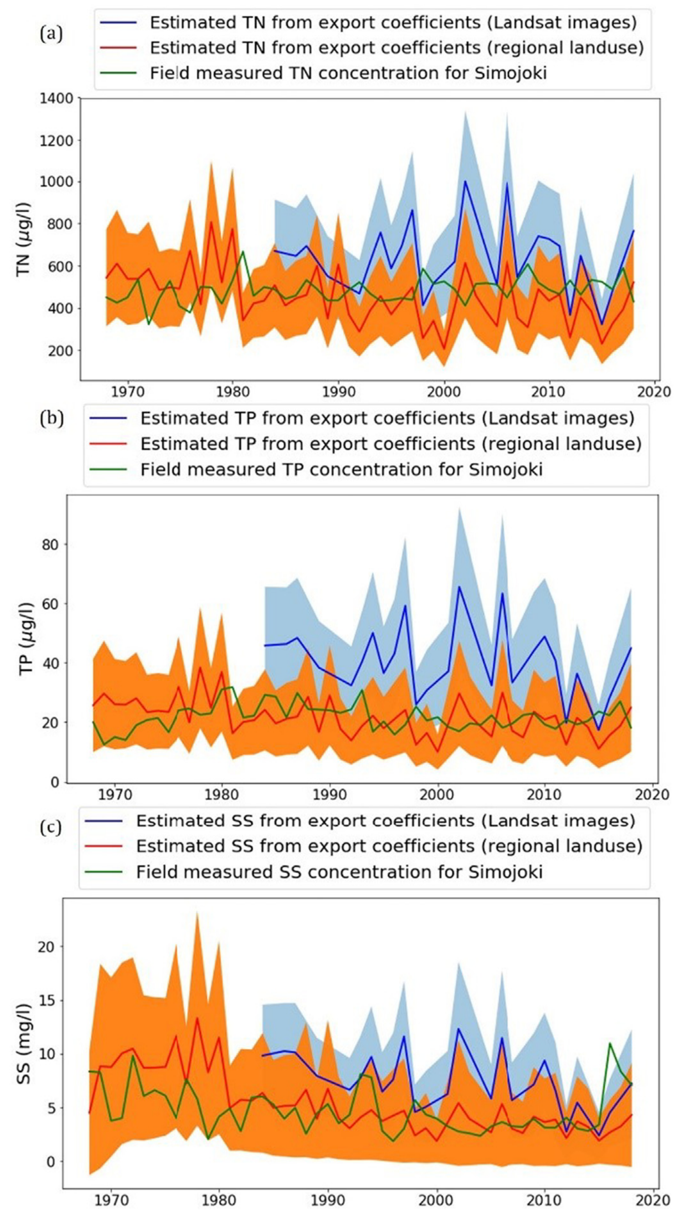

Fig. 6. Estimated and measured concentrations of total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) at the Simojoki outlet. The red line shows estimated concentration based on regional land-use data (1968–2018) (uncertainty boundary shown as orange shaded area) and the blue line shows estimated concentration based on Landsat land-use data (1984–2018) (uncertainty boundary shown as blue shaded area). The green line shows measured concentrations.

4. Discussion

Use of land-use data derived from Landsat images in the specific export coefficient approaches (based on recent data on coefficients) was effective in estimating nutrient loads and made it possible to analyze spatial loading patterns throughout the study catchment. The export coefficients for each specific land-use also included the long-term effect on loads of water protection measures in the study region (Finér et al., 2010). The specific export coefficient approach applied in this study differed slightly from that in previous load calculations (Kenttämies, 2006) through the use of different export coefficient ranges for different nutrients, even within land-uses. The uncertainties associated with the approach, mainly derived from forest management activities in the peatland-dominated catchment. Thus, the uncertainty boundary introduced to estimate TN, TP, and SS exports depended on the accuracy of the land-use estimate and representativity of the export coefficient for each specific land-use.

4.1. Use of historical land-use data to evaluate land-use changes

Understanding historical land-use changes are important when formulating measures to improve catchment-scale management of water quality. In this study, best available land-use information based on Landsat satellite images and data in regional land-use statistics showed similar temporal patterns of forestry land-use in the Simojoki catchment from 1968 to 2018. An increase in forestry activities and a decrease in the intact forests were observed in the catchment in the early 1970s, as forest management intensified (Lepistö et al., 2014). A decrease in area identified as open peatlands (although with some fluctuations over time) and a corresponding increase in forest cover after peatland drainage were also evident, reflecting historical changes (Rankinen et al., 2004).

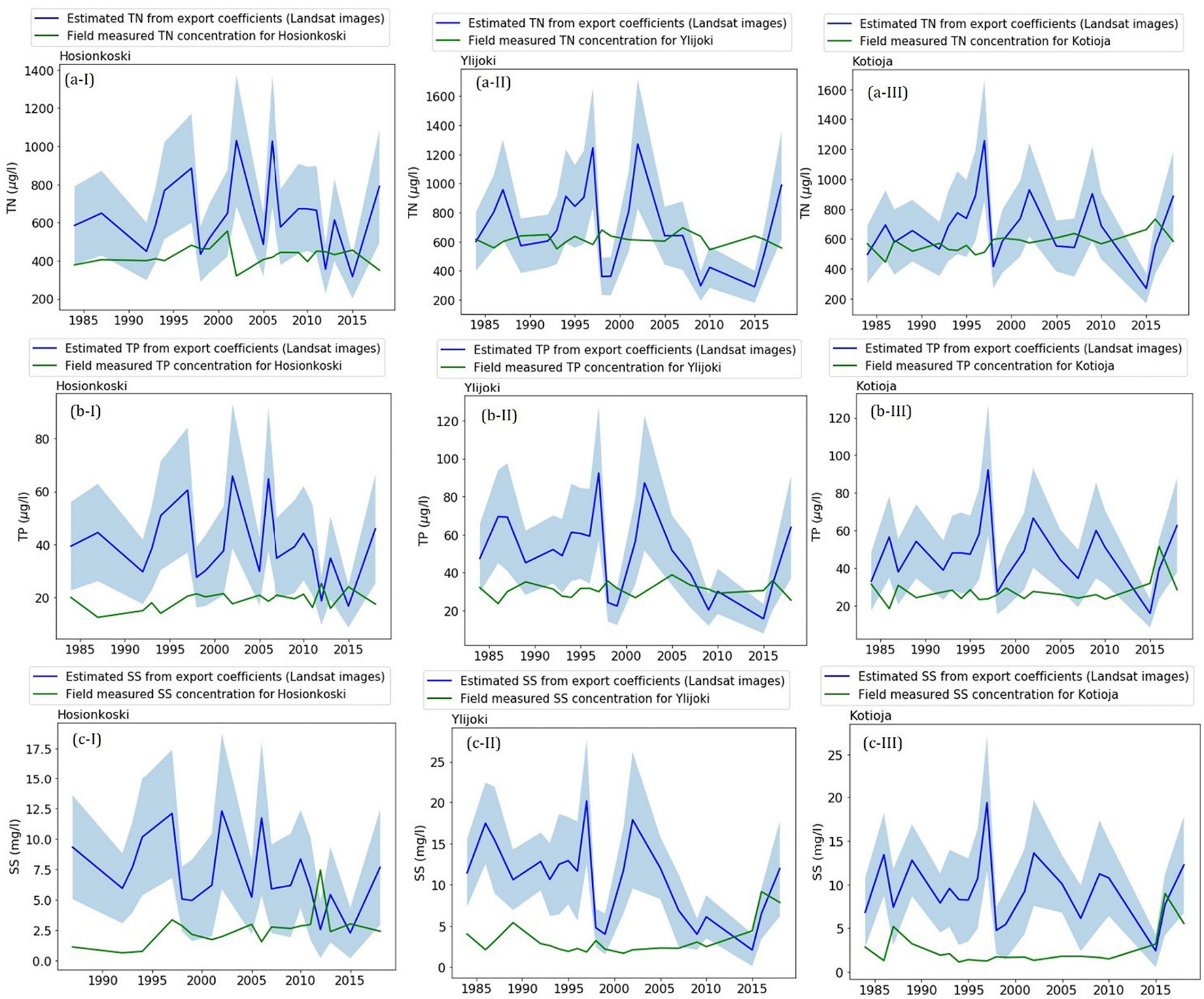

Fig. 7. Concentration estimated from export coefficients (blue line) and measured concentration (green line) of total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) at the Hosionkoski outlet ((a-I), (b-I), (c-I)), Ylijoki outlet ((a-II), (b-II), (c-II)), and Kotioja outlet ((a-III), (b-III), (c-III)). The blue shaded area is the uncertainty boundary based on Landsat land-use data (1984–2018).

Accuracy and resolution are important when using land-use data obtained from Landsat images. Various imaging-related factors, such as cloud cover in Landsat scenes, affected the accuracy of results for the Simojoki catchment, particularly before 2013. Narrower spectral bands, better calibration, and the specific geometry of modern Landsat sensors (Irons et al., 2012) were the main reason for the increased accuracy level in more recent data. Composite image formation for each year from Landsat scenes might also have affected the accuracy, e.g., the random fluctuation seen in open peatland, as also reported for agricultural land-use classes (Wulder et al., 2019). Another possible reason might be uncertainties associated with trained data samples for land-use analysis from Landsat images (Castilla and Hay, 2007). Consideration of more trained data samples can be one way to improve the accuracy of the classified images, especially for images taken from Landsat 5 and Landsat 7.

4.2. Use of the specific export coefficient approach to assess nutrient estimation and historical changes

Although there was considerable variation in flow in the Simojoki catchment during the study years, the estimates obtained from specific export coefficients were in reasonably good agreement with measured values, particularly for TN and SS. Estimated concentrations based on specific export coefficients were also similar to measured concentrations at the Simojoki outlet. However, in some cases, the estimates were less accurate, as the export coefficients were constant and could not capture the hydro-meteorological variability of the catchment. Another plausible aspect for the mismatches of the predicted load could be related to the decay and nutrient transformation effects in the larger river systems, the process that specific export coefficients do not cover. The export values that were monitored in different empirical studies for different land-use practices, include seasonal loading information arriving from different land-use activities. However, the measurements and monitoring were done in small catchments close to land-use activities and thus, estimated loads did not include decay processes that occurred from land to sea in the surface water (river) system.

Regional land-use statistics do not contain spatial information, whereas Landsat images can reveal spatiotemporal historical, present, and future trends, which is important in large-scale quantitative assessment in peat-dominated catchments (Haghighi et al., 2018; Lambin, 1997; Linderholm and Leine, 2004; Schneider and Gil Pontius, 2001; Verburg et al., 1999). The more precise information on spatial land-use coverage for each year resulted in more variation in estimated loads and concentrations based on Landsat data 1984–2018 than those based on regional land-use data 1968–2018.

Table 1
Trend analysis for total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) load and concentration for all catchments. ***$p < 0.001$ (dark black arrow), **$p < 0.01$ (dark blue arrow), *$p < 0.05$ (light blue arrow), ns: non-significant. Arrows indicate direction of trend.

	Based on regional land-use					Trend in estimated data		Trend in measured data	
			From	To	n				
Simojoki	Load	TN	1968	2018	51	ns		***	↗
		TP	1968	2018	51	ns		***	↘
		SS	1968	2018	51	ns		***	↘
	Concentration	TN	1968	2018	51	*	↘	***	↗
		TP	1968	2018	51	ns		***	↘
		SS	1968	2018	51	**	↘	***	↘
	Based on land-use from Landsat							Measured	
	Load	TN	1984	2018	35	***	↘	ns	
		TP	1984	2018	35	***	↘	*	↘
		SS	1984	2018	35	***	↘	ns	
	Concentration	TN	1984	2018	35	ns		ns	
		TP	1984	2018	35	**	↘	*	↘
		SS	1984	2018	35	***	↘	ns	
Hosionkoski	Load	TN	1984	2018	35	ns		ns	
		TP	1984	2018	35	***	↘	**	↗
		SS	1987	2018	32	***	↘	***	↗
	Concentration	TN	1984	2018	35	ns		ns	
		TP	1984	2018	35	ns		**	↗
		SS	1987	2018	32	*	↘	***	↗
Ylijoki	Load	TN	1984	2018	35	ns		ns	
		TP	1984	2018	35	**	↘	ns	
		SS	1987	2018	35	***	↘	ns	
	Concentration	TN	1984	2018	35	ns		ns	
		TP	1984	2018	35	**	↘	ns	
		SS	1987	2018	35	***	↘	*	↗
Kotioja	Load	TN	1984	2018	35	ns		**	↗
		TP	1984	2018	35	ns		ns	
		SS	1987	2018	35	ns		ns	
	Concentration	TN	1984	2018	35	ns		***	↗
		TP	1984	2018	35	ns		ns	
		SS	1987	2018	35	ns		ns	

Using data on flows and concentrations of different catchments that contribute to the sea, Räike et al. (2020) found an increasing trend in TN load for different regions in Finland. Drainage activities within catchments have been found to increase nutrient concentrations from catchments to the sea (Nieminen et al., 2017). Land drainage for forestry and forest ditch maintenance can both increase nutrient (TN, TP, and SS) loads and concentrations in peat-dominated catchments (Joensuu et al., 2002; Nieminen et al., 2018a). Analysis of field measurements showed significant increasing trends in TN concentrations and loads 1968–2018, but these trends were not significant for the later period 1984–2018 (Table 1). In an earlier study on the Simojoki catchment, Lepistö et al. (2008) found significant increasing trends in organic N, which is the dominant component of total N. Climate factors such as soil temperature in the cold season may contribute to higher concentrations of N during low flow in mid-winter and higher mineralization, increasing organic N losses (Lepistö et al., 2008). Estimates based on specific export coefficients couldn't capture the increasing trend seen in measured data and in fact showed a decreasing TN trend. Initial land drainage, followed by ditch maintenance after 1980, were possible contributors to the difference between measured and estimated TN load, as we used 0 kg/ha/year as a TN coefficient for ditch maintenance in this study.

The uncertainty range of the TN load estimates based on specific export coefficients for 1968–2018 was 317–746 ton/year, which was in line with a previous estimate for the Simojoki catchment of 655 ton/year ((Lepistö et al., 2006). For 1984–2018, the estimated mean annual TN loads based on the specific export coefficient for the Kotioja (4.44 ton/year) and Ylijoki (15 ton/year) sub-catchments were slightly higher than estimates reported by Kortelainen et al. (1997), which were 3.6 ton/year for Kotioja and 13.4 ton/year for Ylijoki in the period 1976–1992.

The specific export coefficient approach indicated decreased TP and SS loads and concentrations for the Simojoki catchment, which was also same as the measured data. Uncertainty might arise in TP estimation from export coefficients (Table A.1 in SM), as these only represent the TP content exported from corresponding land-use to the outlet, regardless of the quality of the soil in the land-use.

Considering the land area supplying the different outlets, we found disproportionately high streamflow and nutrient load at the Simojoki outlet compared with at the outlets of the sub-catchments. We also found some significant opposing trends between the estimates based on export coefficients and the measured values for the sub-catchments, with higher uncertainty in smaller catchments. Therefore, export coefficients for the specific land-use classes were less representative of the measured load in small catchments. For large catchments, underestimates and overestimates balanced each other out when using the same export coefficient values.

Some environmental changes occur slowly, especially in soils (Araújo and Rahbek, 2006). However, long-term (decadal) land-use changes in catchments have not been thoroughly documented, although historical land-use can have a significant role in nutrient and sediment loading. Thus, identification of previous land-use and subsequent estimation of nutrient and sediment loading based on these land-uses are important for understanding status and assessing long-term environmental impacts. The method based on specific export coefficients developed in this study allows the catchment-scale consequences of land-use changes for nutrient and sediment loads to be assessed at a decadal scale. From an environmental management point of view, the inclusion of more detailed spatial information about drainage activities and the effects of hydro-meteorological inputs on load estimation would make the proposed method more useful.

5. Conclusions

By combining specific export coefficients with land-use data from Landsat and regional land-use statistics, we obtained a clear picture of nutrient load and SS export in the peatland-dominated Simojoki catchment over decades. The estimates obtained matched measured values for large catchments but were less accurate for smaller catchments. Overall, the uncertainty in estimates relative to measured values ranged from 7% to 20% for TN, 0% to 18% for TP, and 13% to 43% for SS. The uncertainty boundary was able to capture 90% of measured TN, TP, and SS loads or concentrations, which could fluctuate from 29% in all cases. The specific export coefficient approach also predicted similar (negative) trends ($p < 0.001$) to those seen in measured values for TP and SS, but showed some opposing trends for TN. Overall, the results illustrate the importance of evaluating historical reasons for changes in nutrient and sediment loads and concentrations when assessing the effects of large-scale peatland drainage.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors (Codes and detailed results are available in supplemental materials).

CRediT authorship contribution statement

Joy Bhattacharjee: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Hannu Marttila:** Conceptualization, Methodology, Writing – original draft, Investigation, Supervision. **Samuli Launiainen:** Conceptualization, Writing – review & editing. **Ahti Lepistö:** Writing – review & editing. **Bjørn Kløve:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.146419.

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